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Special Issue: Contemporary Adjustments to Teaching Water Economics in Light of Challenges Facing the Water Sector and Its Users

(Special Guest Editors: Ariel Dinar and Mehdi Nemati)

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Applied Economics Teaching Resources

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Teaching and Education Commentary

Contemporary Adjustments Needed to Teaching Water Economics in Light of Changes Facing the Water Sector and Its Users: Introduction to the Special Issue

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JEL Codes: A2, Q15, Q2, Q25
Keywords: Climate change, demand management, groundwater, graduate and undergraduate teaching, interdisciplinary teaching, water economics curriculum

Abstract
Water resources management in many countries faces challenges that stem from a combination of impacts of climate change, population growth, and globalization. This introductory note argues that contemporary adjustments are needed to the curriculum of teaching water economics in light of these changes. The note reviews the contribution of each of the thirteen papers in the special issue to the question posed in the title of that special issue. The note concludes that while efforts and new ideas embedded in the papers reviewed, are effective, there is still room and need for additional aspects to be considered in the new water economics curriculum.

1 Motivation for the Special Issue

The water sector has been experiencing increased levels of climate change-induced water scarcity, frequent and longer droughts, water quality deterioration, human health implications, infrastructure fatigue, increased competition over dwindling resources, conflicts, and globalization, among other issues. These issues have various impacts on water managers and users across different sectors (e.g., agricultural, industrial, hydropower, environmental, and urban). In addition, new water sources, such as desalinated ocean and brackish groundwater, treated wastewater, and flood water, have been introduced in recent years for more substantial use by these subsectors. Furthermore, several management practices have been introduced, including joint (cooperative) management of various types of open-access water sources. These changes and challenges require skills that incorporate physical, institutional, and economic expertise on the part of water resource planners, managers, and policy makers.

Does the water (resource) economics curriculum used in our classes address such challenges and skill needs? Does it allow proper education and training of the next generation of water economists, planners, and managers?

Water economics has been taught for many decades at undergraduate and graduate levels. Teaching approaches included the traditional profit/utility-maximizing agents' behavior (e.g., farmers, households), where individuals decide to allocate a given amount of water among consuming activities. Main issues such as availability, allocation, pricing, investment, technology, and management of water resources have been at the forefront of the field of water economics. In recent decades, water resources worldwide have seen many transformations both locally and globally, making the challenges facing water-using agents much more complicated and, as a result, requiring a broader set of more advanced skills for the tools and methods they employ.

This AETR Special Issue (https://www.aetrjournal.org/) addresses whether the water economics curriculum is ready to cope with the increased level of challenges regarding water quantity, quality, security, and derived complications. Papers in the special issue that are summarized and synthesized in this introductory note also provide examples of how to introduce tools and class activities that address such new challenges to the water economics curriculum. The following section consists of a short description of the various papers in the special issue. All in all, there are thirteen papers describing proposed courses and educational activities, as well as those that were already taught more than once in previous years. Papers describe courses that target graduate as well as undergraduate students. Some courses are designed for economics students, and some can accommodate non-economics students. Most papers provide (either in the paper or in a supplementary appendix to the paper) information about the syllabus, homework, or class assignments, students' feedback, and learning assessment at the end of the course.

The general message from this special issue is that our profession has stepped forward to prepare learning material that could help train the next generation of water economists and water managers to successfully meet the challenges faced by the water sector in the years to come. Is that effort sufficient and effective? After realizing what each of the thirteen published papers in the special issue offers, we will try to answer these questions in the remaining introductory note.

2 Highlights of the Various Papers in the Special Issue

Zilberman et al. (2023) present a new development for a water economics course that analyzes water allocation in a dynamic context. Not like traditional courses that focus on the microeconomics of water (e.g., water use at the levels of producers and consumers), this course examines water use and allocation in the context of evolving systems and institutions, similar to what Dinar and Tsur (2021) coined a "comprehensive approach." The paper by Zilberman et al. (2023) elaborates on the components of the course, the key aim of which is to provide students with a historical, global perspective and build on the role of political economy and public policy in the development of water systems. The paper presents the six elements of the course: an introduction to basic facts and features of the evolution of water systems; the political economy of water systems and their evolution over time; a cost-benefit analysis of developing water supply chains; regulatory interventions such as pricing, allocation, and management of water; negative externalities and environmental implications of water use; and global water issues. The paper also includes a set of assignments for the students in the course.

Brouwer (2023) describes the objective, methods, and structure of a graduate-level course offered to students in the Department of Economics and other schools and departments on the University of Waterloo, Ontario, Canada campus. The course introduces real-world challenges by linking theory and practical examples. The course aims to help students realize the role economic theory plays in real-world practical water management. The course's theoretical component is based on several water economics textbooks and concepts used in the context of water. The practical part consists of four main components: (1) a multi-source water allocation game; (2) a group assignment related to dam building and the subsequent monetary impacts on different sectors; (3) a survey data collection and analysis assignment, where students experience how different market and non-market valuation methods perform in practice; and (4) a field trip visiting local water facilities to realize practical managerial needs and ways to address them.

Nemati and Dinar (2023) observed that the share of agency staff involved in water decision making with a background in water economics in California and local water agencies is less than four percent. To address such a gap, they developed a general water economics and policy course that focuses on strengthening undergraduate non-economic students' understanding of water economics principles and how they can be used to provide insights into the implications of various water policy options and decisions. The course is targeted toward university upper-level non-economics students. The paper describes the objectives of the course, its building blocks and content, and its achievements in terms of learning outcomes. The paper also presents course achievement results from a learning assessment survey, comparing the knowledge and understanding gained between the first and last week of the course. While the course is specific to California water issues, the pedagogical principles can still be applied to any other state or country and adjusted to the specific water issues and challenges in that state or country.

Ward (2023) calls for introducing innovations in the water resource economics curriculum due to several climate-related challenges faced by those who would become water managers. Some of those challenges include addressing population stress, food security, water security, energy security, environmental protection, peace, economic development, health, climate, and poverty. Few examples exist despite the need for innovations in the water economics curriculum. The paper addresses several curriculum innovations suggested for use in a water economics course. The article presents economic principles needed to form a foundation for curriculum reform in water economics so that students will better understand today's water challenges. In addition, the paper identifies adjustments required to ensure a solid education and training of the future generation of water economists. These two aspects are addressed by describing the range of water-related issues using international contexts. The paper incorporates several innovations to the syllabus, such that they can prepare water economics students to understand better and address emerging water science and policy challenges. A mathematical programming model is implemented as a homework assignment to demonstrate the various concepts used in the class.

Colby (2023) describes the principles of a water resource economics course, which provides a new focus, given global water crises and innovations in effective water management and governance. Among the aspects described are a new generation of water policy tools and an explanation of the role of benefit-cost analyses in the policy process. The paper suggests a more comprehensive approach, emphasizing the role of water in energy, food, and development economics; social justice and cross-cultural considerations; up-to-date understanding of neurobehavior in economic water-related decision making; and the importance of non-market valuation and regional economic methods. Several new aspects provided in the course include geospatial data in water resource economics econometric analyses and more sophisticated treatment of risks related to extreme events such as floods and droughts. The article offers several other practical recommendations for designing upper-level undergraduate and graduate water resource economics courses and includes a list of key topics and sources for class readings.

Whittington and Duncan (2023) describe their experience with developing and teaching a multidisciplinary graduate course from 2010 to 2018. The motivation for the course (like in the case of Nemati and Dinar) was an observation by the authors of a need to train Water Sanitation and Hygiene (WASH) sector practitioners at universities to understand current WASH conditions and to assess possible and actual policy interventions in the sector. The course was designed to be accessible to non-economics and undergraduate students. The course was taught synchronously online at two universities in the United States and United Kingdom. The paper describes the learning objectives and the conceptual framework for policy analysis on which the course was based. In addition, the problem-based learning approach composed of case studies and policy memo assignments that are uniquely developed for this course is described. Because the course has been taught for nine years, the authors were able to extract and share eleven key messages that students are expected to think about when reflecting on the course assignments. The course uses advanced technology, enabling more active participation on the part of the students, and allowing them to watch recorded lectures outside of the class.

Zetland (2023) develops a course that places economic experiences in local institutional and physical contexts and with insights from other disciplines, such as planning and cost-benefit analysis, if they may affect policy consequences. The paper argues that case studies offer a useful way to demonstrate how theory is interpolated for the real world. During this course, students research, write, and present a case study paper on water scarcity affecting a major city and its political and hydrological surroundings. Via the presentation in class, the case helps everyone understand water issues at different scales, local and regional; the scopes associated with water management, such as issues for irrigators and for urban users; and disciplinary perspectives aspects, such as engineering and politics. The use of case studies in the course helps students explore real-world local and disciplinary complexities. It also helps contextualize economics and reveal other factors affecting water management and use. This paper provides a framework for teaching water economics centered on problem-based case studies.

Zekri (2023) introduces a course designed to teach water economics in desert environments. Looking at a map of the world, desert regions cover quite large areas of the globe, and with the desertification of lands, these desert regions could expand over time. Desert regions rely mainly on groundwater aquifers for the supply of water. In contrast, the physical supply systems are less complex than in other environments where surface water prevails and interacts with groundwater. The course highlights the interactions between groundwater and urban water demand in desert regions. Therefore, the course focuses on demand-side policies such as water quantity restrictions, water rate setting, and promoting technology adoption to save water, to name a few policies. In addition to the effectiveness of the policy interventions on water conservation, the paper emphasizes the environmental impacts and energy requirements of desalination technology as a limit to supply. Another important alternative water source for cities is improved efficiency from agricultural water markets. Such water-related policies are demonstrated and taught in the course. In addition, desert cities are located in proximity to irrigated agricultural regions, and thus, the course also addresses the social barriers to using treated wastewater in irrigated agriculture, which can be a significant water source. The course has been taught since 2011 to undergraduate students through lectures and lab work with the support of videos and flipped classrooms. During the last weeks of the course, each student presents a paper on a pre-assigned main issue to the class.

Wada et al. (2023) introduce in their paper the important question of groundwater sustainability, which has been at the center of economic discourse in recent years. Using a specific aquifer—the Pearl Harbor Aquifer, they apply water economic principles to teach students the linkage between welfare maximizing management of coastal groundwater and hydrological principles. Using an Excel model, the authors find the optimal transition paths of groundwater pumping, price, and groundwater head level and the corresponding solutions in the long run. The paper describes very diligently the entire process of reaching a solution, including setting parameter values and modifying objectives, variables, and constraint cells in Excel to facilitate the successful replication of the results. The course expands the nature of the economic framework by extending the economic issues to be optimized. These include watershed conservation, protection of groundwater-dependent ecosystems, and management of multiple connected aquifers. Through a useful tool that demonstrates the consequences of different management options of an aquifer, the authors were able to engage students in data collection, modifications of the algorithm, the introduction of extensions to management issues, and the ability to compare various policy interventions.

Wilson (2023) presents a course on the water markets in practice. Water markets are a public policy tool that can help allocate water to its highest value uses, creating more efficient outcomes. However, many undergraduate students, especially non-economics majors, face difficulty understanding the equi-marginal principle in markets with a relatively large number of agents. This paper presents a classroom simulation that exposes students to the practical complications of establishing and operating a water market and its outcomes. The activity is part of a larger module about teaching market allocations, where students are requested to role-play as managers/agents of businesses that need water for operation once the initial water endowments are assigned to some of the agents. Students have to buy and sell water on the market to maximize their welfare. The paper shares the results of an assessment showing that students gained a deeper understanding of relative welfare gains from water trades and realize how a lack of information and negotiating power may lead to inefficiency.

Rahman et al. (2023) develop a course that integrates water resources into the economics curriculum such that it helps students understand water-related issues, water distribution, and the implications of current water management policies on future water sustainability. The paper argues that teaching water economics in most countries is mainly limited to basic economic theories and applications. The authors examine the current state of water issues covered in undergraduate and graduate courses across various institutions in the United States. Using text analysis of the water economics syllabus, they inquired whether states facing different levels of water stress (four levels of water stress) would respond by different coverage of water issues in the water economics curriculum. Findings suggest that water economics programs in different water stress zones are characterized by different water issues in the syllabus of the courses taught in these states. The paper also surveyed different water economics programs to identify three teaching approaches—active learning, experiential or community-based learning, and inquiry-based learning incorporating water topics into existing economics curricula, enhancing students' understanding of basic economic theory, analysis, and real-world implications.

Kunwar et al. (2023) share their undergraduate experiential learning course on water resources. The course combines learning experience in the classroom with community outreach and international research experience via a study abroad program. The course development closely follows the principles of experiential learning theory and consists of four learning components: (1) field-based data collection, problem identification, and setting a conceptual framework; (2) data analysis, problem identification, and development of potential policy interventions; (3) implementation in the field in a study abroad program; and (4) sharing the findings among classmates and community outreach. The course included a unique feature, benefitting from having graduate students mentor undergraduate students and helping them with empirical analysis, as well as leading discussions in developing policy tools and solutions. The broader impacts of these experiential learning courses were evident in the expanded student learning experience, impact on the community, gaining undergraduate research experience, and showing potential for the course to serve as a model for other teaching institutions.

Edwards et al. (2023) present a paper that focuses on training students to calculate price elasticity of demand for policy purposes. This paper builds on recent developments in understanding consumer responses to water pricing, including equity issues and water utility interest in adopting innovative pricing approaches. Instructors of water economics courses can use the tools developed in this paper to teach urban water pricing to both undergraduate and graduate audiences. The paper includes a set of activities and resources to integrate concepts of price elasticity of demand, conservation pricing, utility considerations, and equity issues. Following the use of such materials, students are expected to know how to calculate prices (average and marginal) and elasticities and explain these values in the broader context of conservation and equity.

3 Discussion

All thirteen papers in this special issue add separately and jointly to our understanding of possible advancements in teaching water economics at the undergraduate and graduate levels of economics and non-economics courses on water economics and policy. Several papers provide information on specific courses or parts of courses that can be adopted and adjusted by instructors teaching water economics at the undergraduate and graduate levels. Several papers provide components that can be incorporated into existing courses. Several papers develop algorithms to address specific issues using Excel and GAMS. Different pedagogical models, such as active, experiential, and inquiry-based learning, are explored as well.

Our suggested take-home from this special issue is that the water economics discipline, while making significant progress and innovation in the water curriculum, still needs to keep investing resources to improve the coverage of courses and monitor their effectiveness on the students in the classes. We have not seen interdisciplinary collaboration in preparing the courses. As we move into the uncertain future, the water economics curriculum should reflect multidisciplinary considerations and collaborations to make the courses more comprehensive and inclusive of various approaches, priorities, and methods. The papers in this special issue provide valuable insights for incorporating multidisciplinary approaches in the water economics curriculum. These approaches can potentially enhance the scholarship of teaching and learning by shedding light on their impacts on student learning, post-graduation outcomes, and the generation and distribution of water economics knowledge. By exploring these impacts, educators and researchers can better understand the effectiveness of these approaches, improve teaching practices, and contribute to the advancement of water economics education.

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Feature Article

Teaching Water Economics Using Dynamics and a Political Economy Framework

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JEL Codes: Q25, Q55, Q12, R12, P14
Keywords: Allocation, benefit-cost analysis, environment, evolution, political economy, water

Abstract
We propose a framework for a water economics course that analyzes water allocation in a dynamic context. The proposed course has six elements: first, an introduction to basic facts and features of the evolution of water systems; second, the political economy of water systems and their evolution over time; third, benefit-costbenefit-cost analysis and developing water supply chains; fourth, the pricing, allocation, and management of water; fifth, the environmental implications of water use; and sixth, global water issues. We present suggestions for exercises of each topic.

1 Introduction

Water economics is a major topic of teaching in Agricultural and Resource Economics programs. This subject can be used both to teach about the specific challenges of water resource management and to introduce students to some of the more generic problems of resource management. Water resources have unique features, and addressing the associated challenges requires creative solutions and the expansion of various topics and skills that applied economists may have. Water challenges are evolving, but some of the basic principles we have introduced can be applied to changes in water systems in evolving environmental problems. For example, the principles of decision making of resource allocation over space and time, technology adoption, and control of externalities can apply to water and other natural resource systems.

Although previous courses focus on the microeconomics of water (e.g., water use on the levels of producers and consumers), this course examines water use and allocation in the context of evolving systems and institutions (courses by Colby 2020). This course is unique in that a key aim is to provide students with a historical, global perspective that emphasizes the importance of political economy and public policy on the development of water systems. Such a perspective will provide students with an expansive (i.e., from diversion and extraction to consumer) view of water resources and an understanding of how key issues (e.g., water scarcity, issues in water management, climate change) affect supply chains. This paper describes a possible class structure for teaching a water economics class with the following six segments: first, an introduction to basic facts and features of the evolution of water systems; second, the political economy of water systems and their evolution over time; third, benefit-cost analysis and developing water supply chains; fourth, the pricing, allocation, and management of water; fifth, the environmental implications of water use; and sixth, global water issues. Each section has a background text and a few suggested exercises. The exercises are generic and must be adjusted to specific locational considerations and the skill levels of the students. Table 1 presents a curriculum based on this paper, and the Appendix provides a set of more advanced quantitative practice exercises.

Table 1: Suggested Course Curriculum

Topic		Required Reading List
1. **Basic facts and features of water systems**	• Water use patterns and purposes (e.g., consumptive and nonconsumptive use) • Dimensions of water supply chains • Dynamics of water use and population growth • Emerging water technologies • Water management problems and potential solutions	Schoengold and Zilberman (2007), Sedlak (2014)
2. **Evolution of water systems over time**	• Comparative water policies and institutions from a global and historical perspective • Impact of political economy in water resource allocation • Transitions in water management regimes (e.g., water rights to water trading)	Cochrane (1979), Wilhite (2005)
3. **Benefit-cost analysis and developing water supply chains**	• Historical perspective of evaluating water projects • Benefit-cost analysis for water resources (theory and practice) • Timing of water projects and dynamics of supply chains	Griffin (2016), National Research Council (2010), Zilberman et al. (2023), Chakravorty et al. (2009), Sedlak (2014)
4. **Pricing, allocation, and management of technology and water use**	• Overview of water pricing regimes (e.g., block pricing) • Dynamics and challenges of water pricing • Allocation of water over space • Management of surface and groundwater • Adoption of modern irrigation technologies	Schoengold and Zilberman (2007), Chakravorty, Hochman, and Zilberman (1995), Dinar and Tsur (2021), Caswell and Zilberman (1986), Taylor and Zilberman (2017)
5. **Economics of water quality**	• Economics of pollution and basic principles of environmental laws • Risk assessments and environmental regulations	Easter and Zeitouni (2006), Xepapadeas (2011), Lichtenberg (2010), Olmstead (2020)
6. **Global water issues**	• International transboundary water issues (e.g., water scarcity and political conflicts) • Implications of climate change on water	Dinar et al. (2007), Ansink and Houba (2015), Bates, Kundzewicz, and Wu (2008)

Class Segment 1: Basic Facts and Features of Water Systems

Before teaching the basic economics of a natural resource system, especially water economics, it is important that students are familiar with the basic elements of both natural and institutional water systems and the challenges they face. It is important to instill in students that economics is inspired by reality and actual problems. Basic water system features should be emphasized to students and illustrated by facts. Water also has multiple dimensions that should be recognized. An instructor must distinguish between rain or snow-fed systems versus irrigation systems and combinations of the two.

This is the first opportunity to discuss the role of water storage in overcoming seasonality and randomness in the water supply. In irrigated systems, one must distinguish between groundwater and surface water.

Furthermore, the timing of water use is very important. Groundwater and snowpack dynamics in the mountains can serve as water storage (Somers and McKenzie 2020). There are also diverse water use patterns. We can distinguish between consumptive uses, which may include agriculture, industrial, and municipal; and nonconsumptive uses, which may include environmental, hydro, and recreational use (Quesnel, Agrawal, and Ajami 2020). Finally, water allocation systems vary. There is some water trading, but allocation, in many cases, is done according to water rights (Schoengold and Zilberman 2007).

Second, it is important to provide an overview of the current state of water use dynamics. This era is facing a growing population and growing water use per capita in developing and middle-income countries, where most of humanity lives (Wada and Bierkens 2014). Analyzing water resource evolution and use per capita issues is very instructive and leads to an appreciation for the heterogeneity across water systems. Some countries, like Canada, are water-rich, but others, like Jordan, are water-poor. But even in Canada, there exist desert regions (for example, Saskatchewan). The uneven distribution of water over space gives rise to water projects that transfer water, water trading, and historically, even wars. Traditionally, agriculture has used 80 percent of the water in many countries (Young and Haveman 1985). However, with population growth, increased standards of living of consumers, and increased demand for environmental amenities, the share of water allocated to agriculture may decline, but overall water use in agriculture may increase because of population and income growth. Countries seek to enhance the available water supply through conservation and improving agriculture productivity. Furthermore, water supply may increase through desalination and other water quality improvements. An exercise analyzing water use dynamics within several countries will provide students with a better understanding of the challenges of water systems and the forces that cause them to adapt.

Third, water technologies evolve. The water system and supply chain have multiple dimensions: diversion and extraction, conveyance, and distribution among consumers. And finally, technology for water application and use. Over time water economies change with the introduction of new technologies. For example, improved pumping and water extraction allowed the expansion of agricultural production to areas with deep aquifers and mountain ranges. The improved lining of canals reduced water conveyance loss and increased the cost-effectiveness of water systems. Improvement in irrigation technologies will increase water-use efficiency (increasing the percentage of applied water utilized by the crop), which is likely to increase yield and reduce water use and runoff. Sedlak's book (2014) provides a good background for the evolution of water technologies. Irrigated agriculture tends to increase yields and quality, compared to rain-fed agriculture. It allows for increased precision in water application and an expansion of the growing season. Increased supply of agricultural output, which allows us to meet the needs of our growing population, can be attributed partially to the significant expansion of irrigated agriculture (Ruttan 2002). Students can understand this development by using data to document the increase in irrigated agriculture over time at different locations and related changes in production, land use, and yield.

While irrigation has led to sizable productivity increases in agriculture, it is important to emphasize the improved productivity of irrigated agriculture compared to rain-fed agriculture and its important role in food supply and security. In addition, it is also important to provide some background on improvements in other aspects of agricultural activities. This includes improvement in breeding technologies and the use of fertilizer to improve water productivity. It is valuable to emphasize differences in the productivity of water use across nations, so students are aware of some of the potential to improve productivity on the one hand, and major sources of inequality among countries on the other hand. Finally, it is important to familiarize students with the components of a water system, maybe through field trips or through media. Given the challenges of water resources, there is a perception of a water crisis in terms of increased demand and rising water prices. One of the key issues addressed in this paper is that it is not a water supply problem but rather a water management problem. This emphasis will provide a better background to provide justification to introduce better allocation policies and better supply expansion strategies.

In addition to the challenges of water supply, the water system has many other problems. They include water quality and contamination by salinity, fertilizer, and toxins, which may lead to major health crises and waterborne diseases. Waterborne diseases are responsible for hundreds of thousands of deaths annually. Water quality degradation may lead to a long-term reduction in agricultural productivity and increased salinity of groundwater as well as problems of waterlogging, where percolating irrigation residues encounter a barrier and a loss of agricultural land. Another challenge is over-pumping groundwater, which leads to aquifer depletion and may reduce water resource availability in the long run (Boggess, Lacewell, and Zilberman 1993).

Exercise 1.1

A) Identify some of the challenges facing water resources around the world.

B) Suggest some solutions to reduce water resources lost and increase water supply availability.

C) Suggest how can economics contribute to enhancing water resource availability and use them in a way that benefits society.

Exercise 1.2

Ask students to consider a country or a state, and use publicly accessible data to conduct a simple statistical analysis of the state of water in that country or state.

Exercise 1.3

A) Conduct a field trip to a large water system. Explain the workings of the system and the institutional arrangements behind it.

B) Show and discuss a movie about water. Some possibilities are “Cadillac Desert,” “Chinatown,” “Until the Last Drop,” or “Written on Water.”

Class Segment 2: Political Economy of Water Systems and Their Evolution over Time

Water resource use has expanded over time. The Romans built major aqueducts that provided fresh water to the population and supplied water for agriculture. In the river culture of China and Egypt, it was the role of the government to develop strategies and solutions that would protect the population from floods and droughts. The evolution of water resources throughout history was, in many ways, affected by government policies and regulations. The current water situation and infrastructure are affected by policies of the past, and these policies were affected by the political economy considerations of policy makers. The importance of water politics has been recognized in popular culture in books like *Cadillac Desert* and movies like “Chinatown.” The importance of political economy in water resource allocation has been recognized long ago (Ostrom 1962) as well as recently (Garrick, Hanemann, and Hepburn 2020). Furthermore, Cochrane (1979) provided an overview of the evolution of U.S. agriculture and the importance of government policies in shaping agricultural production as well as natural resources. Based on these sources, we suggest that water institutions and allocation respond to political and economic considerations, which change over time. Furthermore, changes in conditions may lead to institutional transition. Heterogeneity among regions may lead to diverse water systems and water policies. A better understanding of the evolution of water systems is a major challenge for economic research.

The factors that affect water institutions include water scarcity, the government's ability to tax and finance water projects, as well as the political objective of the community and the government. Regions with water abundance, financially weak governments, and a desire for economic growth may establish a water rights system, like the prior appropriation system, that provides individuals who divert water the right to use this water if they stay in business. Prior appropriation systems are homesteading systems and have been used in the western United States and many parts of the world where relatively poor governments pursued the development of water resources. It resulted in local water projects. In situations with water abundance and where the government is in relatively good financial shape with the capacity to raise income through taxes and desires economic growth, the government may engage in the financing and building of water projects. This was the situation in the United States in the twentieth century (Teclaff 1996). Since the 1950s, major water projects have been built and operationalized around the world. However, once water becomes scarce, and new projects are expensive, the implicit price of water increases, leading to investment in water conservation strategies. Furthermore, increases in scarcity of water increase the likelihood of introducing water trading (Zheng, Liu, and Zhao 2021). When there are growing concerns about environmental quality issues, the government introduces environmental regulations of various types and may even consider pricing externalities. Finally, concern about equity issues may lead to establishing water systems that incorporate a tiered pricing system allowing low-income individuals to attain water at a relatively low price (Schoengold and Zilberman 2007; Chong and Sunding 2006).

The biggest challenge of water policy, where economic research can make a big difference, is the transition from one water management regime to another. For example, the transition from a water rights system to a water market system may take a long period and will benefit from economic research input. Not all transitions are alike. They are affected by history, transaction costs, and political economy. They may be gradual or surprising. Yet, a crisis may lead to transitions. For example, the depletion of groundwater aquifers may lead to establishing surface water projects, conveying water from one region to another. An accident—for example, the breaking of a dam resulting in a flood—may lead to the introduction of changes in dam design. A long drought, additionally, may lead to relocation. Systems are rigid, and a threshold must be crossed that generates political alliances that result in changes. For example, much evidence shows that droughts have led to crises and change (Wilhite 2005). Economics can provide a foundation for water policy reform, including the design of water projects, allocation of water resources, choice of technologies, and water quality management.

Exercise 2.1

Identify a major water project in your geographic area, provide an assessment of its performance, and identify areas for improvement. Suggest alternative policies, including incentives, that will enhance performance, and explain your choices.

Exercise 2.2

Analyze the evolution of the water allocation systems in your state or country during the last 200 years. What were the sources of water available? How was the water used? What were the types of regulatory systems for management, water supply, and distribution while addressing water quality challenges?

Class Segment 3: Cost-Benefit Analysis and Developing Water Supply

Chains

Benefit-cost analysis has been used as a major tool for public investment and introduced for water project design. Traditionally, decisions about water project design were, to a large extent, political and led to significant inefficient outcomes. Economists recommended that every planned project be evaluated by its expected social net present value, and society should implement only projects with a positive social net present value (Griffin 2016). However, assessing the social net present value of projects is challenging. It should consider the market and nonmarket benefits, which requires obtaining estimates of the outcome of a proposed project on multiple markets as well as its impact on environmental amenities and populations. For example, a new water project may result in changes in the production of agricultural commodities. It may lead to losing bodies of water serving fisheries and recreational amenities.

Water project design must first obtain estimates of the physical outcome and develop a mechanism to assess the value of these outcomes, some of which require market valuation and others that require a nonmarket valuation. A class in water economics should provide the foundation for benefit-cost analysis and nonmarket valuation with application to water projects. A good discussion of benefit-cost analysis for water resources is provided in Griffin (2016). Mendelsohn and Olmstead (2009) provide a useful review of methods for evaluating environmental amenities associated with water resource management. Since significant proposed water projects may have a significant effect on agricultural markets, students should be familiarized with methodologies like computable general equilibrium (Ponce, Bosello, and Giupponi 2012) that can be used to assess the impact of water projects on prices and quantities of affected goods and services. Furthermore, modeling to assess the impact of water systems may consider economic and hydrological considerations as well as provide an overview of some economic assessment models that incorporate market considerations and hydrology (Harou et al. 2009).

International organizations like the World Bank have used benefit-cost analysis for water project design. There is an official set of guidelines for applying benefit-cost analysis to water projects by agencies like the Army Corps of Engineers and the Bureau of Information, which are modified from time to time (National Research Council 2010). The design of these guidelines affects how projects are selected. For example, the same techniques are not used to evaluate environmental benefits and costs. Contingent valuation can be used for complete benefit-cost analyses that include environmental degradation, shifts in recreational opportunities, or otherwise nonmarket benefits and costs. However, this method must be used with caution and follow de facto practices to produce high-quality results. Otherwise, it may lead to an oversupply of water projects (Arrow et al. 1993; Johnston et al. 2017).

Another issue affecting water projects is the reliance on nonstructural solutions versus structural solutions. The design of some water projects may consider only engineering (structural solution) and ignore behavioral elements (for example, introducing water trading or pricing), which may result in a project that will be much more costly. This may serve the interest of engineering companies that design and implement water projects, but not society. Therefore, there is a place for economists and social scientists to be involved early in the design of water projects, and this design should include both structural and nonstructural components (Poff et al. 2016). A key point that may be emphasized in a class is how to incorporate a nonstructural component to augment the engineering and achieve a product that aims to enhance the water infrastructure of the region.

Benefit-cost analysis takes the timing of a project as given. However, the value of the project depends on the time it takes until it is implemented. One key question in project design is not whether the project's net present value is positive, but whether the timing of execution maximizes the net present value. The student should be familiar with the real option literature, which is very useful to assess both the timing of a water project as well as the adoption of new technologies, like drip irrigation (Wesseler and Zhao 2019; Carey and Zilberman 2002).

To some extent, the design of a water project is a supply chain design with several elements (Zilberman et al. 2023). For example, a water project may have an upstream where the water is extracted from a lake, a midstream where the water is transmitted through a conveyance facility, and a downstream where the water is distributed to final users. This water system has multiple transactions, for example, between the organization that controls the upstream and the organization that conveys the water, as well as the organization that conveys the water and the final users.

The design of water projects is different when they are designed by public versus private agencies. Public agencies tend to use benefit-cost analysis procedures that consider social costs and externalities, while the private sector aims to maximize profit. If the downstream organization behaves as a monopoly, its price will likely be higher than the competitive price. This difference in market structure will also affect the amount of water transmitted through the project and its resource allocation (Chakravorty et al. 2009). The analysis of the water supply chain and how it relates to other supply chains, for example, commodities, is becoming an important topic and should be introduced in the class. The students may be given exercises on documenting existing water supply chains and their interaction with other supply chains.

Water systems generate residues that can be disposed of through sewage systems or other means. One key element of water system design is the design of waste disposal systems. A water system may not be sustainable if waste is not disposed of in a socially responsible way. The book by Dinar and Zilberman (1991) provides a wide array of publications that aim to address some of the challenges of waste disposal in water systems and the economic tools to address them.

The design of water projects changes over time. Traditionally, water projects were mainly designed for the transfer of water from one region to another (mining, agriculture, and industry) as well as the generation of hydroelectric power. Over time, water projects have been designed to provide recreational benefits and environmental services. Benefit-cost analysis should consider the benefits and costs to consumers, industry, and the environment. In recent years there has been a growing concern about residues from water projects, which is now leading to the design of water projects with a strong emphasis on waste disposal. Increased water scarcity as well as improvements in water desalinization methods is leading to the increased introduction of water desalinization projects that either desalinate seawater or brackish water. These projects enhance (and may reduce) the demand for further diversion of bodies of water to industrial or agricultural activities. There are currently more than 300 million people relying on desalinated water for their drinking water (Robbins 2019). Israel and Spain reuse significant amounts of their brackish water for agriculture (Burn et al. 2015). Thus, water economics education needs to inform the students about new developments in water technology, and a good source is Sedlak (2014).

Exercise 3.1

Select a major water supply chain and identify the primary components of this supply chain. Who controls the decisions in each segment of the supply chain and the overall management of the supply chain? What are the linkages of the water supply chain with the supply chains of other sectors (agricultural commodities, energy, etc.)?

Exercise 3.2

Identify a major water project in your area—what are the major components of the project, and who controlled its design? What aspects should have been considered in the benefit-cost analysis leading toward the establishment of this project? Has such a benefit-cost analysis been done? What are the major flaws of the project? Explain your answers.

Exercise 3.3

Engage the students in a water rights game. The students are divided into different sources and different water users. Water suppliers have a given amount of water and have a cost function. Water users have water rights and are given a revenue function. Assess resource allocation under different water rights systems. Then, introduce trading via permit market. How will trading affect the outcomes of the game?

Class Segment 4: Pricing, Allocation, and Management of Technology and Water Use

Of special interest is the allocation, pricing, and use of water, especially in agricultural production (Dinar, Pochat, and Albiac-Murillo 2015). There are several key issues that should be emphasized. First, water is frequently not allocated by markets but by other mechanisms. For example, water rights systems are queuing systems. When one speaks about the economic price of water, it is different from the actual cost of water to the farmer. Second, the price of water is elusive. Both the actual and the efficient price of water vary depending on the season (high in summer, sometimes negative in winter), allocation, quality, use, and institutions. Third, it is useful to look at the water within a region and consider fixed costs, allocation over space, water rights and trading, groundwater pricing, and conjunctive use of surface and groundwater.

A good starting point to analyze water allocation is a simple demand and supply analysis. Demand represents the marginal benefit (MB) per water unit and may depend on the quality (see Figure 1), but several elements affect the marginal cost of water. The marginal cost of water at the farm level is the sum of the private marginal cost of pumping (MPC), the marginal cost of conveyance (MCC), the marginal externality cost (MEC) that may result from the withdrawal of water, and the marginal future cost (MFC; in the future when water resources are nonrenewable). Figure 1 illustrates several mechanisms for the determination of price. Ideally, the outcome will be allocated where the red curve intersects the MB curve. When both externality and future costs are ignored, the outcome is at point B. Sometimes the water is subsidized, and the outcome is at point N, which illustrates that incorrect water pricing may lead to significant waste. A more detailed discussion of water pricing is provided in Schoengold and Zilberman (2007).

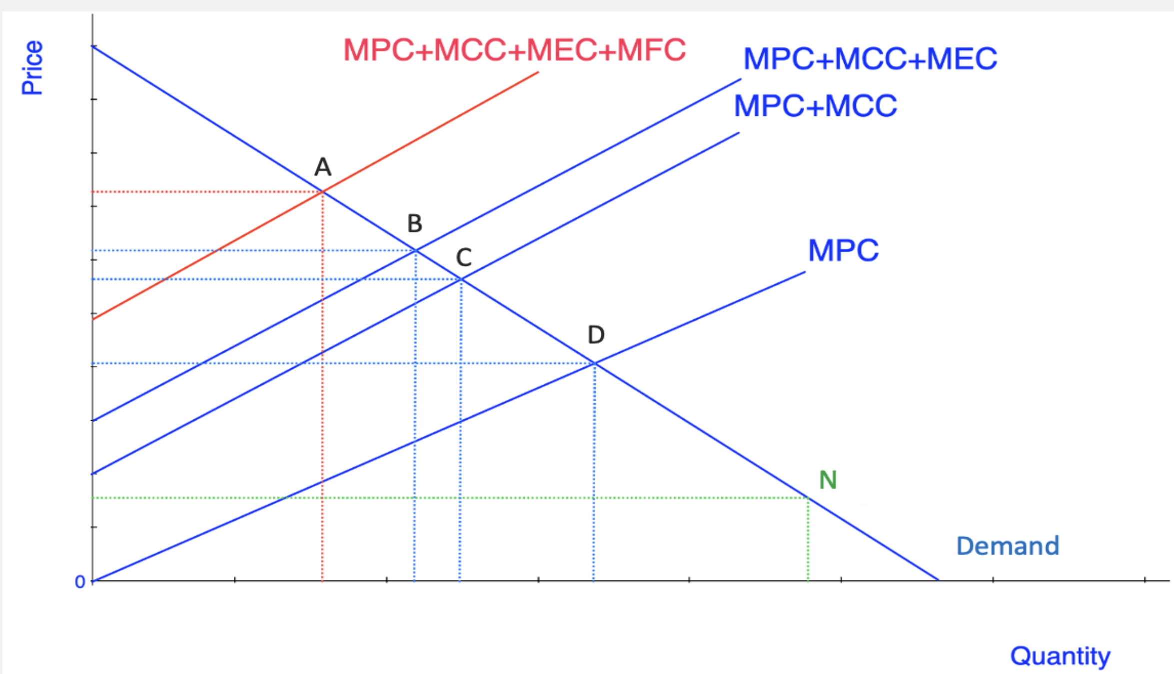

Figure 1: Optimal vs. Subsidized Water—Water Is Overused and Underpaid

The reality of water pricing is very complex as the book by Dinar, Ponchat, and Albiac-Murillo (2015) and Johansson (2000) illustrate. Frequently marginal cost pricing is not exercised and instead, average cost pricing is utilized. In some cases, marginal costs are low, and they cannot cover the fixed costs, so agencies must combine fixed and variable costs. An added complication is to adjust for seasonality. During droughts, water supply declines. As a result, agency revenue also declines and may incur a loss; thus, agencies may need to raise fixed costs to balance their budget. Distributional considerations may lead to tiered pricing. The lesson is that many water pricing systems aim to address cost recovery and not efficiency. Sometimes 50 percent or even less of the costs of operation and maintenance are recovered, which may lead to water subsidization and crises in water systems. Students need to be aware of the financial challenges facing water systems and how to address them. There are several elements and combinations of pricing that can aim to achieve efficiency and solvency, and they can be illustrated through exercises. For example, some combinations may include per-acre costs plus marginal costs, hook-up costs plus marginal costs in municipalities, or per-acre fees plus tiered pricing.

One of the challenges in pricing water is addressing issues of distance. The paper by Chakravorty, Hochman, and Zilberman (1995) presents a framework to allocate and price water within a region. When water originates from the same source and is distributed over time, the conveyance is costly, and one must consider conveyance losses. The allocation of resources and pricing depends on whether there is an investment in conveyance and whether price varies over space. Chakravorty, Hochman, and Zilberman (1995) show that the optimal water price increases with distance. The combinations of optimal pricing and conveyance will result in greater water use, longer canals, and improved welfare compared to uniform pricing or insufficient investment in conveyance. Furthermore, optimal investment in conveyance requires some collective action since individual decision makers would tend to under-invest in conveyance, ignoring the benefit that better conveyance contributes to the well-being of others further downstream in the water system. The study of the allocation of water over space can be a good opportunity to introduce students to spatial economics.

Since water rights systems are prevalent throughout the world, it is important to study the issues associated with the transition from water rights to water markets. Water rights systems are queuing systems, where individuals with senior rights have priority in getting their water when supply is limited, and thus they are better protected against drought and other water shortages. Frequently, senior rights are associated with lower costs of water. The historical evolution of water rights and their adaptation to location variation and institutional consideration is important to understand (see Libecap 1978). A transition from water rights to water markets may have many shapes. In some cases, only "renting" of water rights for one season is allowed, and in other cases, trading may involve more radical transfers of selling water rights in perpetuity across basins. The introduction of water markets may require investment in infrastructure, improved monitoring, and other transaction costs. Finally, water markets require a consideration of the political economy in designing of compensation factors. The literature emphasizes the efficiency gained from water trading but recognizes some of the environmental and distributional indications, as well as emphasizing the importance of sound design and timeliness of reform (as illustrated in Schoengold and Zilberman 2007, and Rosegrant and Binswanger 1994). Case studies from different locations can be developed including comparisons explaining differences in the development of water systems following Hanemann and Young (2020). Reform of water policy requires good estimation of both supply and demand conditions, which has been a subject of important recent research (see Bruno and Jessoe 2021).

A crucially important topic is the management of groundwater. In many cases, there is a tendency to overuse and deplete groundwater because of the tragedy of the commons and weak governance. Understanding the basic economics of groundwater management and even basic hydrological considerations for groundwater analysis is valuable. The seminal paper by Gisser and Sanchez (1980) launched an important body of literature in this area, and some of their findings have been challenged (see the survey by Koundouri 2004). One of the most interesting and challenging topics in water economics is the conjunctive use of surface and groundwater. Students should be introduced to this topic because it familiarizes them with the relationship between flows and stocks in inventory management and the management of natural resources under uncertainty. This topic is of growing importance. A recent discussion of this topic is in Chapter 6 of Dinar and Tsur (2021).

Finally, the efficiency of water use depends significantly on the management of water use by the final consumer—who may be in agriculture or for municipal use. There has been significant research on the adoption of water conservation, and this research is important because it introduces the general notion of water-use efficiency and the challenges of inducing the adoption and diffusion of new technologies. The paper by Caswell and Zilberman (1986) provides a conceptual model for assessing the choice of adoption of modern irrigation technology. Modern irrigation technologies, like drip irrigation, increase input use efficiency, especially in areas where the water holding capacity of the soil is low, but require further investment in new irrigation technology. Low water holding capacity may also result in water logging and negative side effects. Taxation against the unutilized residue (the water not used by the crop and ends up as groundwater or runoff) can be another mechanism to increase adoption. A key point to emphasize is the importance of heterogeneity. Adoption will occur first in locations with low water holding capacity, high water prices, and high output prices. Adoption can also expand irrigated areas to regions and crops that were not irrigated before. Taylor and Zilberman (2017) provided an overview of the diffusion of drip irrigation in California, demonstrating benefits in increased precision and the importance of the development of crop varieties that can utilize the technology. They also emphasize that successful adoption of the technology requires effective infrastructure to support adopters.

There is a parallel area of research on urban water use and the adoption of water conservation in the urban sector. Olmstead, Hanemann, and Stavins (2007) review different pricing regimes for urban water demand, including block pricing, where low-income consumers are allowed low lifeline rates for a certain amount, and water pricing is tiered according to the quantity consumed. Using multiple examples, they also illustrate econometric techniques to estimate demand under multiple pricing regimes. Olmstead and Stavins (2009) compare price and nonprice approaches used for water conservation in the urban sector, including direct control, voluntary arrangement, and different pricing schemes. It is important to emphasize the role of conservation on behalf of water users as it affects the design of water systems.

Finally, it is important to emphasize the inefficiency of existing water allocation mechanisms in urban and agricultural sectors, as well as the challenge of reforms to represent the true cost of water that leads to more efficient resource allocation (Leigh and Lee 2019; Perry 2007). However, reform requires reliable information (not just guesses), good economics, effective administrators, sophisticated legal understanding, excellent political skill and leadership, and patience.

Exercise 4.1

For students with some economic knowledge:

A) Let X be the amount of water used in a system, let the marginal cost of pumping the water be A+aX, the marginal cost of conveyance B+bX, and the marginal cost of water distributed to the final user be C+cX. The demand for water is denoted by D-dX. What are the optimal water quantities used and prices throughout the supply chain (paid by the conveying company, distributor, and final user)?

B) If water pumping is controlled by a monopoly, what are the water quantity and prices by the conveyance company, the distributor, and the final user?

C) If both pumping and conveyance are controlled by a monopolistic firm, what are the water quantities and prices for the distributors and final user?

D) What will be the impacts of a new water-pumping technology reducing pumping costs and increasing demand for prices and volume of water used?

Exercise 4.2

A) A water rights system is established on the principles of (i) first in time is first in right, (ii) use it or lose it, and (iii) no water permit trading. How will water use and productivity be compared under this system with a system that allows water trading? Explain and illustrate graphically.

B) What may be some obstacles in transitioning toward a water trading system?

B) How does the transition from this water-rights system to a system that allows trading affect the adoption of new irrigation technology? Explain.

C) For which crop(s), and where do you expect to see a high rate of adoption of modern technologies like drip irrigation? Explain.

Exercise 4.3

Expanding on the article by Haneman and Young (2020), provide an overview of the water economies of California and Australia, and analyze their economic situations in terms of water availability, water use, and water institutions at the present, and how they have changed over time.

Class Segment 5: The Environmental Implication of Water Use

Water use may cause environmental side effects that frequently affect water quality. When farmers use chemicals that are accumulated in groundwater, it affects the quality of water of individuals who may pump the water and consume it. Addressing these side effect problems requires an understanding of the economics of pollution, the basic principles of environmental laws, and existing policies and their implications. Water side effects problems may be caused by the excess application of fertilizers and insecticides, and industrial waste. Although water contamination by industrial waste tends to be a point-source problem, agricultural waste problems tend to be nonpoint-source pollution problems. When it comes to water, the exact source of the pollution may be unidentifiable, and one needs to develop techniques to provide incentives to reduce pollution either by regulating activities that are associated with the pollution (for example, by taxing fertilizer based on the use and technology of application) or by the collective punishment of a community that is a source of pollution. One approach for collective punishment is an ambient tax where a community is penalized if the concentration of toxic material in the water is beyond some threshold level. An excellent survey of the literature on nonpoint-source pollution with some application to water quality issues is in Xepapadeas (2011). A detailed survey of some of the challenges of managing nonpoint-source water pollution in agriculture appears in Shortle, Abler, and Horan (1998).

Because contaminated water can harm human and wildlife health, understanding the environmental health principles that guide many environmental regulations is important. Lichtenberg (2010) presents the principles of risk assessment that have been applied to environmental regulation. Risk is defined as the probability of a bad outcome within a population (e.g., probability of death) and is an outcome of multiple processes: contamination, transfer and fate, exposure, and vulnerability. Regulations may affect these processes. For example, some chemicals may be banned. In other cases, transfer and exposure can be controlled by regulation on when and how to apply, and vulnerability can be affected by, for example, the provision of medical treatment. Regulation of water quality poses a tradeoff between risk to life and economic costs, and thus the notion of the statistical value of life is important to assess alternative regulations. Students should be able to integrate principles of risk assessment with benefit-cost analysis applied to water projects and resulting externalities.

Olmstead (2020) provides an overview of the literature on the economics of water quality as well as major regulations that affect water quality in the United States. She reviews the literature, evaluating the efficiency of different types of regulations on drinking water quality as well as the quality of water in general. The survey is especially useful because it combines institutional information about real-world policy with an economic assessment, and it can be a model for further training of students. Easter and Zeitouni (2006) selected interesting papers on different aspects of water quality regulation that can be useful sources for teaching the topic.

Exercise 5.1

Have students identify policy-based or regulatory solutions to water quality problems based on the economics of pollution, the basic principles of environmental laws, and existing policies and their implications. Emphasize the importance of examining the source of pollution and how to mitigate this source; is it point- or nonpoint-source?

Exercise 5.2

(For quantitatively oriented students.) Suppose water demand is given by D-dQ, where Q is water quantity, water supply is given by A+aQ, and there exists water pollution with a marginal pollution cost given by B+bQ.

A) What will be the optimal quantity and price of water?

B) What are the quantity and price when externality costs are taken into account and a fee is imposed on each unit of water consumed? What is the optimal pollution fee?

C) Suppose a water clean-up technology is available, and it costs c dollars per unit of water. Under what conditions will this technology be adopted—when the optimal water fee from part 2 is imposed? How will it affect the quantity and price of water to consumers?

Class Segment 6: Global Water Issues

Water issues are often not contained within a single country. Two major issues of research that transcend international borders are transboundary water challenges and climate change. Dinar et al. (2007) provide a perspective on international transboundary water issues addressing both economic and political challenges. Indeed, the sharing of water on the Colorado, Nile, and Mekong Rivers has caused multiple political conflicts. The construction of a dam and diversion of water by an upstream state is viewed as a threat to downstream states and has been a cause of military conflict. Ansink and Houba (2015) provide a review of the literature and an analysis of the challenges of sharing water along a river crossing multiple countries. Division of water rights among states is a major allocation problem, and the allocation of rights in real life and the resulting water-use patterns are suboptimal. This provides opportunities for trading and renegotiation. The paper suggests alternative mechanisms of negotiation and reallocation using game theory concepts and presents several case studies. Frisvold and Caswell (2000) present a nice game theoretical approach for the transboundary allocation of water and use it to assess the allocation of water rights between the United States and Mexico. Assigning students projects that address transboundary challenges and use economic approaches to analyze them can be a very useful problem-based learning exercise.

Climate change has immense implications for water—many of them have been presented in Bates, Kundzewicz, and Wu (2008). Climate change will affect precipitation patterns, lead to more frequent extreme events (floods and droughts), result in snowmelt, change patterns of water movement over space and time, and lead to changes in temperature that affect evapotranspiration and soil moisture, which in turn affects yields and land use. Finally, rising sea water levels will lead to flooding in coastal areas and cause the destruction of coastal aquifers. Piao et al. (2010) provide an interesting assessment of climate change's impact on China's water systems. While recognizing the large uncertainty about this impact, they provide some predictions showing the changes in land use and production patterns that will necessitate significant investment in research to enhance productivity. Nordhaus (2021) is an excellent resource on environmental economics, modeling, and assessment of climate change, emphasizing policy solutions to address climate change challenges and the water challenges associated with it. Zilberman et al. (2004) present a simple framework to assess the impact of climate change on agriculture. In particular, the climate migration from the equator toward the poles may result in the switching of crops, desertification, and new agricultural opportunities. There is a risk of food supply disruption if the loss of capacity due to climate change will not be met by increased productivity in areas that will now be open for increased agricultural production. The reallocation of agricultural production among regions might take time and lead to significant disruption of food supplies. Joyce et al. (2011) assess the impact of climate change on the California central valley, a desert area that has become one of the most productive agricultural regions in the world due to irrigation. They show that climate change will change water supply patterns due to the change in timing and volume of snowmelt and reduce productivity due to soil moisture loss. They consider adaptive strategies to address these issues. Poudel, Xie, and Zilberman (2018) suggest that climate change will lead to a need to construct new dams to capture some of the extra snowmelt and investment in water conservation strategies. They identify conditions under which damming and conservation are either substitutes or complements and suggest considerations to increase the efficiency of dams.

Exercise 6.1
Analyze a case study of a water conflict transcending international borders. Consider the political and social factors that led to this conflict, and how climate change might exacerbate them.

Exercise 6.2
Identify policies that can address the impacts of climate change on water resources both domestically and globally. Consider both adaptation and mitigation strategies. Identify obstacles to implementing your suggested solutions and how to overcome these obstacles.

Conclusions
Water is essential for human survival and political and economic choices regarding water will be important in the future. Thus, water economics education is valuable because it provides an important background about water supply and use processes, and the resulting economic implications for different parties. It also provides immense insight into environmental economics and policy as a whole. Education in water economics also provides an in-depth understanding of property rights, economic development, dynamic systems, and the management of externalities. It is also important as a key element in agricultural education. While we emphasize the content of training in water economics and highlight some resources, water economics provides a lot of opportunities for projects, allowing students to investigate major policy challenges and develop tools to address them through myriad active, experimental, and problem-based learning activities. For example, projects may include studies of water and waste systems, water projects, assessment of water policies, and water intuitions. Students may also benefit from hearing from guest lecturers from multiple disciplines as well as from policy makers.

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Appendix: Additional Practice Exercises

Along with the suggested exercises for each of the sections of the course provided previously, we provide an additional set of detailed practice exercises that can be used as a starting point in developing a more wholistic set of quantitative exercises for this course. This is provided upon request from the AETR webpage (www.aetrjournal.org).

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Teaching and Educational Methods

Reconciling Theory and Practice in Higher Education Water Economics Courses

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Abstract
The water economics course offered at the University of Waterloo provides students from the Department of Economics and other schools and departments across campus the opportunity to learn more about the application of economic theory, concepts, models, and methods to global water challenges. Students are prepared for real-world challenges by linking theory to practical examples. They are brought “into the field” through visits to local wastewater treatment facilities and real-world practical assignments. Emerging trends and water policy challenges in need of reconciliation with economic theory and methods are addressed. The practical examples make abstract water management challenges in the water economics literature real for students. Collaboration with other disciplines and sectors, as increasingly required in the water domain, is emphasized to effectively inform economically efficient water management. The annual course evaluation shows that economics students value especially the applied and interdisciplinary nature of the course.

1 Introduction

The main objective of this paper is to discuss how the water economics course program in the Department of Economics at the University of Waterloo has been set up to accommodate increasing societal and policy demand for a more applied, real-world, collaborative economics profession in the water domain. Water economics is a rather neglected field in applied economics. Although the journal *Land Economics* published its first issue in 1948, and energy and marine resource economics were covered in their respective scientific journals since the 1980s, the first *Water Resources and Economics* journal only appeared in 2013. The number of academic institutes where water (resource) economics is taught as a separate subdiscipline is limited. This despite the fact that planetary freshwater resources have become increasingly scarce over the past decades, the meteorological and hydrological impacts of climate change drive some of the most costly natural catastrophic events in the world, and water is increasingly traded in economic markets. Water is typically introduced as one of the natural resource categories or environmental challenges in the broader environmental and resource economics course curriculum.

The European Water Framework Directive (WFD) adopted in 2000, that is, Directive 2000/60/EC of the European Parliament and Council establishing a framework for community action in the field of water policy, has given an important impetus to the demand for trained water economists. The WFD is one of the first coordinated legal efforts across Europe to address water quality and transboundary river basin management using economic principles (Polluter Pays Principle), economic methods (cost-effective programs of measures), and economic policy instruments (water pricing). The Directive requires that economists work closely with other disciplines and decision makers on water-related challenges and solutions, for example to reconcile hydrological, ecological, and economic scales underlying the identification of the least costly way to achieve good chemical and ecological status of transboundary water bodies shared by multiple water users. At the same time, it introduced a plethora of real-world challenges for economists related to the definition and measurement of water services, cost recovery, environmental and resource costs, and disproportionate costs (e.g., Brouwer 2008; Martin-Ortega et al. 2015).

Similar challenges exist globally. For instance, when implementing policies to achieve Sustainable Development Goal (SDG) 6, that is, "clean water and sanitation for all." One of the specific targets under SDG-6 is "universal and equitable access to safe and affordable drinking water for all" (emphasis in underlining added). The societal benefits of access to clean water and sanitation are evident, especially under the current pandemic, but affordability remains a major concern with no clear universal definition or guideline (United Nations 2022). Moreover, classical dilemmas related to the provision of public services remain, in particular the development of a sustainable business case to attract the necessary investments and sustain the operation and maintenance of built water infrastructure in low- and medium-income countries (Hutton and Varughese 2016).

The water economics course presented here is one of the many graduate-level water courses at the University of Waterloo linked to its Collaborative Water Program (CWP). The CWP gives students from different schools and departments across all six University of Waterloo faculties (Science, Engineering, Environment, Health, Mathematics, and Arts) the opportunity to further develop their skills in interdisciplinary collaboration in the water domain. As such, it is one of the few truly interdisciplinary graduate water programs in the world (e.g., Carr et al. 2017; McQuarrie and MacLennan 2021; Taka, Verbrugge, and Varis 2021). While many water-focused graduate programs exist, they are usually housed within traditional departmental structures and lack the breadth of teaching and diversity of students available in a collaborative program. The CWP combines specialist training with collaboration opportunities, between students from different disciplines and between students and local organizations and communities (e.g., conservation authorities, farmer organizations). The goal of the CWP is to provide students with a broad, interdisciplinary foundation in water science, engineering, governance, and economics, beyond the disciplinary specialist training they receive in their academic home unit. The program consists of classroom lectures and a field work component, which are delivered jointly by 11 departments and schools from across all six academic faculties, including the Department of Economics, allowing Economics MA and PhD students to graduate with a water specialization.

Students in the CWP get a flavor of water economics through an in-classroom lecture, addressing the question why water is of interest to economists and which role economics plays in solving water challenges based on important tools in the economist's toolbox such as cost-benefit analysis (CBA) or water pricing. When discussing the relationship between water and the economy, a key learning objective is to make students understand the distinction between finance or financial analysis and broader welfare economics. The CWP field work typically has relevant economics aspects, such as the identification of economic drivers underlying specific water challenges and solutions for more sustainable watershed management with significant cost and benefit implications. CWP students interested in learning more about water economics are referred to the water economics course taught every Fall term in the Department of Economics.

2 Water Economics Course Curriculum

The water resource economics course is a so-called "topics course" open to students from the Department of Economics and other schools and departments on campus. It is taught at both the graduate and undergraduate level. The course was developed in 2016–2017, and is taught every year during the Fall term. Teaching occurred in-person the first three years (2017–2019) and online in 2020. Since 2021, it has been delivered in a hybrid format, that is, in-person for students on campus and online for students working remotely from home. It is expected to continue this way in the years to come, where in-person lectures are live-streamed to enable remote access. The course outline is presented in the Annex to this paper.

Over the past 5 years, the average annual number of participating University of Waterloo students was 15 (with a minimum of 11 and maximum of 21 students each year), of which on average 15 percent was enrolled in another university department or school (varying between 8 and 20 percent). In addition to these internal enrollment statistics, each year a number of students from outside the University of Waterloo are also allowed to participate, varying between 1 to 5. This includes professionals or practitioners who pay a tuition fee to participate. These participants audit the course and do not do the exams.

The course is advertised as consisting of "classes in which the economics of major global water management challenges are addressed, including droughts and floods, water quality, and the water-food-energy nexus. Particular attention is paid to water resources valuation and pricing." The course aims to increase students' knowledge and understanding of the application of economic theory, concepts, and methods to global water resources management challenges. It combines theory and practice and follows a research-based teaching philosophy, meaning that economic theory, concepts, and methods are illustrated using real-world research results, many of which from the author self. For the theory part, it mainly relies on Ronald Griffin's (2016) book *Water Resource Economics: The Analysis of Scarcity, Policies, and Projects* published by MIT Press (Chapters 2, 3, and 9). In the first 2 years, also Douglas Shaw's book *Water Resource Economics and Policy: An Introduction* published by Edward Elgar was used, but I found that most relevant components were also covered in Griffin's book. For an introduction to water valuation, students read chapters 2 and 4 in Robert Young's (2005) book *Determining the Economic Value of Water: Concepts and Methods* published by RFF Press.

The theory is supplemented with specific applied readings. This includes two papers by Sheila Olmstead on managing water scarcity and water quality published in *Review of Environmental Economics and Policy* (Olmstead 2010a, 2010b). Although published more than a decade ago, these two papers provide students with an excellent introductory overview of the relevant water management issues from an economics perspective. Additional materials focusing on specific case studies like climate change and flood control are taken from the book edited together with the late David Pearce *Cost-Benefit Analysis and Water Resources Management* published by Edward Elgar in 2005.

Students are asked, among others, to write a short discussion paper about a published paper of their own choosing from the journal *Water Resources and Economics*. In doing so, they screen and learn more about state-of-the-art theoretical and empirical literature in water economics and get familiar at the same time with scientific publication protocols and academic review procedures, which is considered especially useful for graduate students who aim to publish their own research. A description of the article assignment is presented in Box 1 below.

The practical part consists of four main components. The first component is the water game *Irrigania* developed by Seibert and Vis (2012), which is played in groups in class (although it can also be played online) and then followed by an intermediate test consisting of questions related to the economically efficient allocation of surface and groundwater associated with the payoff functions underlying the game.

The second component is a group assignment related to dam building in the Niger river basin in West Africa, based on the work of former RIZA and IVM colleagues (Zwarts et al. 2005).[1] Students are asked to form groups of no more than 4–5 persons. They are provided with a database containing the numerical monetary impacts of dam building on different sectors, from hydropower to crop production, livestock, transportation and commercial shipping, fisheries, nature, and wildlife. Based on the database,

[1] RIZA is the former Dutch Institute for Integrated Freshwater Management and Wastewater Treatment, which was part of the Ministry of Infrastructure and Water Management. IVM is the Institute for Environmental Studies, the oldest interdisciplinary environmental research institute in the Netherlands.

Box 1. Discussion Paper Assignment

The discussion paper is a review of an article of a student's own choice published in the journal *Water Resources & Economics*. The paper size is between 2,000 and 2,500 words. Students can work on this discussion paper from the beginning of the course. Once an article of interest has been identified, the student informs the instructor about the selected article, and when approved, the student can start writing the discussion paper (a specific article can only be reviewed by one student, students are asked to select another article if their article was already selected by someone else). The paper is due at the end of the course. Students hence have several weeks to write the paper, depending on how quickly they decide on a specific article. No standard format is provided for the discussion paper, students are asked to develop their own structure based on their own evaluation of the article they read.

The specific learning objectives associated with this assignment are to learn (1) more about a specific water economics topic or specific economic method/model/tool applied to a water challenge, and (2) to critically read and analyze a scientific paper. Students are asked to demonstrate that they have understood the study or topic presented in their paper, for example by describing and discussing the relevance of the problem addressed in the article, the appropriateness of the methods or models to address the problem, the significance of the results, or the logic underlying the article's structure. They can refer to other literature in the field if considered appropriate. They are asked to describe in their own words what the theoretical or empirical contribution of the paper is to the existing literature, what the real-world policy relevance of the paper is, and to what extent they agree (or not) with the conclusions and policy recommendations.

When introducing the assignment in class, students are furthermore informed about the scientific review process in general, from the moment an author submits an article for review to the journal until acceptance of the paper for publication, and I share guidance on possible peer review criteria, such as originality, innovation, and importance of the study; literature review consistency and relevancy; study design, methods, analysis and findings; study conclusions, limitations, and future research directions. The submitted discussion papers are read and evaluated by the instructor and a second reader from the Department of Economics.

they are asked to perform a CBA for different scenarios of dam building, paying special attention to the distribution of the costs and benefits across different stakeholder communities in the transboundary river basin. Using their CBA results, student working groups are asked to write a short report to the responsible water agency about the economic optimum level of dam building and present their recommendations in class to their fellow students. A description of the group assignment is provided in Box 2.

The third component relates to survey data collection and analysis. Students are taught how different market and nonmarket valuation methods work in practice. This includes the design and implementation of household surveys. Students are shown online surveys and are taught how to apply statistical methods to the collected survey data. In the case of revealed and stated preference methods, large data sets are used by students in class to estimate hedonic price models, travel cost models, and choice models. Interested students are referred to the publications associated with the data they are given.

For example, the hedonic pricing database refers to house prices across the Netherlands between 1995 and 2005 and contains more than one hundred thousand observations. The database was collected as part of a study for the Dutch Government in which the benefits of water quality improvements were estimated (Brouwer et al. 2021). Besides financial transaction data, information was collected about

Box 2: Dam Building CBA Assignment

The CBA assignment is a group assessment of dam building in the transboundary Niger river basin. The paper size is between 3,500 and 4,000 words. Students start working on this paper after Cost-Benefit Analysis (CBA) is discussed in class in week 5. In class, students learn the theory underlying CBA, the historical background of CBA implementation in different countries around the world, including by the World Bank, and the different steps in CBA. These steps are exemplified using a real-world example of flood control comparing conventional engineering and nature-based solutions such as floodplain restoration in the Netherlands (Brouwer and Van Ek 2004; Brouwer and Kind 2005). Special attention is paid to the selection of the baseline scenario (the "without" situation in CBA), the inclusion of nonmonetary impacts and their valuation, the importance of distributional impacts across stakeholders in time and space, the choice of the discount rate, uncertainty, and sensitivity analysis. Students learn the technical background of CBA using the pre-coded Excel spreadsheet and examples provided in Brouwer (2022). This spreadsheet teaches students how to calculate net present values, internal rates of return, and benefit-cost ratios. The role of CBA in decision-making processes is discussed, as well as its relationship with environmental and social impact assessment procedures.

The assignment relates to a real-world water management challenge, that is, water, energy, and food security in the context of climate change, for which data are made available to conduct CBA. The case study is accompanied by a film produced by IVM under the Ministry of Foreign Affairs funded program Poverty Reduction and Environmental Management. The assignment paper is presented by each group of students in class, followed by questions from the instructor, students from other groups, and invited guests who present themselves as members of the Niger river basin committee interested in the students' findings and recommendations.

Students are asked to evaluate the incremental costs and benefits of four dam building scenarios to meet demand for energy and food in the river basin:

- Scenario 0: no dam building;
- Scenario 1: Markala dam built for irrigation (operational since 1947);
- Scenario 2: Markala and Sélingué dam built for electricity production (operational since 1982); and
- Scenario 3: Markala and Sélingué dams and the planned Fomi dam for electricity production.

Based on a real-world database provided to students containing sectoral impact data for the four scenarios over a time period of 50 years, they are asked to write up the results of the CBA, advising the relevant water agencies in the Niger river basin ex post about the economic efficiency of the two existing dams and ex ante about the desirability to build a third dam.

The learning objective associated with this assignment is for students to understand how to apply the different steps in CBA to a real-world example and justify decisions related to specific choices in each step such as the baseline scenario, the discount rate, and the CBA decision criteria, including follow-up questions such as how communities negatively impacted by the dam building can be compensated. The assignment aims at the same time to strengthen students' ability to work in groups and their communication skills. Both the written report and group presentation are evaluated. The instructor's evaluation is supported by the invited guests from the Niger river basin commission who have also read the written report and participated in the group presentations and discussions.

house characteristics, neighborhood characteristics, and environmental characteristics, including distances to different types of water bodies (rivers, lakes, canals) and associated water quality variables (including Secci depth, chlorophyl-A, nutrients, and heavy metals). Students are asked to regress house prices on these different groups of characteristics and identify their relative contribution to explaining the variation in house prices. The purpose of the assignment is to improve student understanding of the importance of having access to all relevant characteristics to avoid omitted variable bias, and the need to collaborate with spatial analysts to create the relevant spatial variables and water scientists to integrate water quality monitoring data into the database.

Similarly, students are familiarized with the different types of travel cost models and are asked to estimate an individual travel cost model using survey data that include approximations of the opportunity costs of travel time to test the effect of visitors' travel time on the estimated consumer surplus. The travel cost database is based on the study presented in Mangan et al. (2013) in the *Journal of Sustainable Tourism*. The learning objective of using this study in class is to raise student awareness that the reliability of welfare estimation using travel cost studies also depends on the available survey data and often requires assumptions related to the estimation of travel costs.

For stated preferences methods, students go through the various Willingness to Pay (WTP) and Willingness to Accept (WTA) elicitation approaches and learn more about multiattribute utility theory, preference learning (or preference construction), preference stability, and possible sources of preference uncertainty in stated preferences research. The choice experiment data published in Brouwer et al. (2010) related to climate risks and water conservation in Australia is used to teach students how to estimate simple multinomial logistic choice models. As for the travel cost data, students learn how to derive WTP welfare estimates from the estimated choice models. For all data sets, students are provided with the relevant R codes to estimate the models.

Finally, the fourth practical component is a half-day visit to the local wastewater treatment facility in the Kitchener-Waterloo region, where students are given a tour of the facilities and a presentation by the regional manager about the investments in treatment technologies to keep up with a growing population and new environmental standards for emerging contaminants such as micropollutants or microplastics. Usually none of the economics students visited a wastewater treatment facility before, and their general knowledge of the connectivity between source water protection, drinking water supply, wastewater treatment, and stormwater management is very limited. Improving economics students' awareness and understanding of where drinking water comes from and where it goes after use is an important learning objective at the beginning of the course, as well as identifying where, when, and how economists collaborate with other experts and rely on noneconomic (scientific, engineering) data, for example in cost-effectiveness analysis and CBA (see Figure 1).

The "field trip" to the wastewater treatment plant is usually an eye opener for many to see where wastewater ends up, the investments needed to maintain and expand treatment capacity to serve growing urban populations, and the challenges of transferring these investment costs to the beneficiaries of the provided services. Contrary to students in science, environment, or engineering, this is often one of the very few field trips economics students undertake during their education. The visit gives the municipal managers of the treatment facilities the opportunity to raise student awareness of the operational size of the facilities and the societal and environmental benefits of collecting and treating wastewater. Students learn in class that the United Nations estimates that globally 80 percent of the wastewater flows back into the ecosystem without being treated or reused.[2] When visiting the treatment facility, they see and hear what it takes technically in engineering terms and economically in money terms to achieve SDG 6. More recently, wastewater monitoring also plays a key role in detecting COVID-19 community spread. Students are also made aware of this important function of wastewater plants in monitoring public health.[3]

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[2] https://www.unwater.org/water-facts/quality-and-wastewater/.

[3] In the Kitchener-Waterloo region, this is set up in direct collaboration with faculty members of the University of Waterloo's Water Institute (https://www.regionofwaterloo.ca/en/health-and-wellness/covid-19-wastewater-surveillance.aspx).

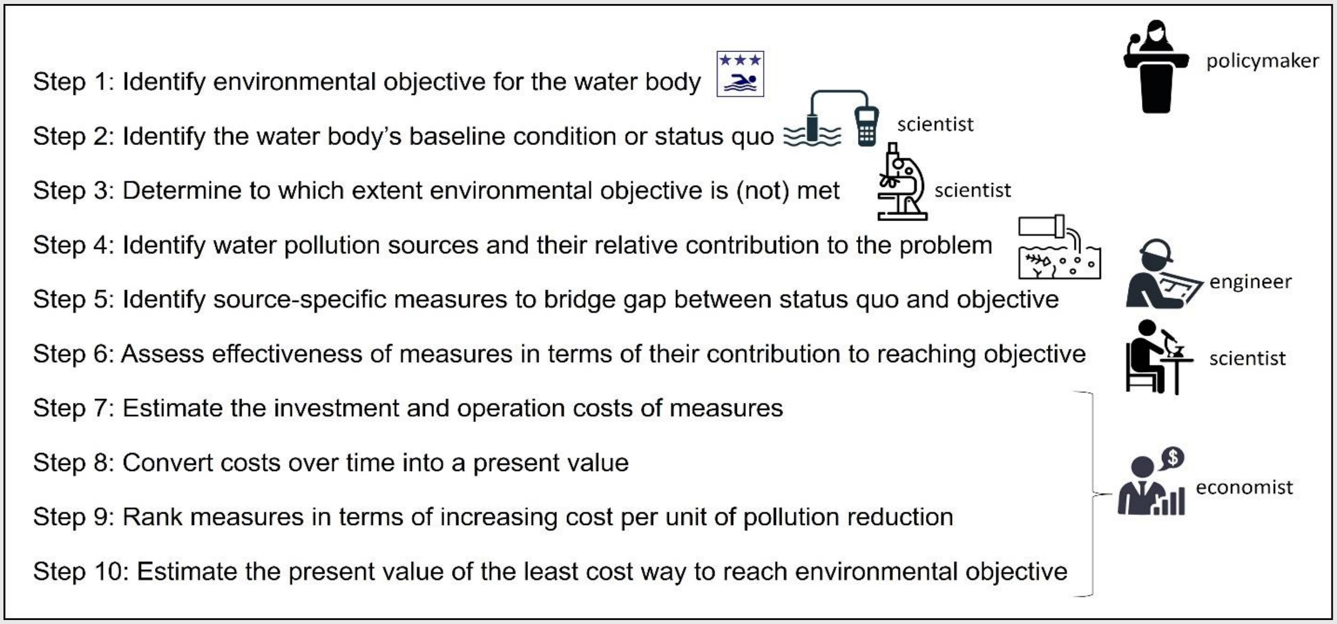

Figure 1: Illustration Used in Class of Collaboration Between Economists and Other Disciplines When Explaining the Methodological Steps Underlying Cost-Effectiveness Analysis

Source: Modified based on Brouwer and Deblois (2008)

The visit to the Kitchener wastewater treatment plant also shows the impact of climate change on the treatment facilities that were originally built in a floodplain to be as close as possible to the river. The floodplain overflows more often than when it was built in the early 1960s due to climate change. Drinking water and wastewater treatment plants are typically very vulnerable to flooding (e.g., Karamouz et al. 2016; Arrighi, Masi, and Iannelli 2018). Students are shown the new facilities that are built on top of the original infrastructure to anticipate future flood risk realities. Moreover, when discussing the pricing of water services to finance the necessary investments in aging water supply and stormwater infrastructure, students are made aware of the challenges cities like Kitchener face to introduce a stormwater user fee based on the amount of stormwater runoff a property's impervious surface creates. The city developed a stormwater credit policy that rewards residents and businesses for reducing the runoff flowing into local drainage systems, for example by installing rain barrels or cisterns and the creation of rain gardens on their property. Students are shown how an actual water bill looks like in class with a specification of a household's water use, its water and wastewater rate, and stormwater charge. Raising awareness is a key component to create public support for increasing the water bill. Concrete practical examples like these make abstract water management challenges in the water economics literature real for students.

3 Linking Theory to Practice

Water has a number of distinct features that sets it apart from other environmental assets. Some of those are accounted for in the theoretical expositions in Griffin's book, such as return flows and their implications for social welfare aggregation. Another example is dynamic efficiency in the context of groundwater depletion and the implication for the rate of groundwater extraction over time. Besides the economic implications of the distinction between stocks and flows, also the economic consequences of the relationship between water quantity and quality are addressed (e.g., Sinclair Knight Merz 2013). Water scarcity has important quality aspects, not least because the available amount of water has an impact on water quality as it dilutes concentration levels of specific water pollutants and in-stream flow affects the ecology of a water system. Differences in boundaries and scales between the economic and water system are pointed out, most importantly the fact that water, including unconfined groundwater, flows in watersheds and river basins, the hydrological boundaries of which usually do not coincide with administrative boundaries of counties, provinces, states or countries, and the boundaries of economic markets. Although market prices can change daily, key economic indicators like Gross Domestic Product (GDP) are typically presented on an annual basis for an entire country or state, while hydrological flow and chemical water quality are often monitored by the water sector at specific locations along water bodies at higher resolution time scales (e.g., hourly or even real-time). In the course, the consequences of these different spatial and temporal scales are discussed for integrated water and economic accounting (e.g., as foreseen in the United Nation's System of Environmental and Economic Accounting (SEEA) or the National Accounting Matrix including Water Accounts (NAMWA) developed by Statistics Netherlands) as a basis for hydroeconomic model development, calibration, and validation (Brouwer, Schenau, and van der Veeren 2005).

The various links made in the course between theory and practice are visualized in Figure 2. The square in the middle of Figure 2 represents a watershed in which various socioeconomic activities take place that make use of the available water resources, either as a source or a sink. Activities on the land (e.g., agriculture, industry, municipal wastewater treatment) influence water quality and aquatic ecology, requiring an integrated watershed management approach. This includes source water protection (e.g., from nitrate leaching or other land use disturbances), and building a resilient water sector with infrastructure that is able to anticipate the impacts of climate change (e.g., increasing stormwater runoff, wildfires disturbing source water intake, etc.) and future demand for treatment capacity due to population growth.

Incentives for watershed collaboration are theoretically explained using Coase theorem. A hypothetical example of upstream and downstream collaboration is presented, and students are shown under which circumstances collaboration benefits all stakeholders living in the watershed. They are also shown how depending on the distribution of property rights such as access to the available water or the right to pollute or the right to clean water, the welfare implications change across stakeholder groups. This provides the theoretical basis for the subsequent lectures on the design and evaluation of payments for watershed services (PWS) based on own work and that of others (e.g., Brouwer et al. 2011; Engel 2016; Wunder et al. 2018). Here, I also discuss the empirical evidence base related to the effectiveness of water pricing in different sectors (households, industry, and agriculture) based on price elasticities of water demand and PWS.

When discussing the water sector, I dedicate a significant amount of time to the use of green infrastructure and nature-based solutions such as forested watersheds to find the most efficient combination of grey and green infrastructure (e.g., Pan and Brouwer 2021). This includes optimizing the connectivity of infrastructure for drinking water, grey (waste) water, and stormwater using hybrid centralized and decentralized water systems. In the classroom, New York City's water supply from the Catskill-Delaware watershed is used as a well-known example (e.g., National Academies of Sciences, Engineering, and Medicine 2018). Many, if not most, economics students do not know where their tap water comes from or where it goes. It often becomes clearer once they visit a municipal wastewater treatment facility, get a tour of the treatment facilities, and see how the treated wastewater is ultimately released again into the same water course from which the water is extracted for municipal drinking water supply. It helps them to better understand that water supply is part of a circular hydrological process and that cities are located in watersheds that supply these cities with water.

Special attention is paid to the economics of wastewater reuse and resource recovery based on the 2022 International Water Association (IWA) open access book *Resource Recovery from Water: Principles and Application*. The chapter on the economic analysis of resource recovery was used for the first time in the course in 2021 to see how useful students considered this new course material

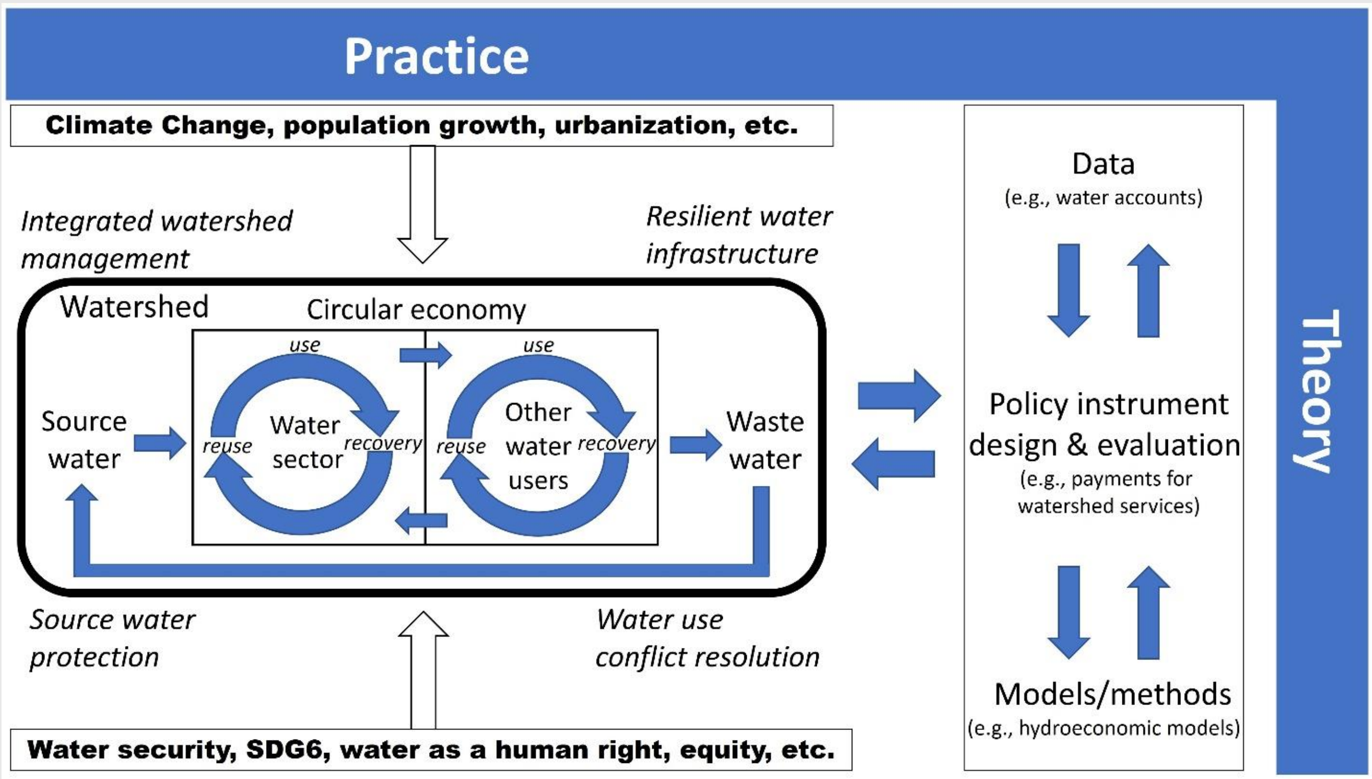

Figure 2: Linking Economic Theory to Real-World Water Management Challenges

compared to existing reading materials, in particular the new case studies making an economic case for resource recovery related to phosphorus recovery and wastewater re-use in agriculture. The practical examples appeared especially helpful to clarify and make students better understand the economic costs and benefits underlying the concept of a circular economy (Kirchherr, Reike, and Hekkert 2017).

Rapidly urbanizing watersheds face a variety of external pressures and trends that have significant impacts on the watershed's water resources and their management.[4] Besides environmental pressures, for instance as a result of climate change, economic growth, and urbanization, societal trends have emerged that translate into principles of "equitable" or socially just water policy and decision-making, such as clean water and sanitation for all (SDG 6). In many cases, water affordability may be considered more important than economically efficient water use or water pricing based on full cost recovery. Often, water is in this case not so much considered an economic good as it is considered a human right. These societal trends shown at the bottom of Figure 2 are real-world trends that increasingly challenge water economists when examining and identifying economically efficient water demand management solutions.

There is undoubtedly competition over the limited available water resources that are increasingly under pressure due to climate change. The course is able to build on an extensive resource economics literature focusing on water allocation under scarcity, also addressed in the water game *Irrigania*. The distributional aspects of water allocation of, for example, dam building in a transboundary context are emphasized, and the concept of "benefits sharing" is introduced as an important additional criterion in project and policy appraisal (Qaddumi 2008). In this context, it is emphasized that

[4] To address these issues more systematically and holistically, I developed the interdisciplinary Water Institute summer school on *Climate Change and Water Security in Urbanized Watersheds: An Interdisciplinary Perspective* in 2019 together with faculty members of the Water Institute. The program of this summer school is delivered by around 20 professors from all six faculties on campus. Due to the pandemic, the summer school was delivered virtually over a period of 3 weeks in 2021 and 2022, with international participation tripling. Since 2021, the summer school is organized together with the Waterloo Climate Institute.

addressing global water management challenges requires not only collaboration between economists, natural scientists, and water resource engineers, but also between economists and other social scientists from environmental law, political science, business administration, sociology, or cultural anthropology. Institutions such as water agencies, transboundary river basin commissions, and water laws and regulations generally reflect more deeply grounded, often historic, underlying world views of how water management should be organized, to whom the water belongs, and how it should be allocated.[5] How existing transboundary agreements can change over time and exacerbate potential conflicts over water use is illustrated for the Nile using own work on the Grand Ethiopian Renaissance Dam (e.g., Kahsay et al. 2015; 2019).

The transboundary Great Lakes shared between Canada and the United States are used as another example to show that water security also has important quality aspects. Although the Great Lakes make up approximately 20 percent of the planet's freshwater resources, the annually recurring harmful algal blooms in some of these lakes due to excessive nutrient runoff (e.g., McKindles et al. 2020) constrain water availability for different water users around the lakes, resulting every year in significant economic damage costs (Smith et al. 2019). This is due to the fact that the Great Lakes' ecosystem is used both as a source and a sink.

The Great Lakes Water Quality Agreement overseen by the International Joint Committee, the oldest transboundary water management organization in the world created in 1909, has as its main goals to ensure the waters of the Great Lakes are drinkable, swimmable, and fishable. Drinkable means in this case that the waters are "a source of safe, high quality drinking water." However, no matter how clean source water is for drinking water purposes, there does not exist something like "drinkable" water quality. Water that is used for drinking water purposes always undergoes some degree of treatment to meet legal standards for clean and safe drinking water, and there are hence always costs associated with the treatment and distribution of water to residential homes. Even if households do not pay directly for their water supply, as was the case for centuries in Ireland until the government announced in 2011 that it would start metering residential water use, it is a general public misperception that water supply is "free of charge," and I use this as a starting point for a broader classroom discussion about water as an economic good (1992 Dublin Statement on Water and Sustainable Development), safe drinking water as a universal right (UN resolution 64/292, July 28, 2010), and financially sustainable business models for water infrastructure.[6]

4 Conclusion

In this article, the set up of the water economics course at the University of Waterloo is discussed, in particular how it tries to train and prepare economists with an interest in water management for a variety of real-world challenges. Both students from the Department of Economics and students studying water from other schools and departments on campus with an interest in economics enroll in the course. During the first month of the course, students with different disciplinary backgrounds are taught basic economic principles to ensure economics and noneconomics students continue the course with the same prior knowledge and understanding of why water use and management are fundamentally part of the economics discipline, which basic economic theory and concepts underly water resources management, and how economists aim to optimize water use based on economic

[5] Bakker (2014) presents an interesting critical review of trends in the water sector, focusing on the privatization of resource ownership and management, the commercialization of resource management organizations, the environmental valuation and pricing of resources, the marketization of trading and exchange mechanisms, and the liberalization of water governance.

[6] I show in my lectures that water consumption per capita was approximately 20 percent higher in Ireland than in the rest of the European Union where consumers pay for their water use before the introduction of water metering, suggesting metering and pricing have an effect on water consumption.

efficiency, as opposed to, for example, simulations of hydrological and biogeochemical processes in the natural sciences.

Special attention is paid in the course to the concept of "value" and value theory in economics (using Adam Smith's "diamond and water paradox"), compared to other social sciences, and the difference between price and value. The use and usefulness of nonmarket valuation methods are discussed across a wide variety of public water services. It is in this part of the course where students discuss how to reconcile principles such as water as an economic good and water as a universal right in practice. This is every year an interesting discussion, not only between economics and noneconomics students, but also between students with different sociocultural backgrounds. Approximately 40 percent of the students at the University of Waterloo are international students from more than 80 countries around the world with very different water experiences.

The results from the annual student evaluation surveys, completed after the course, show that what students appreciate most in the course is its applied and interdisciplinary nature, where economic theories, concepts, and methods are explained and exemplified based on practical water management challenges from around the world. Having students work together on practical examples and address emerging global challenges in integrated water management from different disciplinary perspectives is in line with global trends in impactful interdisciplinary scientific research (e.g., US Committee on Science, Engineering and Public Policy 2005), applied research programming, and practical water policy and legislation. The collaborative aspects of experiential learning advocated in the course are in the spirit of the call for action from America's 2020 Water Sector Workforce Initiative and the guidelines written by the European Water Economics (WatEco) working group, published in 2003 to support the various economic implementation aspects of the WFD (European Communities 2003). The same applies to the call for a two-way conversation between academic researchers and practitioners by the World Bank Director of Water Global Practice, Junaid Ahmad, during the first meeting of the International Water Resource Economics Consortium (IWREC) organized at the World Bank in 2014, so that "the richness of the [academic] research informs the daily operations of the World Bank and the questions that are asked by [the World Bank] clients are taken up by academia."[7]

In conclusion, water merits a specialist course in applied economics instead of being part of a broader environmental and resource economics program. The sheer size of the economic costs of global water stress and mismanagement as estimated for example by the Economist Intelligence Unit (2021) shows the urgency of the global water crisis. However, a legitimate question is which additional skill sets to those already taught in environmental and resource economics do students need to address the economics of water resources? The answer to this question is found in the fact that water security challenges have become so widespread (including places where there did not use to be water security challenges due to mismanagement and global climate change), so complex (e.g., not enough water, too much water, poor quality water, and combinations thereof), and so intertwined with other environmental pressures (e.g., climate and land use change) that standard environmental-economics textbooks on resource scarcity and pollution control have started to fall behind. Being able to understand the economic aspects of wicked, multidimensional water problems requires that economics students have a thorough understanding of the complexities involved without having to become a scientist or engineer themselves. This is achieved by connecting them with water graduate students in other disciplines (e.g., science, engineering, public health) with an interest in economics. Asking them to collaborate on joint assignments and pointing out where in the economic analysis such collaboration is essential to get both the environmental and economic "facts" right, including the identification of the risks and uncertainties involved, is crucial to doing sound (i.e., valid and reliable) economic analysis and

[7] https://www.worldbank.org/en/news/feature/2014/09/23/the-role-for-water-economists-in-shaping-policy-and-implementation.

creating credible and applicable economic narratives to support policy and decision making toward water security.

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Appendix

Table 1: Course Outline

Week	Course Description	Materials Used in Class	Reading Materials
1	Course introduction: the relationship between water and the economy	±75 slides based on own materials: -What makes water special? -Water as a source and sink -Relationship water and economy -Water as an economic good -Value and price of water -Why price water?	Olmstead (2010a, 2010b)
2	Supply and demand of water and optimal water allocation	Slides based on Griffin, chapter 2*	Griffin, chapter 2
3	Empirical estimation of supply and demand curves	Slides based on Griffin, chapter 3*	Griffin, chapter 3
4	Cost-effectiveness analysis and cost-benefit analysis	±60 slides based on own materials	Brouwer (2022)
5	Water pricing	Slides based on Griffin, chapter 9 and ±20 slides based on own materials	Griffin, chapter 9
6	Water game and intermediate test	Online water game*	Seibert and Vis (2012)
7	Watershed cooperation and payments for watershed services	±45 slides based on own materials	Brouwer (2018)
8	Economic valuation of water services	±40 slides based on own materials	Young, chapter 2
9	Presentation CBA assignment and field trip to wastewater treatment plant	-	-
10	Nonmarket valuation methods: revealed preference methods	±35 slides based on own materials	Young, chapter 4
11	Nonmarket valuation methods: stated preference methods	±50 slides based on own materials	Johnston et al. (2017)
12	Recap—what have we learned? Submission discussion paper	±50 slides based on own materials	-

* This includes own slides that further explain some of the figures and results presented in the reading materials.

The final grade of the course consists of the following four elements:
- Intermediate test following the water game (week 6)
- Group assignment CBA dam building (week 9)
- Discussion paper (week 12)
- Final exam based on all teaching materials at the end of the course

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Teaching and Educational Methods

Teaching Principles of Water Economics to Non-Economists: Lessons from California

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JEL Codes: A22, L95, Q25, Q51, Q53, Q58
Keywords: California, non-economist, policy, teaching, water economics, water literacy

Abstract
Economic analyses are essential in water management and allocation among sectors and regions that face water scarcity. State and local agencies in charge of water management in California play a major role in making appropriation decisions and designing policies on such issues. Economic decisions are even more critical with the predicted, more frequent water scarcity due to population increases and climate change impacting water resources. Since most of the staff members in these agencies are non-economists, they may lack the skills to develop accurate analyses and make economic decisions on water management. In addition, university graduates, to be placed in water agencies after graduation, often lack an economic background from the various courses offered on water issues. For those reasons, we present in this paper the building blocks and content of a water economics and management course targeted toward university upper-level non-economist students while providing details on the weekly course content and learning assignments. In addition, we evaluate course achievement results from a learning assessment survey, comparing the knowledge and understanding gained between the first and last week of the course.

1 Introduction

The rising population combined with increased frequency, longevity, and severity of climate change-induced droughts have resulted in elevated pressure on water resources in California and greater competition among all water-consuming sectors. In addition to these effects, water in California is not evenly distributed temporally (i.e., year-to-year variations) and spatially (i.e., northern versus central and southern California) to meet water demands in terms of quantity with adequate quality. All of that makes water management even more complex and essential. Most precipitation occurs during the winter months in the northern part of the state, while more water is needed during the summer months in the Central Valley and Southern California (Cheng et al. 2016; Escriva-Bou et al. 2017; Hanak and Lund 2012; Lee, Nemati, and Dinar 2021, 2022; Mann and Gleick 2015; Sandoval-Solis 2020; UNESCO UN-Water 2020).

To manage this complex water system, alternative policies, and infrastructures were introduced and implemented to improve water quality, water-use efficiency, and water supply security. These policies are based on economic and engineering principles. Examples of such policies include water transfers or exchanges, building reservoirs, introducing conservation programs, and implementing the Sustainable Groundwater Management Act (SGMA), to name a few (Hanak et al., 2011). Economic perspectives can provide insights into the implications of various water policy options and decisions and could help with the management of what otherwise might be an overwhelmingly complex system (Green 1997). A recent report estimates that in 2016 about 1.7 million workers were directly involved in "designing, constructing, operating, and governing" U.S. water infrastructure.[1] However, water

[1] https://www.brookings.edu/research/water-workforce/

management decision-makers in many states are engineers, teams of engineers, and other technical staff that are usually non-economists. Water managers typically have civil engineering and environmental science degrees, and those with economic degrees are not common (less than 2 percent).[2] In California, state and local agencies are involved in making decisions on their water management systems to meet stresses from climate, population, and land-use changes. The California Department of Water Resources (DWR) and the California State Water Resources Control Board (the Board) are the principal regulatory agencies with jurisdiction over California's water resources at the state level (Gray 1993, 2015). However, only 72 of the 2,038 employees (3.53 percent) in DWR and 16 of 970 employees (1.67 percent) on the Board have economic degrees (Table 1). In the Metropolitan Water District of Southern California, a major wholesaler and decision maker in Southern California, only 13 of about 774 employees (1.72 percent) have economic degrees. This portion gets even smaller in local agencies; for example, in the Eastern Municipal Water District—a major water retailer in Southern California—only one of 347 employees (0.15 percent) has an economic degree (SignalHire 2022).[3]

Table 1. Most Common Majors of the Employees at the California Department of Water Resources and the California State Water Resources Control Board

	Social Sciences			Non-social Sciences			Other*
	Business	Economics	Management	Environ-mental Science	Engineering	Geology	
# Employees	138	106	183	313	680	138	1,449
% Employees	4.59	3.53	6.09	10.41	22.61	4.59	48.19

Source: Authors' calculation based on the survey data from all the employees in 2022 using the SignalHire database at https://www.signalhire.com/.
Note: *The category "Other" includes majors such as accounting, biology, computer science, chemistry, and law.

In addition, previous work finds a lack of fundamental knowledge about water resource management among students across the disciplinary spectrum who will be the next generation of decision-makers and analysts. Importantly, previous studies suggest that complex and interdisciplinary topics related to water resources were found to have the lowest levels of understanding. Some studies highlight that most students do not know where their drinking water comes from or the treatment processes it undergoes before and after use (Brody 1993; McCarroll and Hamann 2020; Sadler, Nguyen, and Lankford 2017; Sherchan et al. 2016). At the University of California, Riverside (UCR), we also realize problems regarding our students' fundamental knowledge of the major economic principles and policy issues affecting California's water systems and their management.

To help address these issues at UCR, we planned a general water economics and policy course. This course focuses on strengthening undergraduate non-economic students' understanding of water economics principles and how it can be used to provide insights into the implications of various water policy options and decisions. To achieve this goal, we designed and taught an innovative upper-level undergraduate course, "Water Economics, Management, and Policy: California and Beyond." In this

[2] See here for the most common majors for water resources managers in the United States: https://www.zippia.com/water-resource-manager-jobs/education/?survey_step=step2.
[3] Numbers are calculated by the authors using the survey data from all the employees in these agencies in 2022 using the SignalHire database. See here for more information: https://www.signalhire.com/.

article, we discuss the details of the course content, student's assignments, and evaluations, present a measure of learning outcomes, and describe the lessons learned from teaching it in 2021 and 2022.

2 The Course: Water Economics, Management, and Policy—California and Beyond

2.1 Components and Learning Objectives

This course was created to introduce students to the complexities of water resource management and policy in California and, through this conduit, to extrapolate from what they learn to other states and countries with similar water issues, such as Arizona, Colorado, Texas, Australia, Israel, Mexico, Spain, and South Africa (all featured in the course). California is a water-scarce state that exhibits special characteristics that make it a microcosm for water policy challenges that confront other regions worldwide as well. Students learn, evaluate, and discuss the main elements of the water economy in California, the problems it faces, and the economic, institutional, policy, and engineering approaches used to address them. By the end of the course, students should be able to (i) describe contemporary water problems in California and the other states or countries discussed; (ii) describe the reasons for the problems and how different types of policy interventions and economic principles may or may not be successful; (iii) explain the major features of California water policies, and (iv) discuss the efficiency and equity goals of, and the challenges faced by water policymakers.

The course is a four-unit senior-level undergraduate elective course. The course was offered in Spring 2021 for the first time and then again in Spring 2022. Each quarter about 40 students enrolled in the course. The students enrolled in the course were 3rd and 4th-year students from various colleges across the campus with majors in biology, economics, education, environmental sciences, math, public policy, psychology, political science, and sustainability studies. For each course topic (i.e., each weekly unit), students were assigned a short and informative reading list to be prepared ahead of the class. All the readings required for the course were provided to the students through an online learning management system (Canvas).

The class assessments were amended after we first taught the course in 2021. The initial assessments were eight in-class quizzes (10 percent), eight problem sets (40 percent), a mid-term (20 percent), and a final exam (30 percent). We interviewed the students in an informal group setting (after the midterms) for their feedback on the content, delivery methods, assessment methods, content, and any other major issues with the course in general. After presenting the module in Spring 2021 and receiving feedback from the students, we decided that the number of quizzes and problem sets was excessively high and needed a more in-depth assessment method. So, we reduced the number of quizzes and problem sets from eight to four and added a couple of policy brief assignments. The course components and their grade distributions in Spring 2022 are reported in Table 2.

The purpose of the graded quizzes is to verify basic knowledge of the topics and engage the students in class discussions. Each quiz consists of 10 True/False and multiple-choice questions and is based on the most recent topics studied (i.e., not cumulative). In addition, we designed the problem sets and policy briefs to test for a deeper understanding of the material and for students to develop practical knowledge of the current water issues, policies, and alternative solutions from an economic perspective. Specifically, we included a question in each problem set regarding issues with the current policies in place and alternative solutions practiced in California.

In the policy briefs, we asked the students to provide a concise summary of a particular issue, the policy options, including principles of economic instruments used, and their recommendations on the preferred option. Policy briefs are aimed at informing readers who are acting as federal, state, and local policy makers and regulators. Previous studies show that policy briefs as an assessment method serve multiple functions: tests students' deeper understanding of the material, encourage students to develop

Table 2. Course Components and Grade Distributions

Activity	Percentage of Final Grade
In-Class Quizzes (4 + 2[a])	10% total (2.5% each)
Problem Sets/Assignments (4)	20% total (5% each)
1-page Policy Brief (2)	20% total (10% each)
paMidterm Exam	20%
Final Exam	30%

[a] 2 Learning-outcomes quizzes on the first and last sessions are not for grading.

"real-world" skills, engage students, and help them practice a distinct form of writing (Lightfoot 2020; Mathews 2022; Moody and Bobic 2011). To prepare the students and make the structure of the policy briefs as uniform as possible, we provided a template (see Appendix A) that outlines the key elements in the brief and a grading rubric as well as the suggested topics for the brief to select from (see Appendix A). The key aspects of the one-page policy briefs include: (1) a concise, attractive, and clear title for the non-specialists; (2) a list of authors (up to 2 students); (3) a 130-word summary that includes a description of the problem addressed, a statement on why the current approach or policy option needs to be changed, and suggested recommendations for improvement of current legislation or immediate action; (4) a description of the problem in which students discuss the important issues related to the problem, why they are important in California's water economy, and highlighted positive and negative effects on regions and subsectors; (5) the economic and management aspects that need policy intervention in which students focus on economic, management, institutional, and legal aspects (such as overuse of water, malfunctioning of water right system, decrees that were issued) that call for policy intervention; and (6) policy intervention recommendations in which students describe the suggested policy intervention or reform and their opinion or criticism on the reform or policy interventions using concepts from the class. Finally, we also require students to pay attention to the in-text references and provide a complete list of the sources used in the text.

2.2 The Course Content

Table 3 presents the topics and content covered during each week of the quarter. The course is 10 weeks long,[4] and one topic is covered per week. All the topics are related to California's major water issues and policies, as well as the role of economic principles in providing insights into the implications of various water policy options and decisions. We invited relevant water managers, regulators, and practitioners as guest speakers to the class when available.

2.2.1 Week 1: Introduction to the course: Work arrangements, water endowment, and the water system of California

During the first week of the class, we focus on the "water endowment and the water system of California." First, we provide an overview of water availability in California and compare it to other similar states and countries. Next, we review the various water sources in California, unpredictable water availability, and the population concentration that leads to an imbalance between supply and

[4] Classes at UCR are quarter-based in which each quarter is 10 weeks long. This class was offered twice a week at 80 minutes per meeting.

Table 3. Weekly Topics Covered in the Course[a]

Week	Topic	Required Reading List
Week 1	Water endowment and the water system of California	Brown and Matlock (2011); Carle (2015); and Dinar et al. (2020)
Week 2	Regional and sectoral water uses	Hanak et al. (2011); Lee et al. (2021, 2022); and Mount and Hanak (2016)
Week 3	The California water hardware and software	Carle (2015) and Hanak et al. (2011)
Week 4	Water markets, The 1991 Drought Water Bank, and groundwater banks	California Department of Water Resources (1991); Grafton et al. (2010); Jezdimirovic, Sencan, and Hanak (2019); Luxem (2017); and Schwabe et al. (2020)
Week 5	Climate change and California's water	EPA (2016); Escriva-Bou et al. (2017); Jessoe, Mérel, and Ortiz-Bobea (2020); and Smith and Mendelsohn (2007)
Week 6	Review, midterm exam, and students' feedback	-
Week 7	Policies to address water scarcity in California	California Department of Water Resources and State Water Resources Control Board (2018); Gleick (2010); Hanak et al. (2018); and Maggioni (2015)
Week 8	The SGMA of 2014	Conrad et al. (2016) and Kiparsky (2016)
Week 9	The San-Joaquin—Sacramento Delta	Hanak et al. (2018); Lund et al. (2010); Tanaka et al. (2011); and Sunding et al. (2002)
Week 10	The salinity and drainage problems	Chang and Brawer Silva (2016) and the San Joaquin Valley Drainage Program (1990)

[a] We are happy to share the details in each topic along with the discussions/slides for each week upon a reasonable request.

demand, complicating water management in the state. Topics include the hydrological cycle, the role of snowfall/snowmelt, the water conveyance system, primary surface water sources, groundwater and their relations to rivers, recycled water, and desalinated water. We introduce a couple of water scarcity indexes used in the literature to assess water scarcity in California over time and discuss future concerns for the California water sector. Once the students learned about available water in California, we moved to the next section of the course, which discusses water use both between different regions of the state as well as various sectors (i.e., agriculture, environment, and urban). We emphasize how economics can help make such decisions on resource allocation.

2.2.2 Week 2: Regional and sectoral water uses

During week 2, we focus on the "regional and sectoral water uses" in California. Following our discussions in week 1, we continue with the unusual water supply situation in California (and in several other states and countries, such as Colorado, Israel, and Spain) of having most of the water resources in one region (such as Northern California) and most of the population and economic activity in another part (such as Southern California). We review how much available water in California is used in various parts of the state (e.g., Northern, Southern, and Central). For each region, the class also focuses on agricultural, municipal (residential), and environmental water use. We also discuss various water use measures and apply them to the state and the representative regions or subregions. In this week, students learn to distinguish between the concepts "crop per drop" and "economic value per drop" and their implications in the case of the irrigation sector. We try to conclude with the role of water in the state's economy. Once the students learn about the water availability and water allocations among regions and sectors in California, we move to the next section of the course, where we discuss both infrastructure and connectivity between the regions as well as the instructions and regulations which could play a major role in allocating the available water beside the economics logic.

2.2.3 Week 3: The California water hardware and software: The delivery system, allocation rules, institutions, and water rights

The third topic of the course focuses on "California water hardware and software: the delivery system, allocation rules, institutions, and water rights." During this class, we connect all water projects in California into one network and try to understand how that network operates. We realize that such a pipe/canal network (hardware) needs support from another system of institutions (software). During this week's class, we review several important legal and institutional arrangements in California and compared them to the system in other water-scarce countries, such as Australia, Spain, and Israel. Also, during this week, we discuss important water institutions (e.g., water rights, water markets, pricing, water districts) used in California, and discuss their advantages and disadvantages, given the state's unstable water supply situation over time. Once students learn about the available infrastructure and regulations, we move to the next section of the course, that focuses on the water markets and how its economic concepts could improve the efficiency of the resource allocation using markets while considering both institutional as well as the available infrastructure constraints.

2.2.4 Week 4: Water markets, The 1991 Drought Water Bank, and groundwater banks

For week 4, we focus on the role of water trade and surface and groundwater banking in addressing water scarcity. We review statistics on trends in water supply and demand by source and sector and how they have changed over time. We analyze recent data showing how water trading has changed over time—in terms of transactions and volume—both at the state and sector level aggregates. In addition, to put these numbers in perspective, we compare the performance of water markets in California to other western states and other countries, such as Chile and Australia. Students also learn about water banking and managed aquifer recharge as additional tools to move water from abundant to scarce places and between years with ample supply to years with limited supply. We review the principles and performance of the 1991 State Water Bank that was active during and after the prolonged drought of 1986–1991.

Now that students learned about water availability, allocation, and markets, we turn our focus to climate change impacts and how these impacts will reduce the available water and lead to competition among sectors and between regions for the available water even further, and how economic concepts, such as pricing, water markets, can help us reach better allocation solutions.

2.2.5 Week 5: Climate change and California's water

Week 5 focuses on climate change and California's water, in which we go beyond the physical impact of having less water or altered precipitation over time. Based on California's climate change assessment report, we discuss the long-term implications of climate change on all water subsectors and summarize the relative vulnerability of water-using sectors and regions.[5] In addition, students learn about the interaction between climate change and the groundwater system, as well as adaptation and mitigation strategies to cope with the impacts of climate change on the water system in the state.

2.2.6 Week 6: Midterm exam

During week 6, students take a midterm exam, and we provide an overview of the materials covered and the expected materials in the next four weeks. This week, we also urge the students to provide, in a general discussion format, their mid-quarter feedback on the course content, assignments, grading, and other. The feedback was very useful in terms of understanding where the students are struggling, what would encourage them to engage in our discussions, how they feel about the course content, and its delivery as well as our assessments. As mentioned before, we used this feedback to change various aspects in the structure as well the delivery of the course. For example, we adjusted our assessment method and weights on each activity in Spring 2022 based on the feedback from students enrolled in Spring 2021.

The second half of the course is dedicated to major water polices in California (urban water polices, ground water policy, salinity, the Delta, and salinity) and how we can use economic principles to evaluate these polices, improve them, and suggest alternative polices.

2.2.7 Week 7: Policies to address water scarcity in California

During the second meeting in week 6, we focus on policies to address water scarcity in California. We discuss principles of economic tools, using examples related to addressing water scarcity, increasing water conservation, and improving water use efficiency. Students learn about the advantages and disadvantages of demand-side management strategies, such as water pricing, rebate programs and subsidies to water users, water-use restrictions, and programs to enhance new technologies that increase water use efficiency and encourage conservation. In addition, we discuss supply-side management strategies, including increased supply of treated wastewater, desalinated water, stormwater, and imported water (water transfers). We compare different water sources (traditional and new) using simple cost-benefit analysis principles.

2.2.8 Week 8: The SGMA of 2014—A paradigm shift in managing California's dwindling aquifers

Building on the discussion from week 7, week 8 focuses on the recent groundwater policy in California, known as the SGMA of 2014. During the long drought in California (2012–2016), water users turned to groundwater as a substitute for the dwindling surface water sources that were critically reduced. The groundwater law in California allowed at that time for each landowner to pump as much as they needed (and were able to) from the aquifer to which they had access. Lowering groundwater levels in many aquifers due to the open access nature of groundwater in many locations in California led to negative

[5] See here for more information: http://www.climateassessment.ca.gov.

externalities in terms of depth and quality and affected groundwater availability for users.[6] Realizing the potential long-term damage from unregulated groundwater pumping, in 2014, the state of California enacted SGMA, a revolutionary institution by which groundwater is managed and developed in California. The class describes the situation for groundwater pumping in the Central Valley of California, the impacts of pumping on groundwater levels and related problems (e.g., land subsidence), economic principles of the SGMA, plans for future operations of SGMA, institutions identified and created by SGMA, and the prospect of groundwater sustainability in the state of California.

2.2.9 Week 9: The San-Joaquin—Sacramento Delta

During week 9, we examine from different perspectives the special role and the fragility of the "Delta" as the main water hub of California. We discuss the threats to the Delta, different plans to modify the way the Delta operates, and the state's plans to modify them. The class was exposed to considerations of water quality effects on the Delta ecosystem and the economic value of constraints placed on water transfer from the Delta; to the evaluation of different plans to sustain the Delta while keeping the agricultural demand for water satisfied and cost-benefit principles used to compare between these alternative plans; and the political economy of interest groups in the region and outside the region regarding such an important ecosystem.

2.2.10 Week 10: The Salinity and Drainage Problems on the West Side of the San Joaquin Valley

The last week of the course focuses on the salinity problems in the San Joaquin Valley. In the early 1950s, the state and the federal government started developing two giant water projects to convert California from a desert state to a blooming state. We discuss the pros (benefits) and cons (costs/negative externalities) of these water projects, focusing on the salinity and drainage issues that emerged in the mid-1980s in the form of elevated salinity and selenium contamination and their associated social costs. This class also covers several of the policy interventions to deal with the damages of salinity and drainage, such as land retirement, groundwater management, discharge of drainage to the San Joaquin River, protection of species, restoration of infected locations, provision of alternative sources of water, and introduction of new institutions, policies, and technologies such as pricing of water and subsidies for more efficient irrigation technologies to enhance conservation of applied water.

3 Learning Outcomes Survey

To assess the knowledge gained and understanding of concepts realized by the students during the course, we developed a California water knowledge survey and tested students' water literacy at the beginning and end of the course. The survey also serves as a measure of the class "success" rate. The survey consists of 10 True/False and multiple-choice questions (Table 4). A total of 63 students in our Spring 2021 and Spring 2022 classes responded to the survey questions. This survey also is a tool to assess if the learning objectives were met in the course. As indicated earlier, the course has five learning objectives, and the questions below address one or more of these objectives.

As indicated in Table 4, on average, 60 percent of the students answered the questions correctly at the beginning of the course. This number increased to 85 percent by the end of the class. The improvement was much more significant for some basic knowledge-type questions (e.g., questions 2 and 3). To measure the improvement (knowledge gain), we calculated the ratio of week 10 vs. week 1 for each question presented in the last column of Table 4. Calculating the ratio considers the relative

[6] Open access institutions allow any groundwater user to tap into the aquifer, leading to the tragedy of the commons that has been transformed into lower water level in the aquifer, thus making pumping more expensive, and intrusion of lower quality water from adjacent aquifers or from the ocean, when aquifers are close to the ocean.

Table 4. Water Literacy Survey Questions (Percent of Correct Responses to True/False Questions)

Survey Question	Percent Answered Correctly		Ratio (Week10/ Week 1)
	Week 1	Week 10	
1. The majority of California's population resides in Northern California.	88	94	1.06
2. The California water system's primary water sources originate in Southern California.	54	88	1.62**
3. Statewide, average water use is roughly 50% environmental, 40% agricultural, and 10% urban.	39	92	2.35***
4. The water we drink in the Inland Empire (IE) region originates within the IE.	75	84	1.13
5. The sale value of agricultural products that are produced in California is in the range of:	41	64	1.58**
6. Approximately___ percent of statewide electricity and ___ percent of natural gas go to pumping, treating, and heating water.	65	88	1.34*
7. The California Delta is the confluence of:	58	89	1.53**
8. SGMA stands for:	81	98	1.22*
9. Water is moved from Northern to Southern California using ___.	79	97	1.22**
10. The Colorado River supplies roughly ___ percent of all water for Southern California cities and suburbs.	24	59	2.47***
Average	**60**	**85**	**1.41**

Notes: Based on the authors' calculations using the student survey results in the first and last session of the classes in 2021 and 2022. ***, **, * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

percentage values of weeks 1 and 10.[7] As indicated in this column, students' overall performance increased by 1.41, on average. For some basic knowledge questions and those related to Southern California, the gain was much more significant (e.g., questions number 2, 3, and 10). The results in this table and our discussion with the students indicate that, on average, the course met the learning objectives.

4 Lessons Learned and Concluding Remarks

Given that we have had two rounds of teaching in this class (Spring 2021 and Spring 2022), learning from our experience and students' feedback is essential for future considerations. Students indicated in their evaluation feedback that this course opened a new horizon and understanding of the interaction between water users and the environment in California. Indeed, we feel that in a state such as California, where water scarcity is a way of life, such courses, with emphasis on economics and policy (even if simplified), should be offered to any student.

We realized that the set of topics and the order in which they were presented in class are important for the connections students need to make in order to understand the water system's complexity and its interaction with water-related production activities and consequences. We also realized that including external speakers to cover some of the more complicated issues, such as

[7] For example, if the performance in weeks 1 and 10 were 25 and 50, the difference is 25. The same is for the performance of 40 and 65. But the ratio in the first case is 2.00, and in the second case, it is 1.625.

groundwater economics and policies for agricultural non-point salinity pollution, is extremely important. Students had an opportunity to extrapolate from our class presentation to the “real-world” issues that face the water sector of the state, learning from presentations by experts that deal with such specific issues and their economic and policy-related aspects daily.

At the end of the class, and while interacting with many students, we realized that this class included a large set of technical data/information that was hard to process and connect with specific locations and situations. Several students mentioned difficulty comprehending the large volume of information we shared with them in a 10-week course. One lesson we would implement in the future is to add case studies of experiences related to sectors and communities (irrigators, households) affected by both the negative effects of water scarcity or quality and the policy interventions they face, which could improve students’ understanding of these issues and make them more realistic.[8]

Finally, we realize that the addition of “field trips/water tours” is an important teaching and learning strategy that is essential to such an undergraduate course. Field trips encourage experiential learning and student engagement through direct experience with course material and a firsthand look at the water facilities, rivers, and regions critical in the debate about the future of water resources in California. Such local trips include visiting regional water utility facilities, the Carlsbad desalination plant, the Colorado River, Sacramento and San Joaquin Rivers, the Bay Delta, and the Central Valley Project. In future offerings of this class and in collaboration with water utilities, the DWR, the California Water Board, and Water Education Foundation, we aim to implement such trips.[9]

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[8] This would certainly change the composition of activities and assignments the students in future courses will face. At this point in time we are unable to assess quantitively how, but we are right now in the process of planning the Spring 2023 quarter of this course and implement such self-recommendation.

[9] Field trips will be integrated with the lectures. We are considering having one field trip for the course offered in Spring 2023. Most likely, this field trip will be to meet a water utility next to UCR. Such field trips could be completed within the time allocated to the class in one weekly meeting and sometime during the lunch break, which the class overlaps with. For future planning, we may need to consider longer field trips.

Appendix 1

Policy Brief Template

1. Title
The title should be concise and clear for non-specialists. It should be easily understandable and attractive.

2. Authors
All authors of the policy brief should be listed.

3. Summary
The word limit for the Summary text is 130 words. The summary commonly includes: (1) a description of the problem addressed; (2) a statement on why the current approach/policy option needs to be changed; and (3) suggested recommendations for improvement of current legislation or immediate action.

4. Description of the problem
Discuss the important issues related to the problem that you identify and why they are important in California's water economy. Highlight positive and negative effects on regions and subsectors.

5. The economic and management aspects that need policy intervention
Focus on economic, management, institutional, and legal aspects (such as losses, overuse of water, malfunctioning of the water rights system, decrees that were issued) that call for a policy intervention.

6. Policy intervention recommendations
What is the suggested policy intervention or reform? Using concepts/materials from the course, what is your opinion/criticism on the suggested reform/policy interventions.

7. Sources
Please indicate all the publications that are relevant to the policy brief or link to other policy briefs or press releases dealing with the same issue. Standard bibliographic information should be provided. **[Do not count toward your 1-page limit.]**

List of Suggested Topics for Policy Briefs
1. Water trade as a mechanism to address water scarcity among regions
2. SGMA as a framework to address groundwater problems in California
3. Use of wastewater for irrigation as a solution for water scarcity
4. Management and policy interventions to address salinity problems in agriculture and pollution of waterways
5. Urban water demand management in California: Role of pricing and non-pricing policies
6. Polices to prepare for future climate change in California [e.g., policies on investment, water sources]
7. Role of water rights in California's water management
8. Water infrastructure bill in the context of California
9. Water quality regulations
10. Proposition 218 and California's urban water management

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Teaching and Educational Methods

Innovations for the Water Resource Economics Curriculum: Training the Next Generation

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Abstract
Several climate-related challenges facing water managers require innovations in the water resource economics curriculum. Some of those challenges include the need to address population stress, food security, water security, energy security, environmental protection, peace, economic development, health, climate, and poverty. Despite the need for innovations in the water economics curriculum, little has been published to date describing useful curriculum innovations up to the task. This article addresses several curriculum innovations needing attention. It does so by addressing two questions: (1) What economic principles are needed as a foundation for curriculum reform in water economics to better understand today's water problems? (2) What innovations or adjustments are needed to assure a solid education and training of the next generation of water economists? It addresses these two questions by describing the range of water-related issues facing water managers internationally as well as relevant economic foundations needed for student engagement. It follows by describing several innovations that can prepare water economics students to better understand and address emerging water science and policy challenges. Results of a simple linear programming model are presented.

1 Introduction

Several climate and related challenges facing water managers require innovations in the water resource economics curriculum by which instructors can vigorously engage college students. Some of those challenges include the need to address population stress, food security, water security, energy security, environmental protection, peace, economic development, health, climate, and poverty. This article addresses several curriculum innovations needing attention by addressing two key questions: (1) What economic principles are needed as a foundation for curriculum reform in water economics to better understand today's water problems? (2) What innovations or adjustments are needed to assure a solid education and training of the next generation of water economists? The paper describes the range of water-related issues and challenges facing water managers internationally as well as relevant economic foundations needed for student engagement. A summary of the more important economic principles (Eamen, et al., 2020, Mouratiadou and Moran, 2007, Ward, 2012) is provided to guide understanding of innovations needed for university water resource economics curricula in order to better train the next generation of water economics professionals worldwide. It follows by describing several innovations that can prepare water economics students to better understand and address emerging water science and policy challenges. Results of a simple linear programming model are presented, as well.

2 Background

2.1 population

Growing populations continue to increase stress on water supplies. Internationally, much of the anticipated population growth will take place in Global South communities in Latin America, Asia, and Africa, for which there is already much burden imposed from health, food, energy, and water challenges. With foreseen population growth, all major water uses, especially those uses for irrigation and urban use, will need guidance from innovative regional water resource plans.

Water storage is an important resource. Additional reservoir storage, aquifer recharge, and even large water towers can save water in times of heavy natural supply such as the early 2023 California floods, for later use when shortages occur. It has been known for years that urban wastewater has served as a significant source of water, but it needs to be regulated and treated to guard against psychological stigma and real health effects for urban use and to protect against contamination.

Water recycling, also known as water reuse or water reclamation, has been practiced for centuries. The ancient civilizations of Egypt and Rome both had sophisticated systems for collecting, treating, and reusing wastewater. In modern times, water recycling has become increasingly important as a means of conserving water resources and reducing pollution. It is used for a variety of purposes, including irrigation, industrial processes, and even as a source of drinking water in some cases. The technology and techniques used for water recycling have evolved over time, but the basic principles have remained the same. Building urban water recycling facilities for handling shortages when first line supplies are cut off is an old idea. For example because of conflicts that occurred among the various kingdoms of the Iberian Peninsula during various parts of the Middle Ages, the successful regions of Al-Andalus were managed with defensive architecture that assured an internal water supply when the first line disappeared (Garcia-Pulido and Martin, 2019).

Virtual water (Allan, 1998, Gleeson, et al., 2012, Hanjra and Qureshi, 2010, Hoekstra and Chapagain, 2007, Hoekstra and Mekonnen, 2012) can respond to population growth pressures. Water scarce communities save their own limited water by importing food and power from communities better endowed with water. Water embedded in these imports adds a smaller price to the final good than producing them using their own water. Virtual water stands to be a lower cost method for the importing community than developing their own water sources, another classical argument characterizing the gains from trade (Gadgil, 1998, Jackson, et al., 2001).

2.2 Food Security

Future crop yields will need to increase considerably to stay up with growth trends in population, income, and water demands. Internationally, the capacity to protect food security will be constrained by levels of water and land useable and affordable for irrigated crop production and by technological advance in crop productivity, as well as on capacity to substitute non-water inputs for water. One important work addressed this challenge head-on (van Ittersum, et al., 2013). This and other works have made it clear that assessing food production capacity on every parcel of land where crops and livestock are grown is required to guide choices on policy design and private investment activities for which goals are to increase future crop yield and productivity of farm water use. Several other works have investigated this challenge (Hanjra and Qureshi, 2010, Kang, et al., 2009).

2.3 Water Security

The need for sustained water security occurs everywhere, especially in big cities in the Global South. The importance of sustainable water demand management (SWDM) is much higher in the rapidly growing big cities of the world, for which groundwater depletion and water deficits are taking place with little assessment of their long-term viability. One work from the year 2017 took a serious look at this problem (Arfanuzzaman and Rahman, 2017). Several other works have also assessed various methods to enhance water security (Alvarez, et al., 2018, Bakker, 2012).

2.4 Energy Security

Water security is tightly connected to energy security, with classic examples coming from hydroelectric power and water purification. Along those lines, energy remains an important element of economic development and sustained growth. Renewable energy sources provide a widely available and environmentally acceptable choice to support energy security for many communities in the face of reduced worldwide supplies of fossil energy. One paper found the integration of renewable resources with water purification and desalination is becoming increasingly economically attractive (Eltawil, et al., 2009). Several other works have investigated linkages between water resources and energy security (de Amorim, et al., 2018, Jalilov, et al., 2013).

2.5 Environmental Protection

Economic analysis has an important role to play in informing goals and means of supporting environmental protection. Much of the world's forecast population growth will occur in the Global South, already challenged by water, food, energy, and health difficulties. Increasingly, the various competing uses of water, namely irrigation, residential, and commercial water uses, need to be integrated into overall water management, for which environmental protection is an essential element (Operacz, et al., 2018). Other works have addressed protection of the water environment (Falkenmark, 2001, Loring, et al., 2013).

2.6 Economic Development

Economic development contributes to stress on water resources, but the causality also runs the other way: Well-managed and affordably priced water contributes to economic development. That is, there is a simultaneous relationship between water and development. Regarding the role of water in economic development, one work from 2012 found that water contributes to economic development (Ward, 2012). Several works have described the linkage between water and development (Araral and Yu, 2013, Brown and Lall, 2006, Duda and El-Ashry, 2000, Hambright, et al., 2000, Hamoda, 2004, Proskuryakova, et al., 2018, Ringler, et al., 2004, Schulz, et al., 2018, Sofroniou and Bishop, 2014).

2.7 Health

Water has a special connection to many dimensions of human health. One review work found that an estimated 779 million people are at risk of schistosomiasis, of whom 106 million (13.6%) live in irrigation schemes or in close proximity to large dam reservoirs (Steinmann, et al., 2006). Several other works have examined linkages between water and health to support economically workable interventions (Cannas, et al., 2020, Thomson, et al., 2019).

2.8 Climate

A wide variety of regional, national, and international evaluations of the water-connected impacts of climate change have been investigated since the 1990s, using a variety of methods and approaches, as well as climate models. Climate change presents a large but unknown future risk of unpredictable changes in numerous elements of water supply and use (deep uncertainty). A few of these dimensions include snowmelt, aquifer depth, streamflow, evaporation, and crop evapotranspiration (ET). Much serious work continues in the search for more fleet-footed water institutions to help quickly adapt to whatever unexpected changes emerge. The idea is to inform water using communities on the nature of measures to affordably and quickly adapt to unexpected changes in future water demands or supplies

(Ward, 2012). Several of other works have investigated connections between water, climate, and various climate water stress mitigation policies (Birol, et al., 2006, Esteve, et al., 2015).

2.9 Poverty

Safe affordable water is essential to all, but especially important for the livelihoods of more than one billion who live on less income than $US 1 a day. This is especially significant for the rural poor internationally employed in agriculture. One 2010 work found that in many parts of the Global South, water remains a limiting factor constraining food production. Increasing the effectiveness of water management in agriculture has the potential to contribute to reduced poverty through several paths: (Namara, et al., 2010). Additional works have addressed this problem, for which there are two well-known ones (Adams, et al., 2016, Castro, 2007).

3 Original Contribution

This paper describes selected classroom innovations that can be used by instructors to improve student understanding and use of economic principles to guide choices in water program and policy design. After reviewing three classic economic assessment methods, it focuses on addressing the question: What classroom innovations can contribute to a solid education and training of the next generation of water economics students and practitioners? It describes and elaborates on a few classroom innovations that can prepare water economics students to better address emerging water science and policy challenges.

4 Economic Foundations

4.1 Cost Benefit Analysis

Instructors may notice that students are often surprised to discover that one of the earliest written attempts to systematize cost benefit analysis (CBA) for a water application came from an 1848 work by the French engineer, Jules Dupuit summarized in a recent work (Brown, 2004). Dupuit's insights were later generalized by Alfred Marshall in his several editions of Principles of Economics (Marshall, 1890).

Dupuit set the bar high by calculating what would today be described as the net economic welfare resulting from a water project such as building a bridge. Dupuit investigated the utility that bridge users would gain from its use if built. He concluded that a good way to measure the individual bridge user's utility is to find out the user's willingness to pay for its availability, not by revenue received from charging those who used the bridge. Willingness to pay could be summed over users of the bridge and compared to the cost of building and operating the bridge. Dupuit's willingness to pay concept established a conceptual foundation for assessing the total economic value of a water-related project. He concluded that the cost of building it would be easier to measure than the benefits since the lion's share of those costs consist of elements bought and paid for like materials, engineering expertise, labor, and maintenance. From this exercise of comparing the discounted net present value of benefits and costs, an informed decision could be made on whether to build the bridge, with what technologies to build it, and in what time period to start construction.

The most widespread analytical tool of choice used by water economists to guide water economics decisions as of early 2023 remains CBA, sometimes called benefit cost analysis. CBA is a systematic approach to measuring the economic performance of a proposed water policy, project, or program (Young and Loomis, 2014). Numerous others have made contributions (Medellin-Azuara, et al., 2015, Stillwell and Webber, 2014).

Among other applications, CBA is used by water resource economists to identify choices that provide the best outcomes for water resource projects or plans. Today, CBA sees two common applications: (1) to discover if one proposed project or policy is economically sound, measured by how much its benefits exceed its costs in discounted net present value (DNPV) terms; (2) to provide common denominator comparisons among competing project or policy choices by assessing DNPV of each plan.

The practical utility of a CBA for a water resource project, proposal, or plan depends on the accuracy of the measured costs and benefits. Innovative instructors will show students that this accuracy is not desired by all special interests. Such an instructor will show to students a good example of groups that band together, known as "iron triangles," of which one example consists of Congress, government bureaucracies, and special interest groups (Gais, et al., 1984). Another example of an iron triangle community consists of farmers, bankers, and real estate interests who would benefit from a new federal irrigation project. These groups often go to some length to include or exclude important costs or benefits to produce an overall CBA assessment that favors the economics surrounding their special interests.

4.2 Cost Effectiveness Analysis

Water economics instructors will discover that students may find it attractive to apply a less demanding kind of economic analysis of water programs. Cost-effectiveness analysis (CEA) assesses the comparative costs of two or more programs that accomplish the same outcome. CEA is different from CBA, for which CBA assigns a monetary economic value to the package of outputs supplied. CEA is often used in water resources policy analysis for which it is undesirable, impossible, or illegal to measure monetary values of output, such valuing the reduced probability of an endangered species going extinct. The classical implementation of CEA compares costs of two or more proposals to achieve the same outcome, such as seeking the least cost method for supplying a given number of sick days avoided from safer drinking water provided (Aulong, et al., 2009, Balana, et al., 2011).

4.3 Pure Impact Analysis

Innovative instructors will find a way to use modern methods to show students there are times when water policy analysis must be conducted when information is lacking on both costs and benefits, for which environmental impact assessment (EIA) is a classic example. Despite weak access to data on benefits and costs, political leaders wish to be informed. One author wrote in 2005:

> *"Compared with CBA or CEA, EIA makes no effort to convert consequences into common denominators such as dollars of cost or benefit. Because no common denominators are attempted, large amount of raw information are placed in the lap of decision makers and the public who must make their own common denominator comparisons, e.g., compare various kinds of program cost to various environmental improvements produced." (Ward, 2006)*

Several works on pure impact analysis have also been published with water-related examples (Al-Agha and Mortaja, 2005, Beltran, 1999).

5 Curriculum Innovations

The water-related challenges described above facing water managers can benefit from innovations in the teaching of water resource economics. A framework for classifying those innovations is presented in the following discussion.

5.1 Innovative Documentation of Importance of Economics

New instructors often seek innovative methods to keeping student attention in describing the excitement of learning about water economics:

- Economics helps us understand the world around us, especially in places and times where important water policy debates are highly publicized.
- Learning economic principles helps us make better decisions.
- Economics carries practical applications: It has applications in a wide range of fields connected to water: business, finance, politics, and policy making.
- Economics helps students think critically, encouraging them to think logically about problems, a valuable skill in any career. Economics can be an engaging and rewarding field of study. By learning economics, students gain a deeper understanding of how the world works and how people make, carry out, and assess choices.

Despite all this, water economics instructors who travel overseas often find that host governments and donors ask instructors to motivate students to take their economics classes seriously. We instructors do this by telling our students that understanding economic consequences of proposed programs permits us to better respond to the threats and opportunities that appear. Much research shows that employers of professionals want skills gained from learning and practicing economics — the capacity to make informed choices, solve problems, manage information, analyze data, and write and speak convincingly.

5.2 Innovative Documentation of the Utility of Economics

New water economics instructors seeking classroom innovations may be surprised to find students of water economics know little of policy debates surrounding today's water problems, for which these students are often even more surprised at the potential role economic analysis can play to inform these debates. New instructors can teach students that a water problem is defined as having water of the wrong quantity (Tse and Hanly, 1998), quality (Uppala, et al., 2005), timing (Arnell, 1999), location (Kastner, et al., 2011), price (Espey, et al., 1997, Friedler and Hadari, 2006), or cost (Espey, et al., 1997, Friedler and Hadari, 2006), or any combination of these.

When students select a policy debate to investigate for an assigned class project, they often select the first topic they find on the web with little critical examination of its importance. New instructors seeking an improved water economics class or curriculum can show students where to go to discover bigger scope policy debates from those of a more limited or local interest scale. Examples of places students can go to learn more about bigger international current waters issues include:

- Scientific articles accessed from the Web of Science, Pub Med, and so on;
- Internet sources, like Google Scholar;
- Popular sources, like online newspapers and other media;
- Public meetings; and
- Internet clubs for members with shared interests.

This author has found that showing students how to find out more about important water policy debates informed by economic analysis elevates their confidence before and after they graduate, as described by graduates who speak to him after graduation.

5.3 Classroom Innovations for Water Economics Instruction

Water economics instructors can learn from experienced faculty, partly by examining several existing textbooks or class syllabi. This author recently found about 15 water economics syllabi for classes taught since 2015 at several North American universities. These include universities in California, Colorado, New Mexico, Texas, Michigan, Georgia, Wisconsin, Wyoming, North Carolina, Ontario, and

Massachusetts. While by no means an exhaustive listing, he noticed several actual or implied teaching innovations that have been used with apparent success, as described below.

5.3.1 Case Studies

Case studies show real-world applications of water resource economics principles. They can involve presenting students with a particular problem or situation and asking them to analyze it using principles learned in class. Despite the desirability of case studies, they present well-known limitations that instructors should assess when deciding whether to use them. Some disadvantages include:

- *Weak generalizability*: Case studies in water resources typically focus on a single or small number of individuals, groups, or organizations, for which specialized findings may not be generalizable to other populations, contexts, time periods, or cultures.
- *Time-consuming*: Conducting a case study requires a significant amount of time and resources, including data collection, analysis, report writing, and presentation.
- *Subjectivity*: Case studies rely on the interpretation of the researcher, which can introduce subjectivity into the findings.
- *Difficulty in replicating*: It can be hard for other researchers to replicate a case study, as it involves collecting detailed information about a specific context that may not be easily accessible to others.
- *Dependence on participant cooperation*: The classroom success of a case study depends on the willingness and ability of the participants to provide accurate, honest, carefully collected, and detailed information. If they are unable to do so, the case study may be compromised.
- *Black Swans*: A black swan is an event believed to be highly unlikely, with three main features: It has a large impact, it seemed unpredictable before it occurred, but after it occurs, people establish a theory that made the event more predictable than previously thought. Most of us fail to acknowledge an underlying black swan until after it takes place. This comes partly from the fact that people are taught to learn many facts with too few theories that could have explained those facts. Spending too much time on case studies risks training students to poorly anticipate or react to black swans. For example, being exposed to a more general theory of water demand could help them predict greatly reduced water use for agriculture in the face of high prices not yet seen. Excessive focus on what we have seen using case studies makes it harder to formulate a theory that generates both the seen as well as the unseen. Stronger theoretical frameworks presented to students enable them to better anticipate and take advantage of opportunities not yet experienced.

A number of well-known peer-reviewed published case studies are especially suitable for instruction in a water resource economics class (Attard, et al., 2016, Hyde, et al., 2005, Le Maitre, et al., 2002, Pejchar and Mooney, 2009, Warner, et al., 2010).

5.3.2 Role Playing

Role playing is an important classroom innovation that can help students understand how various stakeholders might understand and approach water resource management issues. Students could take on the role of a farmer, a government regulator, a water utility, or environmental activist, and then engage in a simulated negotiation or decision-making process. Despite opportunities for innovation from role playing, it presents several limitations:

- *Limited control*: Role playing involves improvisation and manipulation of certain variables, which can make it hard to control the outcomes of the role-playing activity.

- *Potential for student discomfort*: Role playing may be uncomfortable for some students, especially if the scenario involves sensitive or controversial topics, of which water policy debates carry wide ranging and diverse examples.
- *Limited scope*: Role playing may be poorly suited for addressing complex or multi-faceted issues, as it may not allow for a full exploration of all relevant factors. Without much coaching by an experienced instructor, students rarely know or wish to step into the shoes of a person or viewpoint not personally experienced.
- *Limited applicability*: Role playing may not be appropriate for all learning or development goals, as it may not be the most effective method for achieving class objectives.

A few peer-reviewed works have described experience with role-playing exercises in a teaching environment that could be adapted to a college class in water resource economics (Agusdinata and Lukosch, 2019, Bartels, et al., 2022, Bonte, et al., 2019).

5.3.3 Simulation Games

Innovative classroom instructors can present simulations games, namely interactive, hands-on exercises that encourage students to apply their knowledge and explore different scenarios and outcomes. For example, students might play a game where they must make decisions about how to allocate water resources among different users, such as agriculture, commercial, industry, residential domestic use, and ecosystem protection or restoration.

In a water resource economics classroom setting, simulation games can be implemented as group exercises, where students work together to complete the game's objectives. These games often involve role-playing, decision-making, and problem-solving. They can be designed to teach specialized skills or principles important to water resource economics. For example, a simulation such as the famous diamonds/water paradox, can be used to teach students about the principles of water supply and water demand.

Simulation games can be a valuable learning method as they allow students to apply their economic principles and skills in a hands-on, interactive way. However, it is important to carefully consider the goals and objectives of the simulation game, as well as the limitations and potential disadvantages of this method, including these:

- *Complexity*: Simulation games can be complex and require much setup time, which can be time consuming for beginning instructors and may not be suitable for students who hail from a range of diverse cultures.
- *Limited scope*: Simulation games often focus on a particular topic or skill, which means they may fail to cover all material that the instructor wants to cover.
- *High cost*: Some simulation games can be expensive to access, burdening certain institutions or students.
- *Limited accessibility*: Some games may be hard for some students to use due to physical or cognitive limitations.
- *Limited engagement*: Some students may not find simulation games engaging or may not be motivated to participate in them.
- *Limited transferability*: It may be hard for students to transfer the skills and knowledge they learn in a simulation game to a real policy debate.

A few published works have presented approaches for handling simulations games suitable for a class in water economics (Buchholz, et al., 2016, Gunda, et al., 2017, Meinzen-Dick, et al., 2018, Reddy and Kumar, 2012, Song, et al., 2018)

5.3.4 Group Projects

Classroom instructors may find group projects to be an innovative method to encourage collaboration and critical thinking among students. For example, students might be asked to work in small groups to develop a plan for managing a specific water resource, such as a river, reservoir, or groundwater aquifer. This approach allows students to develop important skills, such as teamwork and communication, and can also foster a sense of community in the class. Despite this, instructors need to face some of the well-known disadvantages of group projects:

- *Challenges in managing group dynamics*: Group projects can be hard to manage, as they involve coordinating schedules and efforts of multiple students. Leaving it to the students to organize group projects can put an unfair burden on some whose available time for meetings outside the classroom is heavily constrained. Different students may have different working styles and personalities, which can lead to conflicts or misunderstandings.
- *Unequal contributions*: Group projects can be vulnerable to the well-known "free rider" problem, for which some group members may not contribute as much as others, resulting in an unfair distribution of workload and grades. A common complaint by good students is that weak students have their grades elevated by diligent ones, while top performers are dragged down by the lazy.
- *Dependence on others*: Group projects can depend on participation and effort of all group members, and if one or more individuals shirk their responsibilities, it can burden the project, for which the top performers face a special burden.
- *Time-consuming*: Group projects can be time-consuming, as they often involve multiple meetings and the coordination of schedules and tasks, which cannot be easily coordinated where a group consists of several students.
- *Difficulty in assessing individual contributions*: It can be hard to assess individual contributions of group members in a group project, as the work is often collaborative and interdependent. Asking each student to grade all in the group but himself is one way to deal with the problem, but it can cause strategic behavior: I'll give you an A if you reciprocate.
- *Limited control*: Group projects involve the participation of multiple individuals, which can make it difficult for the beginning instructor to control project outcomes.

A few articles have been published describing experiences with group projects suitable for a classroom environment (Jost, et al., 2022, Laborde, et al., 2020, Van Engelen, et al., 2007, Williams, et al., 2011).

5.3.5 Online Resources

Innovative classroom instructors learn that in our digital age, numerous online resources and tools present themselves for teaching water resource economics, such as interactive simulations, videos, and podcasts. These resources can be a productive supplement to traditional classroom instruction and can help students learn at their own pace and in a way that is more engaging and interactive. Despite their advantages, online resources have several limitations facing instructors:

- *Lack of credibility*: It can be hard to determine the credibility and reliability of online sources, as anyone can post information on the internet, for which there is often little to no peer review.
- *Limited scope*: Online resources may provide a shallower depth or breadth of information as more conventional sources, like books or scholarly articles.
- *Limited control*: Online resources are often beyond the control of the beginning instructor or the institution, which can make it hard to ensure that students are accessing objective and reliable information.

- *Accessibility*: Not all students have equal access to online resources, as they may not have internet access or the required technology.
- *Plagiarism*: It can be easier for students to plagiarize when using online resources such as AI software like Chat GPT©, as they may be more likely to copy and paste information from the internet rather than paraphrasing or summarizing it in their own words. Plagiarism might be kept under control by requiring students to select research projects grounded in their own personal experience.

Beginning instructors in water economics may wish to investigate a few published works describing experience with online resources (Metzgar, 2014, O'Flynn, 2019, Snowball, 2014, Tserklevych, et al., 2021).

5.3.6 Use of Data and Analytical Tools

Innovative instructors find that incorporating analytical tools like spreadsheets, linear programming, CBA, regression analysis, and GIS, into the curriculum can help students develop important skills in data analysis and visualization. These skills can be useful in a variety of careers, including those in the water sector. Despite their desirability, data and analytical tools have limitations:

- *Complexity*: Data and analytical tools can be complex and hard to use, especially for students unfamiliar with them.
- *Time-consuming*: Working with data and using analytical tools can consume large amounts of student time, as it requires collecting and cleaning data, as well as learning how to use the tools.
- *Limited scope relevance*: Data and analytical tools may not be suitable for all types of projects, as they are typically more appropriate for projects that involve quantitative data analysis.
- *Accessibility*: Not all students may have equal access to data and analytical tools, as they may not have the necessary technology or software.
- *Ethical considerations*: Working with data may raise ethical considerations, such as privacy, confidentiality, and the potential for bias. It is important for students to be aware of these issues and to handle data responsibly such as limiting themselves only to peer reviewed published data.

Some works have published analysis of data analytics with relevance to instruction in water resource economics (Batt, et al., 2020, Croushore and Kazemi, 2019, Hillier, 2018, Zimmermannova, et al., 2021).

5.4 Classroom Innovations in Presenting Water Policy Challenges

5.4.1 Developing Water Supply Resilience

Water economics instructors seeking classroom innovation may find that students wish to focus on quick responses to today's crises such as recent news of California flooding in early 2023 or longer-term Arctic Sea ice melt driven by global warming and impacts on sea level rises. Despite the importance of crisis management, water economics instructors will wish to help students think, conceptualize, and assess hard choices in building longer-term resilience, i.e., capacity to adapt to unexpected water-related stresses. Diversifying the water supply delivery capacity through measures like building an expensive backup water source in case a utility loses its main supply sources, though important for resilience, is expensive. Moreover, the cost of developing expensive new sources like desalinated seawater (Elimelech and Phillip, 2011, Greenlee, et al., 2009), may be hard to justify if developed then not used for several years.

Classroom instructors will want to use innovative methods, such as the ones described above, to show students that good water managers "expect the unexpected" and act on it at the right time and place. These instructors will show students how managers can swiftly and effectively change their plans when the time comes. Winston Churchill said to the British House of Commons in June 1925 that "…To improve is to change, so to be perfect is to have changed often..." Churchill's insights certainly apply to the need to continue adapting to unexpected changes in water supply conditions, especially when a big water supplier or user operates in conditions of drought, flooding, and climate change. Stochastic optimization modelling can offer insights into least cost plans for adapting to a steady stream of unexpected shocks in water supply (Falloon and Betts, 2010, Hosseini and Barker, 2016, Milman and Short, 2008, Moy, et al., 1986, Vasan and Simonovic, 2010), but much remains to be learned on how innovative instructors can teach risk management principles to college students to guide water resource supply systems.

5.4.2 Competition for Water

An innovative water economics instructor will wish to help students discover that in the world's arid and semi-arid (dry) regions, a unit of water diverted from a river system at a particular time or place for one use will likely displace water that could have been diverted at a different time or place for a different use, showing the concept of opportunity cost. That is, where water is scarce, there is hydrologic and economic competition for water. Economically rational decisions supporting the development, allocation, and use of water where there is competition for its use need information on measured values of water in its actual or potential uses. What may be the most comprehensive single volume 2014 work on determining the economic value of water (Young and Loomis, 2014), for which that second edition is an update of the first published in 2005. That work presents intellectually comprehensive methods to measure total and marginal values of water in agriculture, urban, flood control, navigation, hydroelectric, environmental, and recreational uses. Two of the better textbooks this instructor has seen covering the full range of water resource economics theories, analytical methods, and policy debates have received much attention (Griffin, 2016) and (Shaw, 2021).

Innovative classroom teaching methods will show that because of the comparative absence of water markets, choices that influence water's development, use, and allocation often take place in the political arena. Despite this lack of a market mechanism, there appear numerous competing demands for financial resources supporting water development and allocation. For that reason, there is an ongoing and important need for rigorous analysis by which the economic value of water-related allocations, projects, and other choices can be compared to their costs. So, the competition for scarce water and the glare of public scrutiny over water choices motivate a need for information on its economic value. Two of the better sources describing methods to measure the marginal value of unpriced water are a well-known article from the mid-1980s (Young and Gray, 1985) describing the use of the 'residual imputations' method followed by the more recent single volume book described above (Young and Loomis, 2014).

5.4.3 River Basin Development

Water economics instructors seeking classroom innovations will find that economic principles (an idea from Plato) and measurement methods (an idea from Aristotle) over time have seen increasing integration with institutional, legal, engineering, and hydrologic views of water management. An original seminal work came from the early 1960s (Maass, et al., 1962). Bringing together economic concepts and assessment methods with a technical understanding of a hydrologic system contributes to information that guides water management choices. Hydroeconomic modeling, discussed elsewhere (Harou, et al., 2009, Ward, 2021), is a good example. When integrated models like these for river basins are developed and applied with contributions by stakeholders, they can become an innovative foundation for joint understanding of insights into water problems to guide informed management and policy solutions.

5.4.4 Protecting Options for Future Water Use

Instructors planning to use innovative teaching methods may want to show students the importance of option value, the economic value placed on an individual's willingness to pay for protecting a water-related asset or service even if there is little likelihood of the individual ever using it (Pindyck, 1991). The option value principle is seen most often in water resource policy design to justify sustaining investments in parks, wildlife habitat areas, and specialized water conservation plans. Option value is an element of the total economic value of specialized or unique environmental or natural resource asset. A water supplier may never use a particular developed well-field, but that well-field still has a value by protecting the option of its use in case it is called on for handling an emergency like reduced flows of a surface source or a terrorist attack on a water delivery pipeline. As such the value of protecting access to future options in case they are needed amount to a willingness to pay a risk premium (Strzepek, et al., 2008) beyond the normal water supply price charged.

5.5 Innovations in Distinguishing Technical and Economic Analysis

Water economics instructors implementing innovative teaching methods will find that students need to know that many policy debates center around what methods can address water problems of the sort described earlier. This author has found it comparatively easy to teach what works and how to make it work, and to do so in detail. Examples include how to build a reservoir, how to erect a water treatment plant, or how to establish or protect the habitat of an endangered species.

What students do not come to college knowing are methods to assess why or if they should be built. They may easily be persuaded of many technical solutions to water problems, but it may require innovative teaching methods to show only a few pay off economically. Instructors may wish to use some of the classroom teaching innovations described above to show students how to conduct an economic analysis to find out which technical solutions pay economically. These can be good exercises. One good way may be to show students a series of programs for dealing with a water problem, such as a drought, then show side by side which ones work versus which ones pay. Of course, a common student response is to show less interest in what pays: Finding what works is a noble motivation in their eyes, while finding what pays does little more than glorify mercenary motivations. Telling them that resources are scarce and need to be allocated to their highest valued use is intellectually on the mark, but rarely a satisfying principle to a young idealistic mind.

5.6 Innovations in Understanding Affordable Safe Drinking Water Supply Methods

Instructors planning to use instructional innovations may find fertile ground in illustrating the importance of finding affordable safe drinking water supplies. These instructors may notice students surprised to find out that much innovative work remains to be done by water economists to inform policy debates over methods to raise the percentage of people worldwide with access to safe affordable drinking water. It remains a problem today, especially in the Global South (Shadabi and Ward, 2022). For example, one 2016 work (Graham, et al., 2016) estimated that more than half of the population in sub-Saharan Africa (SSA) leaves their home to collect water, often walking considerable distances, placing them at risk for numerous health consequences. Historically there has been little published research documenting who is most affected by long water collection times, other than the widely documented understanding that women and children do much of the water hauling in SSA. That 2016 work aimed to learn more about gender differences in labor time used for water collection among both adults and children for households that reported putting more than 30 minutes' time into collecting water. It also estimated the number of both children and adults affected by water collection times exceeding 30 minutes for several countries in SSA. The authors concluded that accessibility to water, water collection by children, and gender ratios for water collection, should be used as indicators for assessing progress in international efforts to improve the performance of water, sanitation, and hygiene.

Water economics instructors can expect to find students surprised that economic analysis gives insights into measures that affordably improve the percentage of world population with access to safe drinking water. Universal access to safe drinking water has been a goal for years (Shadabi and Ward, 2022). When water is contaminated with animal or human wastes, it carries disease. More than 1 billion lack access to safe drinking water sources or to safe drinking water in the home. Dangerous diseases that are transmitted by water routes include cholera, typhoid fever, and various diarrheal diseases, which cause more than 2 million deaths worldwide annually, and give rise to much water-related mortality and morbidity (Mintz, et al., 2001). Water policies that implement centralized solutions will leave millions, especially in the rural parts of the Global South, lacking access. Important classroom innovations are needed to raise student awareness of access to safe drinking water through low cost decentralized technologies that could be used to enhance accessibility and safety of drinking water.

5.6.1 Chemical Disinfection

Classroom instructional innovations can be used to benefit students by documenting that where water sources are polluted, water that will be used for drinking needs treatment to prevent dangerous waterborne disease (Elimelech, 2006). Lacking workable centralized water treatment systems and a good water distribution system, both common in the Global South, this burden sits squarely on the shoulders of rural water suppliers and users. The advantages of water boiling have been known for years, but economically affordable boiling requires an affordable energy source, or may require finding wood at some distance from the home for which walking and carrying on the human back remains the main mode of transportation. Moreover, after the boiled water cools, it can be contaminated again unless protective measures are taken. Several published works (Clasen and Edmondson, 2006, Crump, et al., 2004, Crump, et al., 2005, Lantagne, 2008, Lantagne, et al., 2008, Mengistie, et al., 2013) have found that sodium hypochlorite, the active ingredient in laundry bleach, is a safe, effective, and comparatively cheap chemical method of cleaning water for direct human consumption. A solution of sodium hypochlorite can be produced locally using electrolysis or can be affordably and reliable supplied by private business.

5.6.2 Safe Water Storage

Water economics classroom innovations can be used to show that safe storage matters. One recent work found that replacing unsafe water storage containers with safer ones led to lower rates of cholera transmission in households in Calcutta and reduced diarrhea in children in a refugee camp in Malawi (Mintz, et al., 2001). Storing water in containers with tight-fitting lids and narrow mouths also helps. That practice permits water users to drink the water by picking up the container and pouring water from it, or by opening spigots, while avoiding dipping dirty hands in the container. This is easily shown in a classroom setting.

5.6.3 Public-Private Partnerships

Innovative water economics teaching methods, like the ones described above, can show the importance of introducing decentralized methods to supply safe drinking water in places that lack it. Taking practical advantage of these opportunities will need innovative unique partnerships between private business and government. Business organizations that supply and deliver resources like hand soap, sodium hypochlorite, covered containers with small mouths and spigots suitable for safe storage have unique opportunities to participate in this goal of improving access to safe drinking water internationally.

5.7 Presenting Innovative Methods to Discover Safe Drinking Water Supply Methods

Instructors can use innovative methods to show that many households in the Global South lack access to safe drinking water (SDW) in or near the home. Governments in those countries have an interest in finding ways to raise that access, for which access to a centralized water utility is uncommon. This author sees considerable potential to innovate in the classroom by showing students the use of optimization models like linear programming (LP) or quadratic programming (QP). Optimization models can be used to show water economics students methods to discover measures to supply a population with safe drinking water at minimum cost. A simple example is illustrated here that adapts the classical transportation model (Xu, et al., 2018) to the case of SDW supply. The transportation model has a simple linear program structure, by which by which a mix of water supplying activities and transportation routes are optimized that meet a pre-specified total demand for water (e.g., all households in a village) at minimum cost.

Instructors can show students results of a representative water economics supply model. It was built for this work using the software GAMS© (Appendix B). It can be presented using any of the classroom teaching innovations described above. Results are presented in tables 1-3 and in figure 1. The model is set up as a small-scale linear program for which the model's objective is to minimize the total cost of supplying water to 3 hypothetical villages using three supply methods: boreholes, piped water, and protected springs, for which each has a known cost per unit of water supplied, and for which each village faces a unique labor supply constraint. The goal is to find the cost-minimizing set of supply methods and total quantities of water delivered to each of the three villages under several sets of aspirational delivery levels, defined by percentage of total demand met.

Table 1 shows the data used to drive the results. It shows data for total use that must be met, defined as meeting 100 percent of demand for the base case. For the alternative scenarios, it shows demand successfully met to fall off at twenty incremental reductions of five percent each, ranging from 95 percent to 0 percent. Entries show only the full demand delivery outcomes, to save space. The table shows cost per unit supply, which varies by village and water supply method, for each of the three methods described above, based on conditions unique to each village and water supply method. All three measures illustrated are medically acceptable methods to supply water (Graham, et al., 2016). The

Table 1: Village Water Cost Data

Metric	01_village	02_village	03_village
Total Use at 100 Percent Demand	300	300	300
Cost Per Unit Supply ($US per acre foot)			
Boreholes	15	25	20
Piped Water	120	130	110
Protected Springs	20	15	25
Labor Per Unit Supply (hours per acre foot)			
Boreholes	40	30	20
Piped Water	20	15	25
Protected Springs	50	60	40
Total Labor Supply (Hours Per Year)	10000	8000	6000

table shows labor required per unit of water supply, which varies by supply method and village. For application to practice, these data would be developed from field measurement.

Table 2 shows the results for several runs of the LP model. It shows minimized total cost and quantity of water supplied at various proportions of full demand. It shows that (minimized) costs of supply fall uniformly with the level of demand met. As expected, it also shows output supplied falls off to adapt to reduced percentages of demand met. Equal demand for each village is shown for simplicity. But it is easily generalizable to fit more complex demand patterns

.

Table 2: Minimized Total Cost along with as Quantity of Water Supplied to Three Villages

Portion of Full Demand	Cost of Supply (US/year)				Output Supplied (Acre Feet Per Year)		
	01_village	02_village	03_village	TOTAL	01_village	02_village	03_village
100_pct_demand	15,000	14,500	6,000	35,500	300	300	300
95_pct_demand	11,625	10,975	5,700	28,300	285	285	285
90_pct_demand	8,250	7,450	5,400	21,100	270	270	270
85_pct_demand	4,875	6,258	5,100	16,233	255	255	255
80_pct_demand	3,600	5,733	4,800	14,133	240	240	240
75_pct_demand	3,375	5,208	4,500	13,083	225	225	225
70_pct_demand	3,150	4,683	4,200	12,033	210	210	210
65_pct_demand	2,925	4,158	3,900	10,983	195	195	195
60_pct_demand	2,700	3,633	3,600	9,933	180	180	180
55_pct_demand	2,475	3,108	3,300	8,883	165	165	165
50_pct_demand	2,250	2,583	3,000	7,833	150	150	150
45_pct_demand	2,025	2,058	2,700	6,783	135	135	135
40_pct_demand	1,800	1,800	2,400	6,000	120	120	120
35_pct_demand	1,575	1,575	2,100	5,250	105	105	105
30_pct_demand	1,350	1,350	1,800	4,500	90	90	90
25_pct_demand	1,125	1,125	1,500	3,750	75	75	75
20_pct_demand	900	900	1,200	3,000	60	60	60
15_pct_demand	675	675	900	2,250	45	45	45
10_pct_demand	450	450	600	1,500	30	30	30
05_pct_demand	225	225	300	750	15	15	15
00_pct_demand	0	0	0	0	0	0	0

Table 3 shows more information from the same model run. It shows the cost-minimized water supply plan by proportion of full demand, village, and supply method. It shows that each village needs a different combination of the three supply delivery methods to minimize overall costs. The objective of minimizing costs of meeting known demand, an example of a cost effectiveness analysis described earlier, is a common objective used for communities such as regional or national governments responsible for supplying safe drinking water at the village level. The variation in optimized supply methods by village comes from differences in costs, labor requirements, and labor endowments by village. Figure 1 visually shows the same results seen in table 2. It shows the total cost of water supply by village, ranging from 0 to 100 percent of full demand deliveries. Innovative instructors would remind the skeptical student that with suitable scaling, this model can be used in various villages needing safe drinking water internationally.

Table 3: Cost-Minimized Water Supply Plan by Proportion of Full Demand, Village, and Supply Method

Portion of Full Demand	Supply Method								
	Boreholes			Protected Springs			Piped Water		
	01_village	02_village	03_village	01_village	02_village	03_village	01_village	02_village	03_village
100_pct_demand	200	233	300	0	0	0	100	67	0
95_pct_demand	215	248	285	0	0	0	70	37	0
90_pct_demand	230	263	270	0	0	0	40	7	0
85_pct_demand	245	243	255	0	12	0	10	0	0
80_pct_demand	240	213	240	0	27	0	0	0	0
75_pct_demand	225	183	225	0	42	0	0	0	0
70_pct_demand	210	153	210	0	57	0	0	0	0
65_pct_demand	195	123	195	0	72	0	0	0	0
60_pct_demand	180	93	180	0	87	0	0	0	0
55_pct_demand	165	63	165	0	102	0	0	0	0
50_pct_demand	150	33	150	0	117	0	0	0	0
45_pct_demand	135	3	135	0	132	0	0	0	0
40_pct_demand	120	0	120	0	120	0	0	0	0
35_pct_demand	105	0	105	0	105	0	0	0	0
30_pct_demand	90	0	90	0	90	0	0	0	0
25_pct_demand	75	0	75	0	75	0	0	0	0
20_pct_demand	60	0	60	0	60	0	0	0	0
15_pct_demand	45	0	45	0	45	0	0	0	0
10_pct_demand	30	0	30	0	30	0	0	0	0
05_pct_demand	15	0	15	0	15	0	0	0	0
00_pct_demand	0	0	0	0	0	0	0	0	0

5.8 Instructor Presentation of Behavioral Nudging Applications to Water Resources

Innovative instructors will want to remind students know that nudge theory is comes from behavioral economics (Benartzi, et al., 2017, Thaler, 2018). It is based on the idea that subtle or indirect suggestions can be a low-cost method to influence individual behavior. Nudging is different from other ways to motivate a desired behavior, such as enforcement or legislation. Nudge theory may have applications to influencing desired behavior by water users, for which teaching innovations described above can be used in the classroom.

Instructors can show that some investigations in California, Spain, and Australia indicate that the use of nudges produced positive results in water use reduction, through things like including a neighbor's water conservation outcomes as part of one's monthly water bill. Instructors may find that students are surprised to discover that much more work is needed to see how behavioral nudging can work for programs like water conservation outside the western world. Other work has addressed behavioral nudging (Barnes, et al., 2013), although much works remains to find low-cost behavioral nudge methods to promote adaptation to climate water stress.

5.9 Presentation of Genetic Algorithms

Water economics instructors are likely to find that few students have heard much about genetic algorithms. Development of genetic algorithms (GA) have shown some success for handling complex problems with many random (stochastic) elements (Booker, et al., 2012) of which there are many examples in water resource economics (Alvarez, et al., 2004, Kumar, et al., 2006, Oliveira and Loucks, 1997, Reddy and Kumar, 2006, Zecchin, et al., 2005). For some resource applications, GAs have been

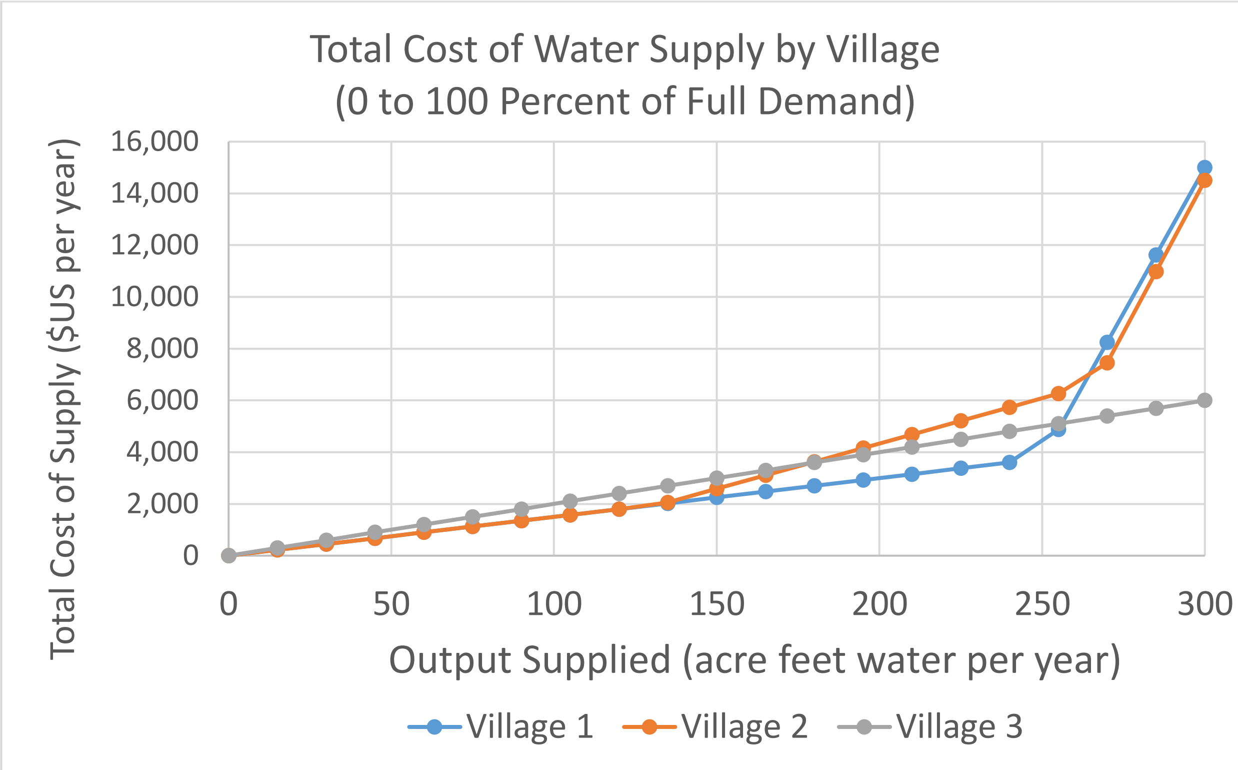

Figure 1: Total Cost of Water Supply by Village (0 to 100 Percent of Full Demand)

motivated by the concept of Darwinian natural selection. GAs typically use biologically inspired concepts like selection, crossover, and mutation. These methods have proven a workable strategy for handling non-smooth mathematical functions commonly seen in water resources for which classical gradient search methods (derivatives of functions) cannot reliably light the path to a global optimum. A good example faces a reservoir manager who needs to optimize or even merely improve the current performance of timed water releases from a dam. Releasing too much water in the short term can threaten future supplies if inflows fail to materialize, raising future water supply acquisition costs considerably. However, releasing too little creates short term economic hardship downstream for the water users who receive no surface water (Ahmadi, et al., 2014). This is a great way for the innovative instructor to document the nature of a hard choice.

5.10 Presentation of Remote Sensing Uses

Water economics instructors can expect to find that many students do not know that remote sensing for water resource applications is the process of measuring and monitoring water-related characteristics of an area by measuring its reflected and emitted radiation at a distance. This is typically done from a satellite or special cameras to collect images sensed from a distance. It can help people discover water-related information above or under the ground (US Geological Survey, 2022). The use of remotely sensed data to connect observed hydrological and economic relations needs much more attention than has been seen to date. However, one work from 2015 gave an insightful example of how this could be achieved (Medellin-Azuara, et al., 2015). Numerous other works have also described the potential for remote sensing tools to support better economically informed water management (Abotalib, et al., 2016), for which many can likely be presented using some of classroom innovations described above.

5.11 Presenting Economics Model Output

Instructors of water economics will want students to know the importance of the economic value of water in guiding choices on water development and use. Despite the need, more classroom innovations are needed to communicate results of economic analysis to interested stakeholders. These people include water managers, farmers, water utility managers, environmental interests, technical advisers, lawmakers, and a wide variety of other stakeholders. Many economic analyses of water programs, especially analyses coming from models, are ignored by most stakeholders much of the time. Posting results of economic analysis to websites to permit water managers to experiment with choices is one way to secure stakeholder attention. One example of an analytical economic model was posted in 2017 at a webpage at the University of Texas-El Paso, and has opened up much discussion in the southwest US region, but it is only a beginning of many more innovative works of this kind needing attention (University of Texas at El Paso, 2021).

Economic analysis of climate adaptation can provide improved capacity for responding to unexpected conditions when they occur, especially droughts and floods. New water economics instructors will likely find that having various economic analysis tools in one's tool kit can help show students how to guide quick choices when the unexpected occurs. Managers and water stakeholders need a well-developed capacity to quickly assemble a plan B when the plan A falls apart because of unanticipated conditions that materialize. For example, a well thought out backup plan B analysis would assess the economic desirability of importing large quantities of distant piped in water when local surface supplies do not appear as expected or the water quality quickly is degraded with a toxic spill. One example of an analysis of this kind was published in 2018 (Abutaleb, et al., 2018), for which classroom instructor innovations would make this kind of work easily accessible to students.

Water economics instructors find out early that students need a better capacity to integrate climate, water, food, energy, and environment. Economic models historically often have a weak physical basis. However, economic models developed since the early 2000s have already taken a big step ahead compared to other decision support models. A good example is a review of the literature of hydroeconomic models published in 2009 (Harou, et al., 2009) with a 2021 update (Ward, 2021).

5.12 Instructor Presentations of Water Shortage Management Methods

Water economics instructors will likely find students of water economics rarely know that big innovations in water planning are needed in the use of economic principles to discover when reducing water demand is a cheaper way to handle water shortages than expanding supply. In the short run, most water utility managers know all too well that the only way to handle shortages is to reduce use, often implemented with rationing of some kind, especially limiting outdoor water use. Once recent work from Korea addressed this problem in an innovative way (Choi, et al., 2012). One of the better-known works that assessed impacts of water rationing as a method to handle shortages was published in 2009 (Olmstead and Stavins, 2009). These works open new lines of thinking to address an important problem.

5.13 Instructor Presentation of Sensitivity Analysis

Instructor classroom innovations for students of water economics are needed in methods to quickly and effectively conduct sensitivity analysis to show impacts of assumptions on outcomes of a CBA. Sensitivity analysis refers to measuring the uncertainty in the output of a CBA based on uncertainty in the data it uses. One work from 2004 described the importance of sensitivity analysis of policy options in the Mediterranean region (Arnell, 2004). Another innovative work from 2007 took a serious look at the use of sensitivity analysis in the conduct of CBA for an important water policy intervention (Hutton, et al., 2007). Many classroom innovations of the sort described above are needed for explaining the importance to students of sensitivity analysis for those who wish to test the sensitivity of outcomes of economic analysis to changes in assumptions or data.

6 Discussion

6.1 Relevance

Curriculum innovations in water economics need special attention because of the large number of water problems the world faces (de Fraiture and Wichelns, 2010, Gleick, 2003, Jury and Vaux, 2005, Schindler, 2001, Zhou, et al., 2001). Water scarcity is a big one. Many parts of the world, particularly in developing countries, face water scarcity due to a lack of access to clean, safe water for drinking and irrigation. Water quality is another issue. Industrial and agricultural activities, as well as sewage and waste disposal, can all contribute to water pollution, making it unsafe for human consumption and damaging ecosystems. Drought, especially when connected to climate-water stress, remains a big problem. Drought, a persistent lack of sufficient water, can lead to crop failures, water shortages, and other serious problems. Flooding is another issue. Heavy rains and rising sea levels can cause flooding, which can damage infrastructure, contaminate water sources, and lead to the spread of waterborne diseases. Water-related diseases remain a problem, especially in the Global South. Poor water quality and inadequate sanitation can lead to the spread of waterborne diseases, such as cholera, typhoid, and hepatitis. Curriculum advances by innovative instructors can do a great service for students of water economics.

6.2 Future Work

6.2.1 Classroom Presentation of Water Risk Management

Instructors can anticipate being asked by students what kinds of water risk management problems need future attention by water economists. This author anticipates future work being conducted in several areas. Maintaining water quality is about ensuring that water is safe for human consumption, agriculture, and industrial uses, all of which are important for public health and economic development. Maintaining water availability comes from the fact that water is a scarce resource, and managing it sustainably is essential for meeting the needs of growing populations and economic activity. Protecting water-dependent ecosystems, such as wetlands and rivers, rely on a healthy water supply to thrive. Managing water risk can help protect these ecosystems and the services they provide. Reducing the impact of natural disasters is a big need: Floods, droughts, and other natural disasters can have severe impacts on water supplies, infrastructure, and communities. Water risk management strategies can help reduce the likelihood and/or impacts of these events.

6.2.2 Research Addressing Water Risk Management

Instructors can also anticipate being asked about the kinds of research methods that can be used in the future to analyze the needs related to water risk management (Kallis, 2008, Larsson, et al., 2018, McDaniels, et al., 1999, Qadir, et al., 2010, Wilhite, et al., 2000). While this author is aware of no comprehensive answers, a few simple ones come to mind. Field research involves collecting data through observations, measurements, and experiments conducted in the field. Field research can provide valuable insights into the impact of water risk on communities and ecosystems. In some cases, surveys can be used to gather information from several individuals or organizations, especially water utilities. Surveys can be conducted in person, by phone, or online, and can be used to gather data on attitudes, behaviors, and experiences related to water risk. Case study research involves in-depth investigation of a specific situation or example to understand a particular issue or problem.

Despite the risk of providing weak generalizable frameworks, case studies do provide detailed insights into how water risk affects specific communities or water-using sectors. Simulation and modeling are common research methods used by water economists. Models and simulations can be used to predict the impacts of different water risk management strategies, based on some of the well-known classics receiving much attention since the early 1950s (Markowitz, 1952, Merton, 1969, Samuelson, 1969). Water economics instructors can expect to find students enjoying the accessibility of literature reviews, which can provide an overview of what is known about a particular water risk issue and identify gaps in our understanding that need to be addressed through further work. Managing water-related risks in the business sector is especially important: Organizations that rely on water, such as agricultural, manufacturing, and mining firms, face a range of water-related risks that can impact their operations and financial performance. Managing these risks is important for maintaining business continuity and economic activity.

7 Conclusions

Innovative instructors need to find and take advantage of several methods to communicate for students who wish to pursue careers transforming communities through better use of water resources. Six classroom innovations were described in this paper: case studies, role playing, simulation games, group projects, online resources, and data and analytical tools. All these innovations are excellent for breaking up the predictability of standard lecture material. Several citations were provided for each of the six innovations described. A few of those water resource challenges include the need to address population stress on the water resource base, food security, water security, energy security, environmental protection, peace, economic development, health, climate, and poverty. Exposing our college students to the range of water challenges faced internationally along with solid economic principles delivered by those innovative classroom methods will help them better integrate science, policy, law, and culture into a framework to design, implement, and assess modern water resource management.

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Appendix A: Skeletal Undergraduate Water Resource Economics Syllabus

1. World Water Issues
   • Water scarcity: Many parts of the world, particularly in developing countries, face water scarcity due to a lack of access to clean, safe water for drinking and irrigation.

   • Water pollution: Industrial and agricultural activities, as well as sewage and waste disposal, can all contribute to water pollution, making it unsafe for human consumption and damaging ecosystems.

   • Drought: Drought, a persistent lack of sufficient water, can lead to crop failures, water shortages, health challenges, and a number of other serious problems.

   • Flooding: Heavy rains and rising sea levels can cause flooding, which can damage infrastructure, and contaminate water sources.

   • Water-related diseases: Poor water quality and inadequate sanitation can spread waterborne diseases, such as cholera, typhoid, and hepatitis.

   • Climate Change: Climate change can have a significant impact on water resources internationally. Some of the ways in which climate change affects water include:

   • Changes in precipitation patterns: Climate change can lead to changes in the amount and distribution of precipitation, including more frequent and severe droughts in some regions and more intense and frequent rainfall events in others.

   • Rising sea levels: As the Earth's temperature increases, polar ice caps and glaciers are melting, leading to rising sea levels. This can cause coastal flooding, erosion, and can contaminate fresh water sources with saltwater.

   • Increased risk of water-related disasters: Extreme weather events, such as hurricanes, floods, and droughts, are likely to become more frequent and severe as the climate changes. These events can damage infrastructure and contaminate water sources, making it difficult to access clean water.

   • Changes in water quality: Climate change can also affect the quality of water, for example, by increasing pollutant concentrations in water due to higher temperatures or changing rainfall patterns.

   • Transboundary River Basin Conflicts and Conflict Resolution Approaches, with examples from selected basins: Mekong, Nile, Indus, Amu-Darya, Tigris-Euphrates, Ganges-Brahmaputra-Meghna, Colorado, Rio Grande, Murray Darling, Danube.

2. The demand for water
   • Water uses: agriculture, industry, urban, flood control, ecosystems
   • The elasticity of demand for water
   • Factors that influence the demand for water

3. The supply of water
   • Sources of water supply
   • Costs of water supply
   • Elasticity of supply
   • Factors affecting water supply

4. Water markets and pricing
   • Role of water markets in water resource allocation and management
   • Water price determinants
   • Advantages and limitations of water market
   • Unique challenges in allocating unpriced water

5. Water rights and property rights
   • Legal and institutional frameworks for water rights design and administration
   • Allocation of water rights
   • Efficiency of water rights systems
   • Water rights systems for handling water shortages

6. Valuing water in alternative uses for cost benefit policy analysis
   • Irrigation
   • Urban (residential, municipal, and industrial) uses
   • Flood control
   • Hydroelectric power
   • Navigation
   • Environmental protection or improvement
   • Water quality protection or improvement

7. Water Policy Assessment Criteria
   • Economic Efficiency
   • Distributional Equity
   • Sustainability

8. Economic Assessment Methods
   • Cost Benefit Analysis
   • Cost Effectiveness Analysis
   • Pure Impact Analysis

9. Case studies in water resource economics
   • Examples of successful and unsuccessful water resource management strategies
   • The application of economic principles to real-world water resource issues

10. Analytical tools and techniques (better suited for graduate students)
    • Partial and whole farm budgeting
    • Linear and nonlinear programming for constrained optimization
    • Regression analysis (time series v panel data)
    • Differences in differences regression
    • Input output analysis

11. Scope and Limits of Economic Analysis

12. Emerging challenges in water resource economics
    - Key challenges facing water resource management in the 21st century
    - Role of economic analysis in addressing these challenges
    - The future of water resource economics

Appendix B: GAMS Code Supporting Water Supply Cost Minimization Model

$EOLCOM //

$Title A water supply and delivery problem

$Ontext

This GAMS code solves a problem finding a least cost water supply package for a set of 3 representative African villages under various conditions and water supply aspiration levels. US units are used for this model.

$Offtext

$ontext

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An Analysis of Water Collection Labor among Women and Children in 24 Sub-Saharan African Countries

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ABSTRACT

Background
It is estimated that more than two-thirds of the population in sub-Saharan Africa (SSA) must leave their home to collect water, putting them at risk for a variety of negative health outcomes. There is little research, however, quantifying who is most affected by long water collection times.

Objectives
This study aims to a) describe gender differences in water collection labor among both adults and children (< 15 years of age) in the households (HHs) that report spending more than 30 minutes collecting water, disaggregated by urban and rural residence; and b) estimate the absolute number of adults and children affected by water collection times greater than 30 minutes in 24 SSA countries.

Methods
We analyzed data from the Demographic Health Survey (DHS) and the Multiple Indicator Cluster Survey (MICS) (2005–2012) to describe water collection labor in 24 SSA countries.

Results
Among households spending more than 30 minutes collecting water, adult females were the primary collectors of water across all 24 countries, ranging from 46% in Liberia (17,412 HHs) to 90% in Cote d'Ivoire (224,808 HHs). Across all countries, female children were more likely to be responsible for water collection than male children (62% vs. 38%, respectively).

Six countries had more than 100,000 households (HHs) where children were reported to be responsible for water collection (greater than 30 minutes): Burundi (181,702 HHs), Cameroon (154,453 HHs), Ethiopia (1,321,424 HHs), Mozambique (129,544 HHs), Niger (171,305 HHs), and Nigeria (1,045,647 HHs).

Conclusion

In the 24 SSA countries studied, an estimated 3.36 million children and 13.54 million adult females were responsible for water collection in households with collection times greater than 30 minutes. The authors suggest that accessibility to water, water collection by children, and gender ratios for water collection, especially when collection times are great, should be considered as key indicators for measuring progress in the water, sanitation and hygiene sector.

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$offtext


 Sets
    i   water supply sources       / boreholes, protected-springs, piped-water/
    j   villages                   / 01_village, 02_village, 03_village/
    s   proportion of full dermand  /100_pct_demand, 95_pct_demand, 90_pct_demand, 85_pct_demand, 80_pct_demand,
                                 75_pct_demand, 70_pct_demand, 65_pct_demand, 60_pct_demand, 55_pct_demand,
                                 50_pct_demand, 45_pct_demand, 40_pct_demand, 35_pct_demand, 30_pct_demand,
                                 25_pct_demand, 20_pct_demand, 15_pct_demand, 10_pct_demand, 05_pct_demand,
                                 00_pct_demand/

 Parameters

    proportion_full_p(s)  proportion of full water supply scenario

    / 100_pct_demand   1.00
      95_pct_demand   0.95
      90_pct_demand   0.90
      85_pct_demand   0.85
      80_pct_demand   0.80
      75_pct_demand   0.75
      70_pct_demand   0.70
      65_pct_demand   0.65
      60_pct_demand   0.60
      55_pct_demand   0.55
      50_pct_demand   0.50
      45_pct_demand   0.45
      40_pct_demand   0.40
      35_pct_demand   0.35
      30_pct_demand   0.30
      25_pct_demand   0.25
      20_pct_demand   0.20
      15_pct_demand   0.15
      10_pct_demand   0.10
      05_pct_demand   0.05
      00_pct_demand   0.00/

    b_p(j)  demand at village j (acre feet per year)

     /    01_village   300
          02_village   300
          03_village   300  / ;

Table money_cost_unit_p(i,j)  money cost per unit supplied ($ per acre foot)
```

```
                         01_village   02_village   03_village
    boreholes               15           25           20
    protected-springs       20           15           25
    piped-water            120          130          110
;

Table labor_unit_p(i,j)    labor requirements per unit water supplied (man hours per acre foot)

                         01_village   02_village   03_village
    boreholes               40           30           20
    protected-springs       50           60           40
    piped-water             20           15           25
;

table labor_supply_p(j,s)   labor supply by village (man hours per year)

                 100_pct_demand
   01_village       10000
   02_village       8000
   03_village       6000
;

labor_supply_p(j,s) = labor_supply_p(j,'100_pct_demand');

set ss(s);  //aspiration scenario
ss(s) = no;   //switches s off, back on later

positive  Variables

        village_output_v(j,s)  village water supply                  (acre feet per year)
        tot_output_v(j,s)  total output by jth village               (acre feet per year)
        total_output_v(  s)  total output by aspiration              (acre feet per year)
        output_v  (i,j,s)  output supplied from ith water source     (acre feet per year)

         village_cost_v(j,s)  village cost by j                 ($US per year)
        cost_v(i,j,s)  cost by i and j                          ($US per year)

        labor_v(i,j,s)  labor use by i and j                 (man hours per year)
         tot_labor_v(  j,s)  total labor used by village     (man hours per year)
        tot_lab_v  (    s)  total labor                      (man hours per year)

variable
        tot_cost_v(s) total costs over villages              ($US per year)

        tot_cost_looped_v    total cost looped               ($US per year)
        tot_labor_looped_v   total labor looped              (man hours per year)

Equations
        village_cost_e(j,s)  village cost by j               (acre feet per year)
        cost_e(i,j,s)  cost by i and j                       (acre feet per year)

        labor_e(i,j,s)  labor by i and j                     (acre feet per year)
        village_output_e(j,s)  village output                (acre feet per year)
        tot_labor_e(j,s)  total labor                        (man hours per year)
        tot_lab_e  (  s)  total labor 2                      (man hours per year)

        tot_cost_e(  s)  total cost - objective fn minimized       ($US per year)
```

```
        total_output_e (  s)  total output                (acre feet per year)
        tot_output_e  (j,s)  total output                 (acre feet per year)

        tot_cost_looped_e    total cost_looped            ($US per year)
        tot_labor_looped_e    total labor looped          (man hours per year);

        village_cost_e (j,ss)..   village_cost_v(j,ss) =e= sum(i,     cost_v(i,j,ss));
        tot_cost_e     (  ss)..     tot_cost_v   ( ss)      =e= sum((i,j), cost_v(i,j,ss));

        cost_e (i,j,ss)..      cost_v(i,j,ss)      =e=  money_cost_unit_p(i,j) * output_v(i,j,ss);
         labor_e(i,j,ss)..    labor_v(i,j,ss)    =e=       labor_unit_p(i,j) * output_v(i,j,ss);

        village_output_e(j,ss).. village_output_v(j,ss)  =e= sum(i,  output_v(i,j,ss));
        tot_output_e(j,ss)..     tot_output_v(j,ss)  =e= sum(i,  output_v(i,j,ss));
         tot_labor_e (j,ss)..     tot_labor_v(j,ss)  =e= sum(i,   labor_v(i,j,ss));

        tot_lab_e      (  ss)..       tot_lab_v   (ss) =e= sum((i,j), labor_v(i,j,ss));

        total_output_e(ss)..       total_output_v(ss) =e= sum(j, tot_output_v(j,ss));

         tot_cost_looped_e..         tot_cost_looped_v =e= sum(ss, tot_cost_v(ss));
        tot_labor_looped_e..       tot_labor_looped_v =e= sum(ss, tot_lab_v(ss));

* upper and lower bounds follow

        tot_labor_v.up (j,s)    = labor_supply_p(j,s);
        tot_output_v.lo(j,s)    =  proportion_full_p(s) *  b_p(j);

Model water_supply /all/ ;

parameter
mod_stat_p(s)  optimality status

loop(s,    // aspiration scenario

ss(s) = yes;

Solve water_supply using lp minimizing tot_cost_looped_v ;

ss(s) = no;

);

* post optimality writes to spreadsheet

parameter

village_cost_p(j,s)  village cost                ($US per year)
tot_cost_p(s)  total cost                        ($US per year)
tot_labor_p(j,s)  total labor                    (man hours per year)

output_p(i,j,s)  output                                (acre feet per year)
total_output_p(s)  total output by aspiration          (acre feet per year)
shad_price_labor_p(j,s)  shadow price of labor         ($US per man hour)
shad_price_output_p(j,s)  shadow price of output       ($US per acre foot)
;

village_cost_p     (j,s) = village_cost_v.l(  j,s) + eps;
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```
tot_cost_p(  s) = tot_cost_v.l    (    s) + eps;
tot_labor_p(j,s) = tot_labor_v.l   (  j,s) + eps;
output_p(i,j,s) = output_v.l      (i,j,s) + eps;
total_output_p (s) = total_output_v.l(    s) + eps;
shad_price_labor_p(j,s) = tot_labor_v.m   (  j,s) + eps;
shad_price_output_p(j,s) = tot_output_v.m  (  j,s) + eps;

execute_unload "village_water_June_14_2022_926am_usmdt.gdx"

*data
b_p
money_cost_unit_p
labor_unit_p
labor_supply_p

*optimized results
village_cost_p
tot_cost_p
tot_labor_p
output_p
total_output_p
shad_price_labor_p
shad_price_output_p

;

$onecho > gdxxrwout2.txt

i=village_water_June_14_2022_926am_usmdt.gdx
o=village_water_June_14_2022_926am_usmdt.xlsm

* Next we use GAMS' GDX facility to write to an excel spreadsheet

epsout = 0

par = b_p                 rng  = data_demand!c4               cdim = 0
par = money_cost_unit_p    rng  = data_cost_per_unit!c4          cdim = 0
par = labor_unit_p         rng  = data_labor_per_unit!c4         cdim = 0
par = labor_supply_p       rng  = data_labor_supply!c4           cdim = 0

par = village_cost_p       rng  = opt_village_cost!c4            cdim = 0
par = tot_cost_p           rng  = opt_total_cost!c4              cdim = 0
par = tot_labor_p          rng  = opt_total_labor!c4             cdim = 0

par = output_p             rng  = opt_output!c4                  cdim = 0
par = total_output_p       rng  = opt_total_output!c4            cdim = 0
par = shad_price_labor_p   rng  = opt_shad_price_labor!c4        cdim = 0
par = shad_price_output_p  rng  = opt_shad_price_output!c4       cdim = 0

$offecho
execute 'gdxxrw.exe @gdxxrwout2.txt trace=2';

************************************************************************************
* THE END
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Teaching and Educational Methods

Teaching Water Resource Economics for Policy Analysis

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Abstract
Water resource economics (WRE) course design merits fresh attention, given global water crises and innovations in effective water management and governance. WRE courses need to provide tools for analyzing a new generation of water policy tools and to present a well-rounded perspective on the role of benefit-cost analyses (BCAs) in the policy process. Updated WRE courses can emphasize water's role in energy, food and development economics, social justice and cross-cultural considerations, up-to-date understanding of neurobehavior in economic decision making, and the importance of nonmarket valuation and regional economic methods. Use of geospatial data in WRE econometric analyses deserves attention, as well as more sophisticated treatment of risks related to extreme events so that policy processes can consider these more fully. The article provides a number of other practical recommendations for designing upper-level undergraduate and graduate WRE courses, and includes a list of key topics and sources for class readings.

1 Introduction and Background

As this special issue emphasizes, teaching water resource economics (WRE) merits new attention in this time of global water crises. Innovations in effective water governance and management are arising to address an increasingly unpredictable future. In this article, I focus on themes I find important in teaching WRE as applied to analyzing public policies. The themes are selected based on my WRE research, teaching, and outreach experience over several decades.

I began teaching WRE in the 1980s, within the broader context of graduate and upper-level undergraduate classes in environmental and resource economics (ERE). In the early 1990s, I founded a new WRE class at the University of Arizona. The southwestern United States has a rich history in WRE research, dating back many decades and providing abundant regionally relevant material for teaching (Anderson 1961; Kelso, Martin, and Mack 1973; Howe 1978; Colby 1985; Brown and Ingram 1987; Ward 1987). The WRE course arose based on requests from water research colleagues in a wide range of disciplines to provide WRE training for upper-level undergraduate and graduate students.

Experience with the WRE class I have taught for more than 30 years forms the basis of this article. The class is oriented toward agricultural and resource economics, hydrology, public policy, engineering, law, Native American studies, and environmental science students. The course is available to upper-level undergraduates and to graduate students. The course requires proficiency in differential calculus and undergraduate microeconomics. Class size is capped at 40 students, and the course is offered once each school year. A few years ago, the course title and description were revised to reflect current social issues associated with water: "Economic Analysis of Water, Food, and Environmental Policies" (a list of key topics is provided as an Appendix to this article). Another course I teach at the graduate level, "Incentive-Based Policies and Environmental Markets," also has a significant WRE component, and many graduate students take both courses.

My courses have primarily been taught in person, in the classroom. However, the WRE courses also worked well as synchronous online classes during the COVID-19 pandemic. The interactive exercises translated well to online formats and were perhaps even more appreciated during that time of isolation for many students.

Teaching ERE and WRE to experienced natural resource professionals outside of academic settings has profoundly shaped my university course offerings. I taught for several years in the Kennedy School of Government Environmental Economics Executive Training Program. Participants in that program have extensive professional experience in resource management and seek to deepen their ability to apply economics to natural resource challenges. I have taught for many years in an annual month-long foundation-funded program for environmental professionals from all over the world, Kinship Conservation Professionals. I teach short courses in continuing education programs for judges and water masters in U.S. state and federal courts, for attorneys, and for engineers. These courses provide an opportunity to convey fundamental WRE principles for those who make key decisions on water litigation and water management.

Experience teaching ERE and WRE to working professionals motivated me to create negotiating and bargaining exercises to make WRE concepts and methods less abstract. Teaching working professionals also has shaped my university WRE courses by including material on neurobehavior and cross-cultural conflict resolution, and an overall focus on how economics is useful in design, implementation, and evaluation of public policies (Colby and D'Estree, 2000).

In the following section, I explore several key themes related to teaching policy-relevant WRE. That is followed by a section with brief specific recommendations for designing WRE courses, a summary, and an appendix providing specific course topics and sources for course readings.

2 Themes in Teaching WRE

2.1 Water Policy Challenges and Policy Instruments Are Evolving

Water policy challenges grow evermore complex as climate patterns affect regional hydrology, agriculture, and communities of humans and habitat. Policy tools related to managing water allocation and water quality continue to evolve, relying more on economic incentives. Water policies in many nations now involve extensive stakeholder input intended to reflect diverse values, including environmental water needs, indigenous cultural uses, recreation, and non-use values. Modern water policy initiatives include myriad incentives to reduce water use in agriculture, improve water quality, settle indigenous water claims, trade water to share shortages, and provide water for disadvantaged communities. These trends suggest incentive-based policy tools as an important emphasis in teaching WRE.

A classic contrast in ERE and WRE centers on command and control (C&C) regulations vs. price signals to influence resource use patterns. Examples of C&C policies include fixed quantity limits on pollutant discharges and mandates to utilize specific pollution control technologies (Stavins 2003; Olmstead and Stavins 2009). I find it useful to discuss location-specific case examples of incentive-based water policy tools and C&C instruments, inviting students to identify differences in policy design and performance (Goetz and Xabadia 2015; Colby and Hansen 2022). Incentive-based tools influence water use and pollutant discharge indirectly through economic signals, while C&C policies set explicit directives. Incentive-based tools provide flexibility in adapting behavior and technologies, enabling lower cost achievement of policy objectives. Incentives for research, innovation, and adoption of new tools are stronger when water users can create and choose lower cost approaches (Stavins 2003; Olmstead and Stavins 2009; Colby and Hansen 2022). Students can discover these differences by reviewing and critiquing benefit-cost analyses (BCAs) and other evaluations of actual water policy instruments.

Water use patterns are shifting in interesting ways, providing a dynamic context in which to understand the influence of policy instruments. For example, western U.S. cities with notable population growth are exhibiting decreasing per capita use and, in some cases, reduced total use. The 2007–2009 U.S. recession created some of the observed decline in urban water use, but water usage has remained below pre-recession levels in the recovered economy (Yoo et al. 2014; Bennett and Kochhar 2019). The global pandemic also affected water use patterns. An interesting question to put before a WRE class: after reviewing econometric studies, how much of the decrease in per capita use can we attribute to changes in policy instruments (such as water pricing) and how much to broader factors such as recession, recovery, and pandemic? Water prices and rate structures are only one among many incentive-based policy tools that WRE students need proficiency in understanding and evaluating. Other examples include cost sharing; tax credits and rebate programs for investments in water conservation technologies; consumer labeling for water-conserving products; and cap-and-trade programs to limit groundwater overdraft and water pollution.

2.2 A Broader Role for BCAs

BCA traditionally has been presented as a neutral and objective tool for choosing among resource management alternatives, such as deciding whether society should invest in a proposed infrastructure project or mandate use of pollution control equipment. In WRE courses, I make a point of discussing BCA of water projects that were funded and constructed, despite poor BCA evaluations. Examples for the southwestern United States include the Central Arizona Project and the Yuma Desalting Plant (Kelso et al. 1973; Gillon 2006). This gives students an opportunity to note that political considerations can override economic evaluations, as well as to observe that economists working for stakeholders tend to come up with BCAs that support their clients' positions. I follow reviews of actual BCAs by providing criteria for objective BCAs, criteria which students then apply to critique a BCA study of their choosing.

BCA plays a valuable conflict resolution role beyond its structured examination of benefit and cost numbers. Conducting and reviewing BCAs brings divergent parties together—giving them information on which to base discussions of water management alternatives and proposed projects. The BCA gives participants something specific "to shoot at." Their efforts to repudiate BCA values and recommendations helps reveal their own values to themselves and to other stakeholders. The dialogue process stimulated by critiquing a BCA from multiple perspectives can provide valuable information to decision makers and stakeholders.

WRE courses should ensure that students are aware of alternatives to BCA, such as multicriteria analysis, and the value of considering these alternative frameworks.

3 Water's Role in Energy, Food, and Development Economics

The water energy nexus has received considerable attention over the past two decades, as well as federal research funding in the United States. Energy resources are consumed in diverting/pumping and conveying water, pretreating it for its intended use, removing post-use pollutants, and recycling water for reuse. Significant amounts of water are used to generate electricity and cool power plants. Recent water-energy economic studies provide good choices for class readings, quantifying the economic interdependence of water and energy in various regions (Peterson 2017; Morales-García and Rubio 2023).

Emphasizing the roles of water in food production, processing, and transport links WRE to food-related topics that deservedly capture student interest. Food and development economics now accounts for a large share of undergraduate and graduate students enrolling in applied economics departments. WRE courses that include the role of water availability and water quality in developing economies provide these students with an entrée into resource economics concepts and tools they might not otherwise be exposed to.

4 Neurobehavior in Economic Negotiations

Water resource economists often advise (and study) negotiation and collaborative problem-solving processes, such as regional dialogues on water trading or on infrastructure cost sharing. The importance of interactive engagement in WRE leads me to focus on neurobehavior in several lectures of my semester-long WRE course. Having developed a background in neurobehavior helps me more usefully analyze the many longstanding rural-urban, environmental-agricultural water conflicts that create headlines. A cohesive neuroscience explanation of why people “go ballistic” about water is a valuable supplement to economic explanations.

New understanding of economic decision making provides nuanced alternatives to neoclassical assumptions about rational decision makers (Bossaerts and Murawski 2015). A decision maker’s nervous-system state strongly influences the behavioral response to opportunities and threats, as water stakeholders weigh tradeoffs involving identity, culture, financial well-being, and exposure to risk. In interactions that entail perceived challenges to oneself, and one’s water values and group, protection of self and group becomes a priority—quelling rational cognitive processes (Bader 2016).

Neuroception (continuous noncognitive monitoring by autonomic nervous system (ANS) to identify opportunity and danger), operating in primitive parts of the brain outside of awareness, connects perception of risk with behavioral responses in economic interactions (Porges 2011; Payne 2015; Singletary 2014). A key finding from clinical research is the central influence of perceived physical and psychological safety on decision making (Porges 2011; Bader 2016). Considering economic negotiations from a neurobiology perspective, negotiating processes can stimulate fight-flight-freeze reactions, especially when involving perceived threats to oneself or to one’s group. The fight-flight-freeze ANS states significantly impair parts of the brain that weigh cause and effect and engage in problem solving. Research indicates that people in fight-flight-freeze states respond psychologically and behaviorally to perceived threats as though bodily safety is imminently threatened. This sheds light on the volatile nature of many water negotiations and policy-making processes.

The following example illustrates how pervasively trade-offs involving threat, safety, and neurobehavior arise in WRE. In addressing California Bay Delta policy dilemmas, California faces the daunting obstacle of hundreds of relevant jurisdictions, from the federal government down. Water experts offered this grim descriptor: “… a game of ‘chicken,’ where the management of a declining resource becomes deadlocked” (Hanak et al. 2011; Owen 2022). Michael George, the California Delta Watermaster (oversees administration of water rights), finds that his principal function as watermaster is as a mediator and facilitator. He observes, “The biggest shortage in the water system in California is trust” (Owen 2022). Not shortage of water, not shortage of funding—shortage of trust.

Classes in WRE can offer models of water negotiations structured to address neurobehavioral mechanisms. Respect fundamentally validates each party and addresses primal ANS issues stimulated by conflict—reinforcing validity and value of one’s self and one’s group (Geisler et al. 2013; Bader 2016). Water negotiations can be structured to provide respect, objectivity, and professional facilitation to improve outcomes (Levine 2010; Raio et al. 2013). There are important advantages to offering students a framework for the role of neurobehavior in WRE. Phenomena that previously seemed anecdotal and unrelated now can be understood as expressions of neurobehavior, and anticipated in structuring water negotiations and policy-making processes.

5 Social Justice and Cross-Cultural Considerations

This facet of WRE and water policy deservedly has been receiving more attention in the United States as social justice and cross-cultural issues become more recognized. My classes typically include students from groups underrepresented in U.S. water policy making. These groups (Native Americans, blacks, Hispanics, and others) have not shared proportionally in the largesse of water infrastructure development and federal water and energy subsidies. They have been disproportionately affected by water pollution, drought, floods, and lack of safe drinking water. Many water conflicts have key components involving equitable access to water and its economic benefits (Colby and d'Estrée 2004; Banzhaf, Ma, and Timmins 2019). In my course, I include a segment on indigenous water issues in the western United States and econometric studies using spatial data to examine differential water quality impacts in minority communities (Shapiro and Walker 2021). The social justice and equity theme can encompass different topics that vary by location, tailored to the mix of students in WRE courses.

Drought in the southwestern United States and negotiations over how to address severe and growing shortages in Colorado River water-sharing arrangements have brought to the fore an array of social justice issues. Disproportionate effects of drought on water access for communities of color is becoming increasingly apparent (London 2018; Fernandez-Bou et al. 2023). Another social justice issue involves the roles of Native American nations in providing resilience for regional water supplies. Southwestern U.S. tribal nations, in some cases, have secured senior water entitlements through protracted litigation and negotiations (Thorson, Britton, and Colby 2006). New water-sharing arrangements based on these entitlements are now sought by cities and nontribal farms to alleviate shortages among more junior right holders. Tribes are participating in negotiations for agreements to make their more drought-secure water available. Social justice issues inevitably arise when a historically poor and disenfranchised group (tribal nation) negotiates with a more wealthy and politically connected entity, such as a major city.

6 Evolving Treatment of Risk and Uncertainty

As regional climate patterns shift, WRE needs to provide more sophisticated treatment of risk so that BCAs and other policy processes can consider these more fully. Extreme heat waves, drought, flooding, and other disasters are becoming more frequent and severe than the historical record indicates. Inclusion of economic approaches to climate risk and uncertainty that encompass extreme events will improve the relevance of WRE courses. For example, Dolan et al. (2021) finds that the projected range of changes in economic surplus exhibit far greater uncertainty than underlying climate-related hydrologic uncertainties in their models of major river basins. They identify widespread likelihood of "economic tipping points" that shift a region's capacity to adapt to and recover from water scarcity (Dolan et al. 2021). Niggli et al. (2022) analyzes recent extreme climate events in Europe, Australia, and Africa; they find economic losses related to direct and indirect consequences in various sectors are substantial in terms of portions of national GDP. Their models identified interactions among interconnected sectors that escalate loss and damage—particularly in health, energy, agriculture, and food supply (Niggli et al. 2022). Modeling approaches for economics of extreme events likely exceed mathematics and statistics capacities for most applied economics undergraduate students, so this theme may be best explored in depth in advanced WRE courses.

Neuroeconomics approaches are relevant to WRE risks and uncertainty challenges, providing improved understanding of neural mechanisms in decision making (Faralla et al. 2015; O'Doherty and Camerer 2015; Suzuki et al. 2016; Sherman, Steinberg, and Chein 2018; Korucuoglu et al. 2020; Krönke et al. 2020; Tisdall et al. 2020). Assessing risk and trade-offs in economic negotiations and policy processes is now understood as a complex, multifaceted neural process. Neural correlates of economic value may prove useful in overcoming uncertainties in contributing to water-related public goods (Krajbich et al. 2009; Krajbich and Dean, 2013). Experiments indicate that neuro-revealed values (using real-time functional magnetic resonance imaging) induce participants to truthfully reveal their own value in their bid to contribute to public goods (Smith et al. 2014; Grueschow et al. 2015). This could ease the process of funding public goods related to higher quality drinking water, infrastructure to alleviate water supply shortfalls, and water-dependent habitat for wildlife and recreation.

7 Use of Geospatial Data in WRE Econometric Analyses

WRE research has been revolutionized over the past decade by access to fine resolution (spatial and/or temporal resolution) data on land use, vegetation, crop mix, groundwater levels, water quality parameters, commercial fish catch, daily stream flows, and hourly electricity loads. Use of remote sensing data in econometric models is a worthy specialty in WRE courses, perhaps deserving its own course. A WRE course emphasizing use of spatial data needs strong prerequisites in statistics and econometrics, and could be structured to serve multiple advanced undergraduate and graduate majors. Applied economics journals (such as those listed in the appendix) provide a good selection of research papers that emphasize use of spatial data, providing a source of class readings. All WRE courses, even those at introductory undergraduate levels, can provide materials that illustrate the value of geospatial data in refining our understanding of water challenges and proposed solutions.

8 Nonmarket Valuation

Nonmarket valuation is highly relevant in WRE (e.g., instream flow values and ecosystem services provided by hydrologic functions within natural systems; compensating for and/or assessing losses due to water transfers, etc.) that can contribute to water policy and deserves emphasis in WRE courses (or perhaps its own specialty course). I provide several lectures on the important role of nonmarket valuation, including contingent valuation, travel cost, and hedonic methods (Young and Loomis 2014; Zuo et al. 2015). Using neuro-revealed values to obtain more accurate bids to contribute to public goods is a promising new pathway in nonmarket valuation (Smith et al. 2014; Grueschow et al. 2015). Students learn best practices for conducting these types of studies, and reviewing and critiquing valuation studies.

9 Regional Economic Analysis

Regional economic analysis contributes to improved understanding of many water challenges and potential solutions. Examples of methods to examine regional economies and changes over time include input-output modeling using software such as IMPLAN (Loomis 2002; Young and Loomis 2014; Yoo and Perrings 2017). Concerns over jobs and community economic vitality lie at the heart of many conflicts over sharing water during shortage and allowing water to be transferred into new uses. I would like to give more attention to the role of regional economic analysis and encourage those designing WRE courses to do so.

10 Course Design and Delivery Recommendations

10.1 Calculus, Microeconomics, and Statistics Prerequisites

Calculus is an important prerequisite for upper-division undergraduate and graduate WRE. Without the ability to review and decipher articles on constrained optimization, students lose access to much valuable WRE literature.

Requiring one prior undergraduate microeconomics class allows a WRE class to build on a working knowledge of supply, demand, market equilibrium, and elasticities. I provide refresher readings and exercises the first week of class. Students needing to rekindle their prior microeconomics exposure are motivated to work through these when faced with the first problem set.

A statistics prerequisite is also important and allows students to review and evaluate simple econometric models in WRE literature. While a semester of introductory econometrics would be ideal and would suit applied economics majors, this would be impracticable for students from other majors who take their own discipline’s variant of statistical modeling.

10.2 Design Class to Be Accessible to Multiple Majors

I design my WRE and ERE classes to be accessible to multiple majors. This creates a classroom environment that resembles water professionals' workplaces, composed of people of different expertise and different perspectives about water's value in differing uses. A multi-major class is more challenging to teach compared to only applied economics majors, but the quality of the classroom experience makes this uniquely valuable in the kinds of jobs students land after earning their degrees.

Even those economics students going into academia after earning a PhD will not be working solely with other economists. A distinctive trend over my years in WRE research, teaching, and outreach, is a shift in funding emphasis by U.S. federal agencies, international funders (World Bank and United Nations), and philanthropic foundations (such as Walton, Ford, and Rockefeller Foundations). It used to be common for funders to focus on economics separately from other water-related disciplines. However, the emphasis has shifted to calls for proposals that require multiple disciplines bringing their expertise to collaborative research on water issues.

WRE courses that include students from non-economics majors face the challenge of widely differing backgrounds in economics and calculus. This can be partially addressed by enforcing microeconomics and calculus prerequisites discussed earlier.

10.3 Consider Student's Career Aspirations

Water professionals are in high demand worldwide: water resource economists as well as hydrologists, engineers, fishery biologists, wetland ecologists, public health specialists, and conflict resolution experts (to list a few). Newton (2022) predicts a global shortage of millions of water professionals in the coming decade as an earlier generation of water professionals nears retirement. Water professionals need skills to participate in multidisciplinary teams to address complex water challenges. This reinforces my commitment to making WRE classes accessible to multiple majors.

The primary sector employing students from my WRE classes is academia, for those earning PhDs. For MS students, about half go on to PhD programs, and the other half go into careers working in applied economics in the private, public, and nonprofit sectors. Key employers for MS students and undergraduates in my courses are public agencies at the local, tribal, state, federal, and international level; nonprofit foundations and advocacy organizations; and consulting firms serving stakeholders involved in water resource conflicts. Proficiency in working across specialty fields is essential in all of these arenas of employment. Providing course material that addresses what is useful for each group's desired careers requires specialized forethought and design. For those aiming to be academics, an emphasis on econometric studies and optimization models is reported by past students to be particularly useful. For those working on water issues in the public, private, and nonprofit sectors, the bargaining and negotiations exercises are reported to be especially valuable.

10.4 Include Multiple Interactive Elements

Team assignments and interactive problem-solving exercises are essential for two reasons. They are widely recognized as key elements in adult learning (Hrach 2021), and they provide opportunity to develop interactive skills needed in WRE work settings. Exercises and assignments can be modeled on professional interactions among regional resource agencies and stakeholders. Interactive bargaining exercises keep students engaged and reinforce important concepts about allocating surplus and cost sharing. Online searches provide a wealth of fresh ideas related to design of economic-bargaining exercises (Docsity 2023; Harvard University 2023). (My classes use dark chocolate as the "currency" in these exercises, but instructors can develop their own favorite reward structures.)

10.5 Provide Diverse Examples of Leadership and Expertise

It is important to draw upon examples of economic problem solving and leadership in water challenges from diverse cultures and genders. A student who never sees someone "like them" (whether that is cultural background, skin color, or gender) playing a role in water economics has a much harder time believing they can successfully enter that field. Consider the cultural mix of your students, their genders, and nationalities to choose case studies and examples that help them see leaders and experts who share some of their characteristics. Our deliberate choosing of gender- and culture-inclusive language and examples will help diversify the WRE profession.

10.6 Promote Ongoing Networks after Graduation

Maintaining ongoing contact after graduation is rewarding in many respects. I genuinely enjoy seeing former students thrive in their careers and contribute in their spheres of influence. The data sharing, research collaborations, and professional connections are valuable in many different ways. Employment opportunities arise for newly graduating students with prior students now in a position to hire in their organizations or to serve as mentors to those just starting their careers. I cultivate post-graduation networking by connecting informally and by hosting a happy hour when I am visiting an area with several former students from different eras. An occasional e-newsletter with greetings to former students, that includes their news as well as your own, would be a more structured way to connect former students and keep up your own contacts with them.

10.7 Textbooks, Readings, and Other Teaching Material.

In my WRE courses, I use chapters from textbooks combined with applied economics journal articles. More details on course readings are provided in the appendix. I find it useful and enjoyable to link water economics to a broader cultural context reflected in world film and literature, exposing students to diverse voices and experiences. I provide a list of novels and films that include water economics as one of their themes, and ask students to identify concepts from class in a very brief written assignment on a novel or film they select from the list (see Appendix). I enjoy the insights and new angles on WRE that they glean from what they read and view.

10.8 Types of Assignments

I assign regular problem sets that require differential calculus, short presentations that link a class concept to a contemporary water challenge, team presentations analyzing specific economic components of case studies, and brief written exercises. The term project involves a brief paper and 15-minute presentation on a current water problem that is selected by the student and refined and approved in consultation with me as the instructor.

11 Summary

This article emphasizes specific aspects of WRE that the author has found to be most relevant and worthy of more emphasis among the WRE profession. This means that some standard WRE themes have received little attention here. Water law and regulations naturally are discussed in WRE readings and lectures, and some students may wish to take a water law or water policy class, in addition to WRE. Sustainability is an important contemporary theme, and its economic aspects should be integrated into WRE course materials. Macroeconomics provides useful frameworks for considering broader effects of water policy alternatives and can be brought into WRE course materials and discussions. No doubt readers will identify other themes not mentioned in this article that could form a valuable component in WRE classes.

To improve WRE offerings, systematic evaluation would be useful. Most universities conduct student evaluations of courses and sometimes (especially for junior faculty) peer reviews of course materials and lectures. In addition to these evaluation measures, WRE courses could benefit from a delayed retrospective assessment by students now working as water professionals and by students who have entered a graduate program. These individuals would be in a position to reflect upon the usefulness of WRE courses and ways to improve them. In addition, longtime water professionals could provide insights on what skills and topics are most relevant as they consider hiring students into a water resource career path.

This is an exciting era in which to be teaching WRE. Global water crises and changing patterns of water demand and supply imply that WRE courses need to provide tools for analyzing a new generation of water management strategies and policy tools. Presenting material on neurobehavior in economic decision making and a well-rounded perspective on the role of BCAs in the policy process is valuable in preparing new WRE professionals for their work. Emphasizing water's role in energy, food, and development economics and in social justice and cross-cultural considerations enhances the relevancy of WRE courses to broader groups of students. Nonmarket valuation, regional economic methods, and analytic methods for working with geospatial data also have an important place in WRE courses. Economic treatment of risks related to extreme events merits special attention. The topics addressed in this article could well form a two-semester sequence, as I find they cannot adequately be covered in a single semester. The Appendix provides a list of key topics and sources for class readings.

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Appendix: WRE Class Topics and Primary Reading Sources

Class Topics

I weave in an emphasis on current water policy challenges and innovative policy instruments throughout courses, as well as choosing cases that highlight social justice and cross-cultural considerations.

Some of the topics listed can only be treated briefly during a 14-week upper-level undergraduate and graduate course meeting 2.5 hours per week. The course material requires prior coursework in differential calculus and undergraduate microeconomics.

Review of Microeconomics, Consumer and Producer Theory, Applied to Water:

- Demand and supply, price signals, equilibrium, Consumer Surplus, Producer Surplus and elasticities
- Utility maximation and demand function
- Cost minimization, production function, and derived demand for inputs
- Pareto Optimality given specific assumptions (which do not hold in many water policy settings)
- Diamond Water Paradox
- LaGrangean constrained optimization and first order conditions

Neurobehavior in Economic Negotiations

- Polyvagal theory and autonomic nervous system (ANS) influences on economic interactions incorporated into WRE through readings, case studies, and bargaining exercises

Benefit-Cost Analysis (BCA)

- Guiding principles
- Review and critique of case studies in BCA and policy decisions

Cap and Trade in Theory and Practice

- Conditions for achieving efficiency
- Transferable permits to discharge pollutants and to use water
- Comparing cap and trade to other policy instruments
- End of pipe pollutants contrasted with ambient water quality programs

Risk and Uncertainty

- Expected value and expected utility
- Risk premium, certainty equivalent
- River basin studies addressing water trading and other risk management strategies

Valuing Water

- Why is it important in policy context?
- Use values—agricultural, urban, and industrial
- Nonmarket valuation: travel cost, contingent valuation, and hedonic valuation

Water Pricing

- Rate structures, tiered rates, and seasonal rates
- Marginal capacity cost
- Case studies: urban water utilities

Geospatial Data in WRE Econometric Analyses

- Review recent WRE econometric tudies

Suggested Sources for Course Readings

I update class readings each time a course is offered to replace older material. I add new journal articles and textbook chapters. I also add in-depth, updated journalism coverage of water issues making headlines through articles and videos.

The lists provided reflect my own geographic and topical interests. There are many other excellent books and journals that could be included.

Books

Burnett, K., R. Howitt, J.A. Roumasset, and C.A. Wada, eds. 2015. *Routledge Handbook of Water Economics and Institutions*. New York: Routledge.

Colby, B., and G. Frisvold. 2011. *Risk and Resilience: The Economics of Climate-Water-Energy, Challenges in the Arid Southwest.* Resources for the Future Press.

Dinar, A. 2022. *Advanced Introduction to Water Economics and Policy.* Cheltenham UK: Edward Elgar Publishers.

Dinar, A., and Y. Tsur. 2021. *The Economics of Water Resources: A Comprehensive Approach*. Cambridge UK: Cambridge University Press.

Easter, W., ed. 2014. *Innovations in Water Markets*. Berlin: Springer.

Griffin, R. 2016. *Water Resource Economics*, 2nd ed. Cambridge MA: MIT Press.

Loomis, J. 2002. *Integrated Public Lands Management*. New York: Columbia University Press

Shaw, D. 2021. *Water Resource Economics and Policy*, 2nd ed. Cheltenham UK: Edward Elgar Publishing.

Roumasset, J., ed. 2015. *Handbook of Water Economics*. Berlin: Springer-Verlag Co.

Young, R., and J. Loomis. 2014. *Determining the Economic Value of Water*, 2nd ed. New York: Routledge.

Ziolkowska, J., and J. Peterson, eds. 2016. *Competition for Water Resources: Experiences and Management Approaches in the US and Europe*. Amsterdam: Elsevier.

Journals (with examples of recent relevant articles)

American Journal of Agricultural Economics

Li, M., W. Xu, and T. Zhu. 2019. "Agricultural Water Allocation under Uncertainty: Redistribution of Water Shortage Risk." *American Journal of Agricultural Economics* 101(1):134–153. https://doi.org/10.1093/ajae/aay058

Palm-Forster, L.H., J.F. Suter, and K.D. Messer. 2019. "Experimental Evidence on Policy Approaches That Link Agricultural Subsidies to Water Quality Outcomes." *American Journal of Agricultural Economics* 101(1):109–133. https://doi.org/10.1093/ajae/aay057

Paudel, J., and C.L. Crago. 2021. "Environmental Externalities from Agriculture: Evidence from Water Quality in the United States." *American Journal of Agricultural Economics* 103(1):185–210. https://doi.org/10.1111/ajae.12130

Ecological Economics

Gutiérrez-Martín, C., J.A. Gómez-Limón, and N.M. Montilla-López. 2020. "Self-Financed Water Bank for Resource Reallocation to the Environment and within the Agricultural Sector." *Ecological Economics* 169:106493. https://doi.org/10.1016/j.ecolecon.2019.106493.

Kreye, M.M., D.C. Adams, F.J. Escobedo, and J.R. Soto. 2016. "Does Policy Process Influence Public Values for Forest-Water Resource Protection in Florida?" *Ecological Economics* 129:122–131. https://doi.org/10.1016/j.ecolecon.2016.06.007.

International Journal of Water Resource Development

McIlwaine, S.J., and O.K.M. Ouda. 2020. "Drivers and Challenges to Water Tariff Reform in Saudi Arabia." *International Journal of Water Resources Development* 36(6):1014–1030. https://doi.org/10.1080/07900627.2020.1720621

Suresh, A., K.S. Aditya, J. Girish, and P. Suresh. 2019. "Micro-Irrigation Development in India: An Analysis of Distributional Pattern and Potential Correlates." *International Journal of Water Resources Development* 35(6):999–1014. https://doi.org/10.1080/07900627.2018.1504755

Journal of Agricultural and Resource Economics

Ifft, J., D.P. Bigelow, and J. Savage. 2018. "The Impact of Irrigation Restrictions on Cropland Values in Nebraska." *Journal of Agricultural and Resource Economics* 43(2):195–214. http://www.jstor.org/stable/44840983

Manning, D.T., and J.F. Suter. 2019. "Production Externalities and the Gains from Management in a Spatially-Explicit Aquifer." *Journal of Agricultural and Resource Economics* 44(1):194–211. https://www.jstor.org/stable/26797550

Journal of the American Water Resources Association

Burns, J.B., M. Payne, M.G. Smith, and C. Landry. 2022. "Measuring Trends in Western Water Prices." *Journal of the American Water Resources Association* 58(2):203–219. https://doi.org/10.1111/1752-1688.12992

Yoder, J., J. Adam, M. Brady, J. Cook, S. Katz, S. Johnston, K. Malek, J. McMillan, and Q. Yang. 2017. "Benefit-Cost Analysis of Integrated Water Resource Management: Accounting for Interdependence in the Yakima Basin Integrated Plan." *Journal of the American Water Resources Association* 53(2):456–477. https://doi.org/10.1111/1752-1688.12507

Journal of Contemporary Water Research and Education

Colby, B., and R. Isaaks. 2019. "Water Trading: Innovations, Modeling Prices, Data Concerns." *Journal of Contemporary Water Research and Education* 165(1):76–88. https://doi.org/10.1111/j.1936-704X.2018.03295.x

Kauffman, G.J. 2016. "Economic Value of Nature and Ecosystems in the Delaware River Basin." *Journal of Contemporary Water Research and Education* 158(1):98–119. https://doi.org/10.1111/j.1936-704X.2016.03222.x

Journal of Environmental Economics and Management

Melstrom, R.T. "Residential Demand for Sediment Remediation to Restore Water Quality: Evidence from Milwaukee." *Journal of Environmental Economics and Management* 116:102731. https://doi.org/10.1016/j.jeem.2022.102731

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Journal of Natural Resources Policy Research

Peterson, J.M., and A.E. Saak. 2018. "Spatial Externalities in Aquifers with Varying Thickness: Theory and Numerical Results for the Ogallala Aquifer." *Journal of Natural Resources Policy* 8(1-2):44–65. https://doi.org/10.5325/naturesopolirese.8.1-2.0044

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Land Economics

Adamson, D., and A. Loch. 2021. "Incorporating Uncertainty in the Economic Evaluation of Capital Investments for Water-Use Efficiency Improvements." *Land Economics* 97(3):655–671. https://doi.org/10.3368/wple.97.3.100119-0143R

Guignet, D., M.T. Heberling, M. Papenfus, and O. Griot. 2022. "Property Values, Water Quality, and Benefit Transfer: A Nationwide Meta-Analysis." *Land Economics* 98(2):191–218. https://doi.org/10.3368/le.98.2.050120-0062R1

Natural Resources Journal

Bowen, R.L., J.E. Moncur, and R.L. Pollock. 2020. "Rent Seeking, Wealth Transfers and Water Rights: The Hawaii Case." *Natural Resource Journal* 31(3):429–448. https://digitalrepository.unm.edu/nrj/vol31/iss3/1

Spivak, D. 2021. "The Colorado River Drought Contingency Plan: An Opportunity for Exploring Demand Management Through Integrated and Collaborative Water Planning." *Natural Resource Journal* 61(2):173–203. https://digitalrepository.unm.edu/nrj/vol61/iss2/4

Water Economics and Policy
Fernandes, A., M. Figueiredo, J. Neves, and H. Vicente. 2022. "A Conceptual Model to Assess the Literacy of Water Consumers." *Water Economics and Policy* 8(2):1–21. https://doi.org/10.1142/S2382624X22500072

Häggmark, T., and K. Elofsson. 2021. "The Impact of Water Quality Management Policies on Innovation in Nitrogen and Phosphorus Technology." *Water Economics and Policy* 7(1):1–29. https://doi.org/10.1142/S2382624X21500028

Weather, Climate, and Society
Buchanan, M. K., M. Oppenheimer, and A. Parris. 2019. "Values, Bias, and Stressors Affect Intentions to Adapt to Coastal Flood Risk: A Case Study from New York City." *Weather, Climate, and Society* 11(4):809–821. https://www.jstor.org/stable/26861896

Chiew, E., R.A. Davidson, J.E. Trainor, L.K. Nozick, and J.L. Kruse. 2020. "The Impact of Grants on Homeowner Decisions to Retrofit to Reduce Hurricane-Induced Wind and Flood Damage." *Weather, Climate, and Society* 12(1):31–46. https://www.jstor.org/stable/26892930

Examples of WRE-Related Novels and Films I Recommend to Students:

Novels
The Man Who Killed The Deer, Frank Waters
Milagro Beanfield War, John Nichols
Ceremony, Leslie M. Silko
Mean Spirit, Linda Hogan
Woman at Otowi Crossing, Frank Waters
By The River's Edge, Elizabeth Cook Lynn
River Song and *Winterkill*, Craig Lesley
The Ancient Child, Scott Momaday
Angle of Repose, Wallace Stegner
Mara & Dann, Doris Lessing

Films
Thunderheart
Milagro Beanfield War
Chinatown
Jean de Florette (French, subtitles)
Pow Wow Highway
A Beautiful Mind (John Nash, game theory)
Erin Brockovich
A River Runs Through It

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Teaching and Educational Methods

Teaching Water and Sanitation Economics and Policy with a Focus on Low- and Middle-Income Countries

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Abstract
This paper describes our experience from 2010 to 2018 developing and delivering a multidisciplinary graduate course on "Water and Sanitation Policy and Planning in Developing Countries." This course was synchronously taught at the University of North Carolina at Chapel Hill and the University of Manchester, UK. We describe both our learning objectives and the conceptual framework for policy analysis that were used to structure the course. We discuss our problem-based learning approach to case studies and policy memo format assignments. We summarize eleven key messages that we want students to think hard about when reflecting on the course materials. This aligns with our aim to prepare students to address key challenges of water and sanitation access and provision that they could encounter in careers in the global Water Sanitation and Hygiene (WASH) sector. We discuss how our teaching was improved from 2012 after we converted our in-person class for parallel delivery as two massive open online courses (MOOCs) on Coursera. This afforded more class time to use a "flipped" classroom format, enabling more active participation because students could watch recorded lectures outside class.

1 Introduction

Low to middle income countries face a range of challenges to provide appropriate water supply and sanitation services to their growing populations. We believe there is a need to train Water Sanitation and Hygiene (WASH) sector practitioners at universities to understand current WASH conditions and to critically assess policy interventions in the sector. This paper describes our experience developing and delivering such a course. Our reflections on the course will hopefully assist readers who may wish to develop material on WASH policy and planning for use in their own contexts.

The policy model our course adopts stresses that students should understand current "status quo" conditions and be able to critically assess existing policy interventions. We also engage students with eleven high-level "key messages" across the course material. These address how "ancient instincts" affect water and sanitation behaviors (1), the relationship between raw water supplies and infrastructure (2), path dependency (3), how the state views WASH services (4), the difference between economic and financial analysis of water investments (5), corruption in the WASH sector (6), important attributes of piped WASH services (water is heavy and piped networks are expensive) (7), and how this affects water problems and solutions (8), the difference between optimal and minimal water use (9), uncertainty about the magnitude of the health benefits of WASH interventions in different locations (10), and the multilevel nature of water policy debates (11).

The paper is structured as follows. First, we present an overview of the course development and its approach, which has involved synchronous U.S./UK in-class teaching and parallel development of two massive open online courses (MOOCs). Second, we detail the eleven key messages that we want students to think hard about over the semester (term). Third, we list some case studies that we have found most useful and with which we believe students should be familiar with as they organize their thinking about potential professional work in the WASH sector. Fourth, we discuss some of the participatory exercises we use in our "flipped" classroom (including class debates, the calculation of intervention costs), and the use of formative and summative problem-based learning assessments. Fifth, we offer brief reflections on our experiences with designing and offering the two MOOCs and how this enriched classroom practice. We then conclude with final thoughts.

2 Course Overview and Approach

From 2010 to 2018 we simultaneously taught a graduate course entitled "Water and Sanitation Policy and Planning in Developing Countries" at the University of North Carolina at Chapel Hill and the University of Manchester, UK.[1] The audience for this course included students from several different disciplines (e.g., business and management, environmental sciences and engineering, city and regional planning, innovation studies, pollution control, public policy, public health, sociology, geography, political science) who were interested in problems of poor water and sanitation in low- and middle-income countries.

We set overall learning objectives for students for this course to be as follows:

- To develop the knowledge and understanding of status quo (baseline) conditions in the water and sanitation sector in low- and middle-income countries; and how problems are defined.
- To understand current trends in water and sanitation conditions and where current programs, economic growth, population growth, and demographic changes are headed (dynamic baseline).
- To understand and think critically about the different types of policy interventions (instruments) that can be used to improve water and sanitation conditions in low- and middle-income countries.
- To understand the policy objectives (criteria) that governments and donors use to assess the outcomes of policy interventions in the water and sanitation sector.
- To understand the causal links between policy interventions and outcomes and to critically assess the available evidence about how effective different policy instruments are in improving conditions in the water and sanitation sector.
- To think critically about implementation issues and the lessons learned about implementation, monitoring, and evaluation.
- To develop critical writing and communication skills to better explain policy recommendations in the water and sanitation sector to decision makers.
- To learn how to read and synthesize professional and scientific literature on a policy issue in the water and sanitation sector.

This period beginning in 2010 was in the relatively early days of this kind of remote teaching. We had a video link between a classroom in Chapel Hill and a classroom at the University of Manchester. At both ends this required dedicated camera technology and operators, so we needed more planning than when using current platforms like Zoom and Teams that have since become commonplace. Sometimes Professor Whittington was in Chapel Hill and would broadcast the lecture to students in Manchester, and Dr. Thomas would moderate a discussion of the materials with students in Manchester after the broadcast ended. Sometimes Professor Whittington was in Manchester broadcasting to students in Chapel Hill. Sometimes Dr. Thomas would lecture from Manchester to students in Chapel Hill with the

[1] Beginning in 1996, Dale Whittington taught an earlier version of this course for students at University of North Carolina at Chapel Hill, Duke University, and North Carolina State University. The majority of students were in Masters degree programs, but PhD students and upper division undergraduates were also permitted to enroll. In 1998 and 1999, Professor Whittington simultaneously taught this course in the Department of Urban Studies and Planning at the Massachusetts Institute of Technology and the University of North Carolina at Chapel Hill. No video technology was used; he flew back and forth between Chapel Hill to Boston once per week throughout the semester.

Manchester students present in person. Students at both Chapel Hill and Manchester could participate in discussions and pose questions to their instructors and each other in real time. Around 40 to 60 students took the class in person each year.

In 2012 the University of Manchester put out a call for proposals to faculty who wanted to work with Coursera[2] and create a MOOC under the University of Manchester brand. The winning teams received funding of around US$18,000 to work with the University of Manchester Media Production Unit to record their lectures for the MOOC. The University of Manchester was dipping its toes into the new world of MOOCs and hoped to learn lessons for a broader, more comprehensive initiative. We wrote a proposal, and our course was selected as one of five MOOCs to be launched by the University of Manchester on the Coursera platform. We converted the classroom-based course into an online version in two parts. We recorded our lectures for part one in 2013 and 2014. Part one launched in May 2014, with endorsement from the Global Water Partnership[3], and was taken by 17,500 students from more than 190 countries before it closed later that year. Lectures for part two were recorded from 2015 to 2017 with additional funding support. Part two launched in January 2017, and part one was re-launched, with no set closure date.[4] By November 2022, an additional 25,000 students had taken the courses, bringing total enrollment to 42,500. This currently continues to increase by around 75 students per week.

The class already had a pedagogic approach of placing emphasis on class participation and treating policy challenges in the WASH sector as “wicked problems.” This guided how the material was taught. Our assignments required students to compose “policy memos” that responded to realistic, real-world problem scenarios. However, building a library of recorded MOOC lectures created a new opportunity for us to take this approach farther by adding various “flipped class” approaches. We could have students listen to the lectures before class and use class time for other, more interactive, participatory activities. For example, we used class time to answer student questions about the recorded lectures, for guest lectures, to hold class debates on current topics of special interest, and to give students the opportunity to present and discuss new literature in the field. Often, we would read a new article or paper and then have the author join by video link into the live class session to answer student questions about the author’s research.

The course (and the MOOCs) is organized in two main parts across fourteen taught sessions (for syllabus see Annex 1). The first describes current and evolving conditions in the water and sanitation sector. We want students to have a nuanced understanding of the kinds of situations that they will find in low- and middle-income countries if they chose to enter into professional work in the Water Sanitation and Hygiene (WASH) sector. Topics in part one include infrastructure coverage in the Global South; the provision of water by informal providers (water vendors); costs of service provision; different forms of corruption; water and food relationships; the determinants of demand for improved services; and WASH water development paths and the associated technical, financial, and political disequilibria that occur in different phases (Whittington et al. 2023). The second part of the course covers the different types of policy interventions that have been used to improve poor water and sanitation conditions and what we know about their effectiveness. Policy interventions discussed include government investments, new planning protocols, tariff reforms, subsidy schemes, information provision, privatization, and regulation. We believe this two-part “status quo” and “interventions” structure has broad application to many such courses on water economics topics.

As the course format evolved over the years, we gravitated to the use of more case materials. There are now many excellent cases in the WASH field that illustrate well different aspects of the challenges of improving water and sanitation conditions in the low- and middle-income countries and

[2] https://www.coursera.org/.
[3] https://www.gwp.org/.
[4] The course links are https://www.coursera.org/learn/water and https://www.coursera.org/learn/water-part-2.

the policy interventions that planners and policy makers can deploy. We use these case studies to illustrate a set of eleven key, overarching messages. One can thus conceptualize the organization of the course as a matrix with, for example, ten case studies and eleven key messages. We use each of the case studies to call attention to and re-enforce one or more of the eleven key messages. We will not use a single case study to try to discuss all of the key messages, but typically more than one message can be discussed in each case study.

3 Eleven Key Messages

3.1 Message No. 1: Ancient Instincts

Economic theory has important insights to offer water and sanitation planners, especially in the areas of investment planning and pricing and tariff design. However, students need to appreciate that water policy interventions may evoke powerful emotional responses in the *homo sapiens* that can play an important role in their responses to policy interventions. John Maynard Keynes described the role played by “animal spirits” in the financial markets, and that the decision to undertake an investment was not simply the result of “cold calculation.”[5] In the course we call Keynes’s animal spirits “ancient instincts” and stress to students their importance in understanding water policy debates and designing interventions in the WASH sector. We argue that water has played a crucial role in the evolution of *homo sapiens*, and that this history has left us with four ancient instincts related to water and sanitation that continue to influence our behavior in the WASH sector (Whittington 2016).

The first ancient instinct is our primal fear of losing access to water. When our ancestors on the African savannah went to water holes to drink, they faced the risk of attack by predators. They had to be especially vigilant; the risk of losing access to water was very real and could be life threatening. Finlayson (2014) contends that the *homo sapiens* body evolved for long distance running in part to be able to reach distant water sources, especially if nearby sources dried up or access was denied.

The second ancient instinct is our love of water for relaxation and recreation. Not only did our ancestors need water for drinking to survive, but they also enjoyed water for bathing, cooling off, and the aesthetic beauty of light reflections on water surfaces. We discuss with students their own preferences for swimming, walking on the beach, and camping near scenic bodies of water. These preferences are reflected in the housing premiums that people today pay for waterfront properties where they can see and experience water.

The third ancient instinct is *homo sapiens*’ universal repulsion of the smell of feces. On the African savannah, this ancient instinct served an important purpose, i.e., to encourage people to defecate away from communal living sites. In the course we refer to this ancient instinct in our discussion of the challenge of ending open defecation in South Asia and Sub-Saharan Africa, noting that many people still like to defecate in the open. Understanding *homo sapiens*’ universal repulsion of the smell of feces also helps us examine the concept of “triggering” a community response to end open defecation that is a central idea in the policy intervention community-led total sanitation (CLTS).

The fourth ancient instinct is *homo sapiens*’ reluctance to assign an exchange value to water. Early humans created complex trading systems, exchanging flint, obsidian, shells, hides, and food over long distances. These trading systems established exchange values for many commodities. However, because water was heavy and hard to carry, *homo sapiens* had to live relatively near a water source. This meant that it was not one of the commodities in such long-distance trading systems. As a result, throughout most of human history, water was never assigned an exchange value. This does not mean that humans treated water as a “low-value” commodity. Indeed, water is deeply embedded in almost all spiritual and

[5] “If human nature felt no temptation to take a chance, no satisfaction (profit apart) in constructing a factory, a railway, a mine, or a farm, there might not be much investment merely as a result of cold calculation.” (Keynes 1936, p. 135)

cultural traditions. But because it was not traded, there was no tradition of establishing a monetary value to water.

Throughout the course we discuss the importance of these four behavioral traces from our evolutionary past, especially in the analysis of case studies. Reflecting on these four ancient instincts helps students understand why economists' policy advice is routinely rejected by decision makers and civil society in the water sector and how such resistance to economic advice can sometimes be overcome.

3.2 Message No. 2: WASH Services Require Both Raw Water Supplies and Infrastructure

In the Southwestern United States, water rights lawyers refer to "dry water" and "wet water." "Dry water" means water without the associated infrastructure. "Wet water" refers to having both the water right and the funding to build the infrastructure needed to use the water at the time and location where people want it. In many situations a water right without infrastructure is not worth very much.

This distinction between a water supply with and without infrastructure should be front and center in students' minds as they study water economics and policy—both in low- and middle-income and in high-income countries. A surface or groundwater raw water supply typically must be combined with infrastructure to make it more valuable to users. Infrastructure is used to move water from its existing location to where people want to use it (e.g., water transmission pipelines), to improve the quality of the raw water (e.g., water treatment facilities), and to improve its reliability (e.g., reservoirs, storage tanks). Such water and sanitation infrastructure is very capital intensive, long-lived, and expensive (Whittington et al. 2009). Typically, a community cannot pay for all the water infrastructure it needs out of cash flow. Long-term financing is required to match the benefits of providing water and sanitation services over time with long-lived infrastructure.

The cost structure for raw water supplies is very different than for infrastructure. Both formal and informal property rights determine whether one party can obtain access to a raw water source. Raw water may or may not be tradable depending on the local property rights regime. The state may allocate a raw water supply to one party free of charge, or the price to obtain a water allocation may be high (or obtaining an allocation may not be permissible). The availability of raw water supplies varies greatly by location and over time. Raw water may be available part of the time, but not available at other times, so the price of a raw water supply traded in a water market will have an associated reliability.

The coupling of these two very different goods—raw water and water-related infrastructure—is one of the reasons that water resource economics and policy is such an interesting, complex field of study. Students need to think about the economic value of water with or without the associated infrastructure. For example, the piped water services delivered to households combine a raw water source with infrastructure to produce water and sanitation services that have a high economic value to households and other urban customers. The economic value of these water and sanitation services is much greater than the economic value of a raw water supply in a river that is 100 kilometers from the city.

However, conversely, a modern piped water and sewerage infrastructure system is worth much less without a reliable raw water source. This can occur in extreme drought conditions. For example, in the recent drought in Cape Town, South Africa, the piped infrastructure existed in most parts of the city, but the raw water supply itself was almost exhausted (Visser and Brühl 2019; Muller 2017; Kohlin and Visser 2022). In such a situation, the infrastructure itself cannot deliver the water services people want and the economic value of the infrastructure without the raw water supply is essentially zero until the drought is over and the raw water supply returns.

Students also need to realize that policy discussions about the human right to water may not properly account for this distinction between raw water supplies and water with infrastructure. This is true for discourses in both civil society and high-level policy circles.

3.3 Message No. 3: Path Dependency

Building water infrastructure in cities almost always involves adding on to existing infrastructure. This requires a careful consideration of what is already in place, which in many cases may not be ideal. For example, in many cities wastewater flows from residential customers are combined with stormwater. In extreme (or even normal) precipitation events, the volume of wastewater may be too great for the available wastewater treatment facilities, and raw sewage must be discharged untreated to surface waters (unsatisfactory combined sewer overflows). One can replace combined sewer systems with separate stormwater and wastewater networks, but this requires major capital investments.

Similarly, single-family housing is typically plumbed for only one line to supply potable water throughout the dwelling. Treated potable water is not required for flushing toilets or watering lawns, but residential customers are "locked in" by past investments in indoor plumbing and public piped network investments to housing units. Residential wastewater collection infrastructure does not separate urine and feces, even though both the treatment and disposal issues involved with these two waste streams are very different.

Students need to understand that the capital required to provide water and sanitation services is embedded in both the infrastructure outside the house (typically publicly owned) and the plumbing inside the house (typically privately owned) (Whittington 2020). The problem of path dependency is especially severe in multifamily housing units. For example, if the plumbing within a multifamily apartment or condominium building is not initially designed for metering individual units, it is often prohibitively expensive to later retrofit units with meters. In some cases, installing meters to a single individual unit could require multiple meters, one for each distribution line entering a unit (Davis and Whittington 2004).

WASH students need to appreciate that it can be prohibitively expensive to quickly change the way piped water and sanitation services are delivered in a city, even if this seems desirable, i.e., to make these services more resilient to a changing climate. One possible solution is to require new infrastructure standards on new construction, while existing buildings are allowed to continue with their existing infrastructure.

3.4 Message No. 4: The State Often Considers WASH Services to Be Merit Goods

Many students refer to piped water and sanitation as "public goods." What they typically mean is that the public has a strong interest in having high-quality WASH services provided to its citizens. Often students also have a strong preference that WASH services be provided by the public sector. This is another reason that they refer to WASH services as "public goods." From our perspective, it may or may not make sense for WASH services to be supplied by the public sector. This varies by both time and location.

We want students to understand economists' definitions of (1) "public goods," (2) "merit goods," and "externalities." We consider it is not helpful to define WASH services as "public goods" because consumption by one person *does* reduce the amount of water available to others, and capital used to supply infrastructure to one group of households cannot be used to supply a different group. On the other hand, some water resources (e.g., scenic lakes) may be public goods in the sense that the utility one person derives from viewing its natural beauty *does not* diminish the experience available to another one person (as long as the site is uncongested and unspoiled).

However, WASH services—especially sanitation services—*do* have positive externalities. In our experience many students are familiar with the concept of an "externality," but have difficulty both defining it and understanding its significance for WASH policy interventions. There are many definitions of "externality" in the literature. In this course we use a simple one:

An externality is an effect or consequence of the production or consumption of a good or service on a third party that was not the intention of the consumer or producer of the good or service. This unintentional consequence of consumption or production may be positive (welfare-enhancing) or negative (welfare-reducing) on the third party.

For WASH students, an important example of a positive externality is the health benefit to others that may result from the safe disposal of a household's feces. A household practicing safe disposal may itself receive a direct health benefit, and a neighbor may also receive a health benefit (a positive externality). The household practicing safe feces disposal may not have intended to provide a health benefit to their neighbor, but this occurred anyway. If a household does not take this positive externality into account, from a social perspective they will make too little investment in safe feces disposal.

In the WASH sector students tend to be unaware of the possibility of negative externalities associated with the provisions of WASH services. However, these can also occur and are location specific. The provision of piped water services inside dwellings and public spaces in very crowded slums may facilitate the spread of diseases (Bennett 2012). Finding the appropriate policy response to both positive and negative externalities requires a quantitative estimate of the magnitude of these externalities, which is typically difficult to obtain and will vary significantly by time and location.

We believe it is helpful for students to think of WASH services as "merit goods," which are defined as goods or services that the state has determined households should receive regardless of their ability to pay (Hanemann and Whittington, 2023). The key idea is that the determination of whether a good or service is a merit good is based on some concept of need, rather than on the basis of a household's ability and willingness to pay. A good example of a merit good is primary education. Almost every state wants all children to have at least a primary education regardless of their family's income. Health care is an example of a service that some but not all states treat as a merit good.

We emphasize to students that designating water and sanitation services as merit goods is not the same as to claim that water and sanitation are *human rights*. What constitutes a merit good is a political judgment made by a state at a particular time and place given competing claims on budget resources. Claims of human rights are not moderated by a state. The state must align its designations of merit goods and its budget resources. This is not how human rights are defined.

We use Table 1 to illustrate the distinctions between a public good, a merit good, and a private good. We start the discussion by pointing out that most goods and services are not either public goods or merit goods. Automobiles, houses, hamburgers, and cosmetic surgery are all goods that the state may regulate but allows the market to determine the prices to be charged. Whether a person has access to such goods depends on their ability and willingness to pay for them.

It is possible that the state could determine that a good or service is both a public good and a merit good. National defense and clean air are public goods because consumption by one person does not reduce the amount available for consumption by others. The state may also determine that national defense and clean air are merit goods that everyone should receive regardless of their income (Case 1). However, as a practical matter, it is not possible to exclude people from a public good like national defense, so some public goods inevitably will be provided regardless of a person's ability and willingness to pay.

Table 1: Public Goods and Merit Goods

	Merit Good	Not a Merit Good
Public Good	Case 1 – National defense, clean air	Case 2 – Television, radio signal
Not a Public Good	Case 3 – Access to health care, primary education, piped water supplies	Case 4 – Automobile, house, hamburger, cosmetic surgery

Television and radio signals are an example of a public good because one person's consumption of the signal does not reduce the amount of the signal available to someone else. However, it is technologically possible to exclude people from receiving such signals. Because most states have not determined that such signals are merit goods, states may allow charging for the signal. Such charges may not be based on a determination of the need or ability to pay of the household. This is an example of a public good that is not a merit good (Case 2).

Access to health care, primary education, and piped water and sanitation services are not classic public goods because consumption by one person *does* reduce the amount available for consumption by others. However, most states have determined that some minimum level of these services should be provided to people regardless of their ability to pay, so these would be merit goods but not public goods (Case 3).

A good class exercise is to break students up into small groups and give each group some examples of WASH-related services (e.g., public handpumps, in-house water treatment technologies, bottled water, tanker truck delivery, septic tank desludging, etc.), and instruct each group to classify these goods or services using this table. Each group can then report back to the class the reasoning they used to make their classifications.

3.5 Message No. 5: Economic Analysis of Water Investments Is Not the Same as Financial Analysis

We want students to understand the difference between an economic analysis and a financial analysis of a WASH investment. In our experience most students without training in economics use the term "economic" and "financial" interchangeably. Students' confusion about the difference is to some extent understandable because monetary units are used to measure changes in both financial and economic criteria, and because increases (or decreases) in people's income due to a WASH intervention may both count as financial benefits (or costs) and as economic benefits (or costs). However, students need to understand that maximizing net economic benefits and maximizing net revenues are not the same criterion. The market (or regulated) price of a good or service is not equivalent to its economic value, although in some cases prices may be good approximations. In practice, WASH projects are often evaluated using both a financial criterion and an economic criterion. For example, it is standard practice at the World Bank to evaluate projects from both perspectives.

Students need to appreciate that the difference between a financial analysis and a benefit-cost analysis lies in the set of protocols and procedures used to transform the physical data on project inputs and outcomes into monetary units. Financial accounting procedures and protocols use market prices to measure the value of inputs and outputs. To conduct an economic (benefit-cost) analysis, a WASH planner may use either market prices or shadow prices to value inputs and outcomes—whichever is appropriate in a specific context or situation.

Another important difference between the use of financial and economic efficiency criteria is that in a financial analysis the analyst typically restricts the focus to a single client or enterprise (e.g., the water utility). A benefit-cost analysis should include the economic gains and losses to all the groups of people (stakeholders) affected by the project or policy intervention.

We use Table 2 to show students that when both a financial criterion and an economic efficiency criterion are used to evaluate a WASH intervention, four outcomes are possible. Cases A and D are straightforward. In Case A, the WASH intervention passes both a financial and an economic efficiency test. This means that the project is both financially feasible (revenues exceed costs), and potentially welfare-enhancing (winners could compensate the losers, and everyone could be better off). In Case D, the project fails both a financial and an economic efficiency test, i.e., revenues cannot cover costs, and the winners cannot compensate the losers and in theory make everyone better off.

Table 2: Four Outcomes of the Use of Both a Financial and an Economic Efficiency Criterion to Assess a WASH Intervention (Project)		
	Projects passes an economic efficiency test	Project fails an economic efficiency test
Project passes a financial test	Case A	Case B
Project fails a financial test	Case C	Case D

Cases B and C are the most interesting for students. In Case B the project passes a financial test but fails an economic efficiency test. This could happen if a water utility or government looked only at the financial returns of a project, which were favorable, but did not consider the negative side effects or externalities. For example, an investment in water vending trucks might look financially attractive to a water utility (and perhaps also to a property owner receiving payments from the sale of groundwater abstracted on its land to the tanker truck vendors). The negative externalities of adding a fleet of tanker trucks to the city's transport network and the depletion of local groundwater resources would be ignored in such a financial analysis. However, an economic efficiency analysis that incorporated the negative externalities associated with traffic congestion, increased air pollution, and groundwater depletion could tip the analysis and result in this project failing an economic efficiency test. However, whether this would occur is an empirical question.

In Case C the project or policy intervention passes the economic efficiency test but fails a financial test. Such a project is economically justified but cannot be self-financing. An example might be a wastewater treatment facility with large positive externalities to downstream water users. In this case the economically optimal fee to charge households for wastewater collection and treatment might fail to raise sufficient revenues to pay for these costs. WASH projects designed to provide a variety of services that have been determined to be merit goods may fall into Case C.

3.6 Message No. 6: The Provision of Water and Sanitation Is Especially Prone to Corruption

The issue of corruption in the WASH sector is a reoccurring theme in the case studies students discuss in this course. It can be uncomfortable or surprising for students, but we want them to realize that the countries with poor water and sanitation conditions (where they may want to work) are also countries where corruption is high. Of course, corruption in such economies is not limited to the WASH sector, but we want students to understand six reasons why the WASH sector is especially prone to corruption. First, because the WASH sector is so capital-intensive, there are large flows of funds changing hands. Big construction projects are always opportunities for contractors to pay bribes to obtain contracts. Because financing is required to implement large, capital-intensive projects, bribes may be paid to facilitate deals. Second, because the price elasticity of the demand for piped water services is inelastic in low- and middle-income countries (Nauges and Whittington 2010), a water seller with market power (e.g., a utility, possibility a water vendor) can restrict supply, raise prices, and increase revenues. Students often assume that managers of water utilities operate the utility to serve the public interest, but this may not be the case (Lovei and Whittington 1993; Davis 2004).

Third, because much of the water and sanitation infrastructure is underground, it is difficult for customers to understand the actual physical condition of the infrastructure. It is easy for the providers of water and sanitation services to siphon off financial resources and allow the physical infrastructure to depreciate, or to install inexpensive, low-quality infrastructure but invoice for more expensive, high-quality infrastructure, without the public knowing what is going on. Fiscal malfeasance can be hard to detect until the accumulated liabilities for repairs and replacement of the infrastructure become very large.

Fourth, there is often a lack of transparency in the billing practices of utilities. Utilities typically present customers with a water bill that they do not really understand. In most cases it is difficult for customers to question or challenge how the water tariff structure was used to derive their bill. We have seen cases in which a customer's water bill was not calculated using the official tariff. This can happen when a utility manager needs more revenue and simply requests the accounting department to "tweak" the customer billing software to generate the required increase in revenue.

Fifth, water utilities rarely face the discipline of the market to operate efficiently. Regulators can try to provide incentives for efficient utility operation, but this is a constant struggle. The lack of market discipline means that the costs of corruption can often be hidden from customers and the regulator. Sixth, there are typically many donors and nongovernmental organizations working in the WASH sector, often with different policies and incentives to disburse funds for projects. This means that if one donor objects to a corrupt practice, the government or utility can often obtain the funds from another donor. We want WASH students to understand that opportunities for corruption arise at multiple scales (international, national, regional, city), and it is a multistakeholder practice. Corruption always requires two parties: someone willing to offer a bribe, and someone willing to accept it. Many different stakeholders in the sector may have an incentive to offer a bribe (a contractor, an employee wanting a promotion, a household desiring a lower meter reading), and many different parties may be tempted to accept it (a senior government or donor official with the power to determine who wins a contract, a utility official with the power to deny an applicant a job or decide whether a network expansion will reach a specific neighborhood).

3.7 Message No. 7: Water is Heavy and Expensive to Move, but Grain is Not

The late Tony Allan, Professor at Kings College London and the 2008 winner of the Stockholm Water Prize coined the term "virtual water" to describe his insight that global grain markets can alleviate local water shortages (Allan 2011; Whittington and Thomas 2020a, 2020b). It is typically much easier and cheaper to use water in site A (where water is abundant) to grow grain at site A, and then ship this grain from site A to site B (where water is scarce) than it is to ship water from site A to site B and grow grain in site B.

We believe this insight about the relationship between water and food is important for our students to understand, even though our course is not about regional water resources management. Local water shortages may fail to materialize if peaceful conditions for trade exist and countries have the financial resources to purchase grain from global markets. Egypt is the classic example of a country with limited freshwater supplies that has relied on grain imports to feed its rapidly growing population. Students studying WASH planning and policy need to appreciate the different order of magnitude of water required for irrigation and for domestic use. As a rough approximation, an irrigation scheme requires 1,000 cubic meters of water to grow enough grain for a person to eat for a year. Fifty cubic meters are required to supply an individual with sufficient water for domestic use from a private connection to a piped distribution system (137 liters per capita per day) for a year. Ten cubic meters of water (27 liters per capita per day) are required to meet minimum (basic) requirements for drinking, cooking, and washing for a year.

We use a simple exercise to drive home these relative magnitudes. We ask groups of students to estimate how many cubic meters of water would be required to fill up the entire classroom that we are all in. For purposes of illustration, assume that our classroom has a space of 500 cubic meters (e.g., 10 meters by 10 meters by 5 meters). We then point out that one would need twice the quantity of water of this classroom volume to grow sufficient grain to feed just one of the students in the classroom for one year. However, the water volume of this classroom would be sufficient to supply 10 students in class with water for domestic use from a piped distribution network for a year. The water volume in the classroom would be sufficient to supply 100 students with a minimum supply of water (27 liters per capita per day) for a year.

This exercise illustrates for students the relatively small amounts of water that the WASH sector needs relative to the water needs of irrigated agriculture. And this exercise assumes that there is no recycling of municipal wastewater.

3.8 Key Message No. 8: Water Problems Are Local, Solutions Are Contingent

It is perhaps understandable that both scholars and students seek solutions to water problems that are widely applicable across time and space. But the late Dr. John Briscoe, Global Water Advisor at the World Bank and the 2014 winner of the Stockholm Water Prize, emphasized that "water problems are local, and solutions are contingent" (Briscoe 2014).[6] What Dr. Briscoe meant was that water problems are typically the result of unique local political, social, hydrological, epidemiological, temporal, and cultural circumstances that are unlikely to exist elsewhere in precisely the same configuration. Thus, local decision makers and water planners need to craft their own solutions to fit their specific circumstances in time and place. These solutions may change because they are contingent on a multitude of factors that are themselves evolving and stochastic.

Dr. Briscoe never argued that local policy makers and water resources planners could not learn from the experiences of others in grappling with related problems in their own locations. Indeed, he spent much of his career at the World Bank investigating case studies and describing experiences that he felt would provide useful insights and lessons for others. But the essential point was that local policy makers and water planners would need to find solutions and then adapt them over time. Cookie-cutter applications of solutions transferred from other places were unlikely to work (Briscoe 2011).

Yet this insight that "water problems are local, and solutions are contingent," is not widely accepted in the WASH sector. In the course we give students examples of policy proposals that are framed as "one size fits all" solutions that can be deployed across space and time. One of the reasons that we rely heavily on case materials in this course is that the cases offer students the opportunity to think about local realities outside their existing experience and perhaps taken for granted assumptions. Case studies help students focus on the timing and sequencing of solutions and to move away from simplistic policy advice that is devoid of the local context. We like to tell students that Dr. Briscoe's advice is actually good news for them, i.e., that their skills will be in demand to craft and then adapt local solutions to water and sanitation problems. We also point out that this is a good argument for them not to spend their career working solely in international organizations.

3.9 Message No. 9: Optimal Water Use Is Not the Same as Minimal Water Use

The economist's concept of optimal water use is that the social costs of supplying the marginal unit of water to a customer should equal the social marginal benefits. It is thus possible that a customer's water use is too high (the marginal costs of supply exceed the marginal benefits). But it is also possible that a customer's water use is too low (the marginal costs of supply are less than the marginal benefits). In our experience, this concept of "optimal water use" is not widely understood or shared by WASH professionals and can be conflated with prevailing notions about sustainability.

For households with piped connections, the common assumption is that "water conservation" is always good—the more conservation the better. For example, "water conservation" is often listed as one of the objectives of water tariff design, i.e., that the tariff should promote or incentivize water conservation. If it is clear that the marginal costs of supply exceed the marginal benefits, then reducing customers' water use indeed makes economic sense. However, in many low- and middle-income

[6] Another formulation of this advice was offered by the economist Joseph Schumpeter in his book *Business Cycles* (1939, p. 412): "[O]ne essential peculiarity of the working of the capitalist system is that it imposes sequences and rules of timing … it is not sufficient to be right [about investment opportunities] in the abstract; one must be right at given dates."

countries, water use by many households already is quite low, and WASH planners need to examine carefully whether they really think households should conserve water.

We stress to students that from our perspective water conservation *per se* does not always make economic sense and should not be an objective of water tariff design. For example, households without piped water connections are typically using very little water. WASH planners should not want them to conserve water.

We thus want students to think carefully about how much water customers are using and its relation to the marginal costs of supply. To do this, it is helpful for students to get in the habit of examining the distribution of residential customers' water use at a specific time and location. The best source for these data are the customer billing records from a water utility. Most such distributions have a long tail of high-water users (see Figure 1).

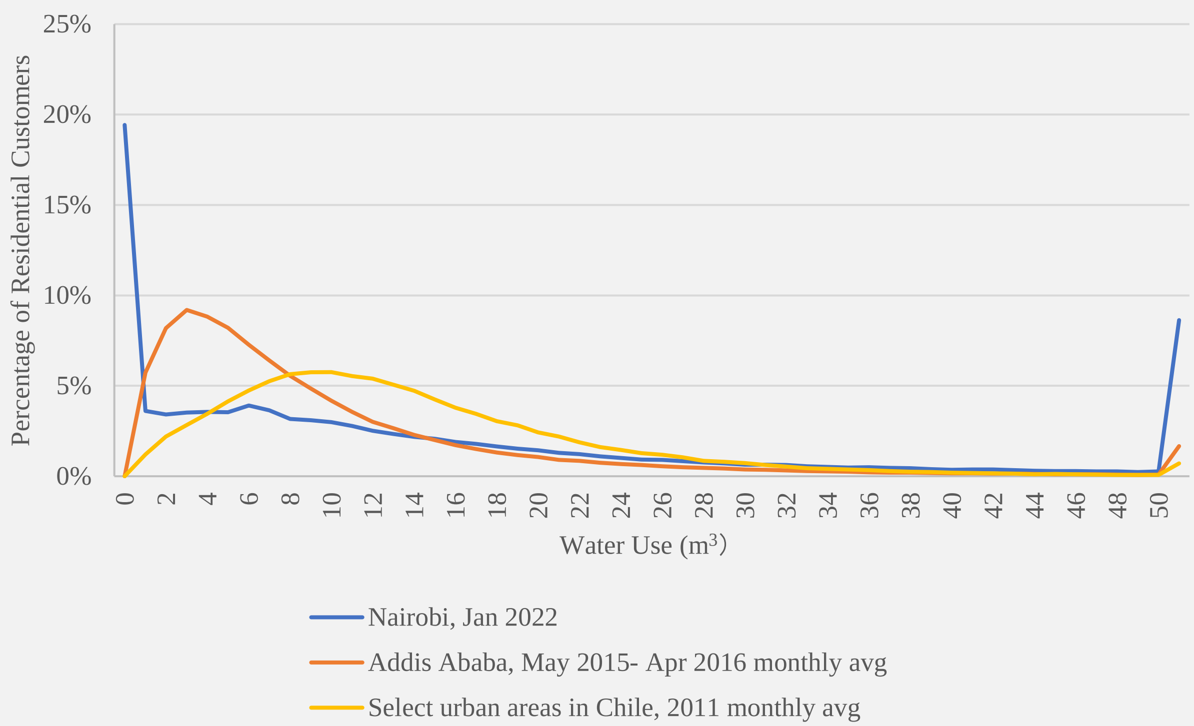

Figure 1: Frequency Distributions of Water Use in Three Urban Areas

Students who are convinced that households should reduce their water use need to think about two strategies: (1) shifting the entire distribution to the left (i.e., incentivizing everyone to reduce their water use); or (2) reducing the water use of the highest water users (i.e., cutting off the righthand tail of the distribution).[7] The choice between these two strategies focuses students' attention on the question of who these high-water users are and why they are using so much water. Are they "wasting" water? Or do they have a good reason for using more water than other customers?

In industrialized countries, one tends to think of high-water users as high-income households that are using more water for residential lawn irrigation and perhaps swimming pools. Students typically have few reservations about recommending policy interventions that attempt to reduce the water use of such households, who they assume are wealthy. However, especially in low- and middle-income countries, customers with high-water use may be households with many members, such as multigenerational households. Also, customers with high-water use may have a business in their home

[7] We are grateful to Professor Michael Hanemann at Arizona State University for pointing out these two strategies to us.

that explains why their household is using more water than households in their neighborhood without a business. It is less clear that such high-water use households are using "too much" water and that WASH planners should focus on cutting off the right tail of the distribution.

When the average water use of households with piped connections is in the range of 100–150 liters per capita per day, as is the case in many low- and middle-income countries, we like to ask students what household water uses should be reduced. Do they think households are taking too many showers (in what might be hot, tropical, or dusty conditions)? Do they think poor households with large families are flushing their toilets too often? Such an exercise helps students reflect on this balancing of the marginal costs of supply and the marginal benefits of additional water use.

This balancing of costs and benefits necessitates an understanding of the long-run supply curve for raw water. Many students come to our course without an understanding of the economics of water desalinization. They implicitly imagine that there is a fixed supply of freshwater that is becoming increasingly scarce due to increasing population and economic growth or perhaps climate change. However, most of the world's population lives near oceans or has access to brackish groundwater. These populations can use desalinization technologies to convert saltwater to freshwater. Coastal populations essentially can have all the raw water supply they want if they can afford to pay for desalinization. Desalinization is still expensive and energy intensive, but the costs have been falling rapidly over the past several decades due to advances in both desalination technologies and solar energy (Hilal, Goh, and Ismail 2023). The problem for these populations is a shortage of capital and energy—or alternatively a shortage of "cheap" freshwater.

There are issues involved in cities becoming heavily reliant on desalinization as a raw water source. Desalinization plants may be subject to natural disasters or intentional sabotage, but then so are other water infrastructure facilities. Desalinization facilities also require an environmentally acceptable approach for brine disposal. Even though the costs of desalination are falling, desalinized water is still too expensive to be a raw water source for irrigated agriculture.

However, recognizing that the supply curve for water for many cities is ultimately horizontal (not vertical) is an essential insight for WASH students. This insight encourages students to look more carefully not only at one raw water source but at a city's portfolio of sources and to think about the concept of optimal water use as a balancing of the costs of water services with the benefits that customers receive.]

3.10 Key Message No. 10: The Magnitude of the Health Benefits of WASH Interventions Is Uncertain, and, at a Specific Time and Place, May Be Modest

Students are surprised and puzzled to learn that the empirical evidence regarding the health outcomes from different WASH interventions is quite mixed (Brown, Albert, and Whittington 2019). This may be due to the heterogeneity of treatment effects in different settings and across households in the same location, as well as the quality of the design and implementation of an intervention. WASH practitioners need to confront the fact that the health benefits of WASH interventions may be modest in a specific time and location.

In the course students review the findings of fourteen randomized controlled trials (RCTs) of CLTS and recent rural sanitation interventions (Radin et al. 2020; Whittington et al. 2020). The results of this RCT research program to evaluate CLTS and related sanitation interventions suggest that the magnitude of the treatment effects was much smaller and uncertain than CLTS proponents once anticipated. Of the ten studies that reported results for reductions in childhood diarrhea, only three found statistically significant decreases, and the magnitude of the decreases in the three studies with statistically significant results was modest.

We want WASH students to come to grips with the policy implications of such results. Student should realize that if the health benefits of a WASH intervention in a specific time and location are small, this does not necessarily mean that the intervention is not justified. WASH interventions have other nonhealth outcomes that people value, particularly time savings. The value of the nonhealth benefits may be greater than the health benefits (Cook, Kimuyu, and Whittington 2016). Students should also realize that even if the health benefits are modest, if the costs of the WASH intervention are modest, the intervention may still be attractive.

Another reason that the magnitude of the health outcomes from WASH interventions is uncertain is that WASH interventions are often part of a multisector intervention. Students often think that WASH investments are like medical interventions, and that health outcomes can be improved without complementary investments in housing, other aspects of community infrastructure, and health care. However, in practice the timing and sequencing of WASH investments need to be coordinated with investments in other sectors. Of course, investing in, say, both modern housing and water and sanitation infrastructure is expensive, but the benefits that accrue to households from multisector investments also can be large.

An important lesson for students is that sound economic analysis is needed to improve the timing and sequencing of such multisectoral investments. WASH practitioners cannot "go at it alone." They need to work together with other planning and government officials to design and implement water, sanitation, housing, drainage, and health care solutions that are tailored to local environmental and political realities.

3.11 Key Message No. 11: Water Policy Debates Occur at Multiple Levels and Scales: Global, National, City, and Household

WASH policy is debated at four main scales: global, national, city, and household. Policy change can be difficult or impossible to implement when WASH professionals working at different scales are not in agreement about what needs to be done. Some WASH professionals are engaged in policy discourse at all four scales, but typically people and their associated institutions are primarily focused on policy debates at just one or two scales. Different policy issues are debated at the global, national, and city scales. We want students to understand these differences and that the role played by economic and financial arguments in WASH policy debates differs across these four scales.

At the global level WASH professionals use economic analysis primarily for policy advocacy, not for resource allocation or budgetary decisions. In our experience global WASH professionals use benefit-cost analysis to make the argument that the benefits of WASH investments dwarf the costs, and thus more international donor funding is justified. Global WASH policy debates are currently focused on the fulfillment of the human right to water and the need for additional financial resources to achieve the Sustainable Development Goals (Heller 2022). Global WASH professionals do not often acknowledge the possibility that some WASH investments would fail a benefit-cost test. Global WASH policy debates rarely focus on the issues of water pricing and tariff design, except to emphasize that tariffs must not threaten the affordability of water and sanitation services. Global WASH policy debates either explicitly or implicitly assume that WASH services should be heavily subsidized.

At the national level, funding for WASH investments is determined as part of a country's budget allocation process. We want students to understand the multisectoral nature of the national budgeting process and to look outside a "WASH silo." For example, if the global policy consensus is that WASH services should be heavily subsidized, it is up to the national government to make WASH a budget priority, which inevitably will entail allocating fiscal resources away from other sectors to WASH expenditures. As another example, at the national scale much of policy discourse that most directly affects WASH services actually involves housing policy. National governments are especially attuned to public concerns about access to housing. Since WASH-related costs embedded in housing are typically of comparable size to the infrastructure costs to supply water and sanitation services to the premises, national policies that affect the affordability of housing have a large effect on the affordability of piped water and sanitation services. A budget reallocation away from housing to the WASH sector may therefore not achieve WASH goals.

We want students to appreciate that when economic analysis is used to help set national budget priorities, WASH investments typically do not figure prominently in the most economically attractive public investments (Lomberg 2012, 2017; National Development Planning Commission 2020). In part this is because in many low- and middle-income countries, WASH funding is captured by middle- and upper-income groups and does little for the poor. It is naturally difficult to mobilize poor households to support policies that do not benefit them.

At the city level, the municipal government and the water utility typically lead WASH policy debates. These officials are concerned about how to meet their service obligations and recover costs. The finances of the water utility are thus a central focus of concern of municipal and utility officials and local stakeholders. Water tariffs are important because they determine customers' water bills and thus the revenues utilities receive. The affordability of water bills often becomes a local political issue.

At the household level, many people lack not only piped water and sanitation network infrastructure, but also modern housing with indoor plumbing. The United Nations Sustainable Development Goal (SDG) 6 for water says that water services should be both "affordable" and available "on the premises." Water and sanitation professionals typically think of the costs of the piped water network to get potable water to the home and the cost of collecting and treating a household's wastewater as the main financial barriers to providing poor households with modern water and sanitation services. However, households also need to make large investments in indoor plumbing, toilets and appliances, and the added floor space needed for showers, toilets, and kitchens to take full advantage of WASH services brought to their premises. Households face tradeoffs between paying for these costs of water and sanitation infrastructure on their property and paying for service providers to deliver water and sanitation services to their property.

Because the provision of high-quality, piped network water and sanitation services is very capital-intensive, how capital investments are financed plays a crucial role in the magnitude of the costs and affordability of WASH services. Such investments will provide services to a water utility's customers for decades, and long-term financing allows these customers to match their payments for services more closely with the time at which services are received. It is not affordable for customers to pay upfront or repay short-term loans for infrastructure that provides services far into the future.

One of the enduring puzzles of the WASH sector is why a simple intertemporal financial deal between lenders and borrowers is so difficult. If the benefits of improved water and sanitation to households are so much greater than the costs, as most WASH professionals argue, why cannot households borrow today to have modern WASH infrastructure installed, and then repay the loan from increased income that results from improved health, time savings from not having to collect water, and cost savings from reductions in a wide range of coping costs (such as purchases from vendors, point-of-use treatment costs, and investments in household water storage)?

Taking a multilevel perspective on WASH sector policy debates can help students better understand this puzzle. During policy debates at each level—international, national, city, household—questions about capital financing for infrastructure hang in the air. Who will be responsible for servicing the debt incurred when large capital expenditures are required to provide improved piped water and sanitation services? At each scale stakeholders may hope to push debt obligations onto someone else, often to someone on another scale. At the international scale, donors push these debt obligations onto national governments. At the national scale, central governments may try to push these debt obligations onto lower levels of government and to utilities. At the city level, questions of where financing will come from and who will incur the debt are especially complex because there are three different groups of stakeholders that need financing for capital investments to improve WASH services.

First, water utilities in low- and middle-income countries—both public and private—need financing to expand network coverage, build water and wastewater treatment facilities, and construct raw water transmission conveyance systems and other non-network WASH infrastructure. But at the city scale, municipal governments and utilities often lack the expertise to structure, manage, and oversee large financial deals. Moreover, municipal and utility officials know that in most cases, there is no consensus among households on what fair, reasonable water bills would be, nor is there agreement among households as to who should pay the higher tariffs needed for the high-quality piped network services provided by a water utility (Truong, Khanh, and Whittington 2020; Fuente, Mulwa, and Cook 2023). When households have not agreed to pay high tariffs for improved services, even low-cost, long-term financing will be insufficient to enable water utilities to provide piped network services to unserved populations. Households then make the individual decisions to self-supply and to purchase services from private-sector providers. Thus, at the city level the intertemporal financial deal between lenders, municipal and utility officials, and households is very hard to finalize, and city-level officials look to higher levels of government for subsidies.

Second, there are many private entrepreneurs that provide WASH-related services that need access to financing to run and expand their businesses and to hire professional staff with the skills needed to improve the quality of services delivered. Tanker truck vendors and wastewater desludging businesses need finance to purchase their trucks. Firms that drill boreholes need financing to purchase drilling equipment and working capital to operate. Bottled water businesses need financing to purchase reverse osmosis equipment. The economic life of trucks, drilling riggs, and reverse osmosis equipment is much shorter than the life of piped water and sanitation networks, so most private sector actors still need access to medium-term financing to effectively provide WASH services. Loans for private entrepreneurs that provide WASH-related services rarely come from higher-level government or donors. Instead, medium-term financing is typically provided by the extended family, private money lenders, and commercial banks.

Third, households themselves need capital financing to fully utilize water and sanitation services in their dwelling units (Whittington 2020). Financing for households to construct and rehabilitate their housing units so that they can utilize the WASH services provided to their premises is rarely considered as part of WASH financing requirements. Yet if households do not make substantial private capital expenditures on their housing units to bring WASH services for cooking, cleaning, washing, and waste removal inside their house, the health and nonhealth benefits of improved WASH are likely to be limited. Long-term mortgage financing for upper-income households may be available at the national scale but is typically “invisible” to WASH professionals. Financing is rarely available from official financial institutions or donors for poor households for such housing expenditures. Instead, poor households typically access capital from personal savings, extended family, and private moneylenders.

This multilevel perspective encourages students to focus on the influence of financing on the design of WASH infrastructure and who ultimately incurs the debt obligations that long-term financing entails. Alain Bertaud (2018) has argued that cities are built the way they are financed. We want students to recognize that the same is true of water and sanitation infrastructure. We also want students to recognize that broad policy debates are occurring at all four scales and that policy consensus at one scale does not necessarily result in progress at other scales. Change occurs when policies at multiple scales align (Geels 2006, 2010).

4 Case Studies

A central component of our course is discussion of case studies. We want students to be aware of what has happened in the water and sanitation sector in terms of both provision of services and policy interventions. We have used many cases during our years of teaching this course, and we are always looking for new ones. We use case study discussions to illustrate the eleven key messages described above and other issues.

Table 3 presents the main case studies that we have used over the years along with the associated readings and video materials that can accompany each. These are arranged in order of the sequence in which we present them to students across the fourteen sessions, in line with the policy model we use to organize the course. The case studies cover locations all over the Global South. Some describe situations that are now quite old; others are new. We tell students that we believe that there are important lessons to be learned from history, and not to look at "old cases" as out of date. We believe that it is useful for students to know how WASH professionals in the past thought about problems posed by these cases. There are lessons to be learned from both successes and failures, and it is possible and necessary to change our opinions as new practices and evidence emerge.

When selecting cases for a course with such a wide geographic scope and that will run for many years, it is important for instructors to reflect on how contextually independent the chosen cases are, whether learning is transferable to other settings, how much "closure" a case involves, and whether the cases are "finished" or are ongoing events and processes (Whitley 2008). We deal with these issues by including several cases we consider "iconic" (Phnom Penh water sector reform, Chilean subsidy design, Manila water privatization, Orangi low-cost sewers, Brazil condominial sewers, management of the Cape Town Drought, UK price regulation model). We almost always use these cases in the course. In our opinion, WASH students need to know these stories and be able to draw their own lessons from these experiences. We deliberately include here the privatization and regulatory experience of the UK, though not a low- to middle-income country.

The UK water privatization and regulation experience has been discussed and debated throughout the world, including in low- and middle-income countries. We believe that using the UK water privatization and regulation as a case study enables students to develop a nuanced understanding of the UK experience and to reflect on its transferability to a low- or middle-income context. Other cases are more easily substituted with new materials that may better illustrate a "hot" policy issue with which students should be familiar to be up-to-date with the literature.

5 Participation and Assessment: Debates, Cost Calculations, and Policy Memos

5.1 Class Debates

Creating the two MOOCs gave us prerecorded lectures that students could watch outside of class, giving us more class time for discussion, participatory group exercises, and student presentations. One format we used was class debate. The process used to develop these debates was exploratory. In-class debates are known to potentially improve students critical thinking and collaboration skills (Brown 2015). To assess whether this format was including or excluding students and their perspectives, we informally monitored levels of participation and whether students were experiencing any difficulties. For the debate structure, we give students a "proposition" to focus the debate and create a small group (typically 2–3 students) to argue in favor of it ("Pro side") and 2–3 students to argue against it. The majority of the students remain in the audience, but have an important role to ask both the pro and con sides questions after their presentations, and then to judge which side they think "won" the debate.

Table 4 presents the organization of a typical class debate. We ask the pro side to begin with a 15-minute opening statement, following by a 15-minute opening statement from the con side. Then the pro side gets an opportunity for a 5-minute response, followed by a 5-minute response from the con side. We then open the floor to questions from the audience for both sides.

Table 3: Examples of Case Studies

Session	Topic	Location	Readings and Resources	Key Messages Covered
1	Water vending	Onitsha, Nigeria	Whittington, Lauria, and Mu 1991	3, 6, 11
2	Water vending, affordability	Coastal Bangladesh	Hoque and Hope 2019	2, 5, 8
3	Water vending, coping costs, household demand for improved services	Kathmandu, Nepal	Whittington et al. 2002; Pattanayak et al. 2005; Raina et al. 2019	3, 6, 7, 10
4	Corruption, water vending	Port au Prince, Haiti	Fass 1988; PBS Frontline "Battle for Haiti," http://video.pbs.org/video/1737171448	2, 6, 8
5	Water development paths	Netherlands	Geels 2006; Whittington et al. 2023	2, 3, 5
6	Condominial sewers	Brasilia and Salvador, Brazil	Melo 2005; Nance 2012; multiple videos from the Appropriate Sanitation Institute: https://www.appropriatesanitation.org/	1, 3, 8
7	Low-cost sewers, participation	Orangi, Pakistan	Hasan 2023; video interview of Arif Hasan conducted by Diana Mitlin https://youtu.be/WBubv3VvUm0; "Orangi City of Hope" video documentary	1, 3, 8
8	Drought management, selection of policy interventions	Cape Town, South Africa	Muller 2017; City of Cape Town 2019; Leonie and Ziervogel 2019; Visser and Brühl 2019; Ziervogel 2019; Kohlin and Visser 2023	5, 7, 8, 9
9	Water tariffs	Nairobi, Kenya	Fuente et al. 2016	1, 4, 9, 10
10	Design of subsidies	Chile	Gómez-Lobo and Contreras 2003; Contreras, Gómez-Lobo, and Palma 2018	4, 10
11	Privatization	Manila, Philippines	Beer and Weldon 2000a, 2000b; Dumol 2000; Wu and Malaluan 2008; Wu, Jensen, and House undated; Video: Manila Water Company Philippines, https://youtu.be/6bJr-aeOsNk	1, 4, 11
12	Privatization	Cartagena, Colombia	Lee 1998	1, 10, 11
13	Sector reform	Phnom Penh, Cambodia	Ching 2009; Biswas and Tortajada 2010; The Connection: https://youtu.be/HBaSjmxXg0w	5, 8, 11
14	UK utility economic regulation model	United Kingdom	Littlechild 1988; Beesley and Littlechild 1989; Gassner and Pushak 2014; video interview with Stephen Littlechild: https://youtu.be/cKv68aRxIM4	1, 9, 11

Table 4: Class Debate Format
• Pro – Opening Statement (15 minutes)
• Con – Opening Statement (15 minutes)
• Pro – Response (5 minutes)
• Con – Response (5 minutes)
• Audience can ask questions of either the pro or con side
• Audience judges the outcome

When there are no more questions from the audience, we judge the outcome. We ask each student in the audience two questions: (1) Did they support or oppose the proposition before the class debate? and (2) Do they support or oppose the proposition after the debate? Their answers place each student in the audience into one of the following four groups shown in Table 5.

Table 5: Approach for Judging the Outcome of the Debate

Student position	Before the debate I supported the proposition	Before the debate I opposed the proposition
After the debate I supported the proposition	Group 1 Support → Support [no change]	Group 2 Oppose → Support [changed to pro side]
After the debate I opposed the proposition	Group 3 Support → Oppose [changed to con side]	Group 4 Oppose → Oppose [no change]

We tell the students that the "winner" of the debate will be the side that changed the most minds. There are limitations to this approach to judging success. It will be most effective when the audience is initially evenly split between supporting and opposing the proposition. One could also calculate the percentage of the students who changed their minds by the arguments made by the pro and con side. However, this simple approach for judging the outcome of the debate creates a simple, fun classroom exercise.

As all the students in the audience make their marks into this table drawn on a whiteboard, it becomes clearer which side will win the debate. We typically ask the audience members to reflect on why one side won, and on the arguments presented by both sides they found most persuasive. We then ask the members of the pro and con side to offer their reflections on the debate.
Table 6 presents some propositions we have used in these class debates. Often, we select a proposition that is topical or controversial in the WASH sector at the time the course is being offered.

5.2 Class Calculations of Intervention Costs

We have found that students have difficulty appreciating the capital intensity of piped water and sanitation services when they are simply presented with an estimate of the aggregate capital cost of a water and sanitation investment. It is much easier for students to appreciate the magnitude of capital costs when they are expressed in the same units as a household water bill (dollars per household per month). We have thus devised a group exercise to take students through the calculations necessary to translate estimates of total capital costs and annual operating and maintenance costs to equivalent household costs per month.

This requires that we introduce students to the concept of and formula for a capital recovery factor. We show students how the capital recovery factor changes with the assumed life of the capital and the interest rate. We discuss the pros and cons of using a real versus nominal interest rate in this

Table 6: Examples of Debate Propositions

Debate Topic	Propositions (Suggested Readings)
Human right to water	The United Nations Declaration establishing a human right to water and sanitation is a big step forward and will result in many more poor households receiving improved WASH services in the future. (Briscoe 2011; Burgess et al. 2020; Heller 2022; Resolution A/RES/64/292. United Nations General Assembly, July 2010. Available at: http://www.un.org/es/comun/docs/?symbol=A/RES/64/292&lang=E)
Health risks of poor water and sanitation conditions	The health risks from poor water and sanitation are a relatively small, unimportant part of "portfolio" of risks confronting poor households in low-income countries. (Collins et al. 2009; Landrigan et al. 2018; Fuller et al. 2022)
Economic value of water and sanitation infrastructure	The majority of water and sanitation infrastructure in low-income countries is best conceptualized as "dead capital." (De Soto 2003)
Ethics of Randomized Controlled Trial (RCTs)	Any risks associated with RCTs in low- and middle-income countries have been overblown and should not impede WASH-related research. (Coville et al. 2020; Deaton 2020; https://twitter.com/joshbudlender/status/1292170843389386761)
Privatization, regulation	UK private water companies should be returned to public ownership. (Helm and Yarrow 1988; Bartle 2003; Helm 2005; Barraque 2012)

calculation. Then we have students multiply the total capital costs of a project (such as a condominial sewer system,improving rural piped water systems, or the very large UK Thames Tideway Tunnel project), by a capital recovery factor to obtain an estimate of total annual capital cost of the project.

Each student group next adds the annual capital cost and the annual operations and maintenance costs to obtain the total annual cost of the investment. We then discuss how many people will use this investment and how many people who use the project should share the costs. We also discuss whether to use the current population or an estimate of the future population. We have students assume an average household size. Dividing the assumed population by household size gives them the number of households served. We tell them to assume that the investment will only serve residential customers; this thus gives them an annual cost per household. The assumptions about the size of the population served and the household size raise important questions about the trajectory of annual costs over time and intergenerational equity that can be discussed.

Finally, we have student divide the total annual cost per household by twelve to obtain an estimate of the total cost per household per month. This estimate can then be compared to an average household water bill to give students a sense of what proportion of the total costs households are currently paying in their water bill and what they would have to pay to achieve full cost recovery. We encourage students to conduct sensitivity analyses on the uncertain parameters in this sequence of mathematical calculations to test how the results change with different assumptions about the life of the capital, the interest rate, population, and household size.

It is useful for students to do this calculation for both a small rural community and for a large city in order to appreciate the effect of economies of scale in the costs of capital investments on costs per household per month.

5.3 Policy Memo Format Assignments

We wanted students to learn to write in a style and professional format actually used in the WASH sector. We thus require students to write their course assignments as short (3- to 5-page) "policy memos" (for an example assignment see Annex 2, an example final exam using policy memos is shown in Annex 3). Assignment instructions were written as real-world tasks that also introduced the idea to students that WASH problems are often "wicked." There may or may not be sufficient existing evidence, and there may be no obvious policy prescription to offer. Writing in this format helps student learn not only how to mobilize evidence relevant to policy and practitioner needs, and to provide well-argued recommendations, but also to have an acute sense of caveats and limitations of available evidence.

We found that writing policy memos was new to most of our students. For our Manchester students, we therefore issued two assignments for each class. The first was a formative piece, with feedback given but no mark was assessed. The second assignment was summative, and was issued only after each student had received feedback on their formative work. This gave students one opportunity to "get it wrong" and to learn, opening up critical thinking and flexibility. This seemed especially useful for individuals new to the policy memo format and to writing about complex and challenging policy topics. Examples of assignment topics we set are presented in Table 7. We also wrote into our assignment briefs clear guidance about what role we wished students to adopt and the expected tasks. We told students that we would adopt a simulated professional role during the assignment period (indicating to students that if this were a real professional assignment, their supervisor issuing it would probably not want to respond to multiple requests for guidance). We also provided students with both written and video guidance on how to write a policy memo.[8]

Over the years of running the course, we built up a knowledge base of how students had attempted each assignment. This allowed us as instructors to learn what students found challenging about the assignments, which concepts from the course could be most effectively mobilized when attempting the assignments, and how best to help students write in a policy memo format. We provide students with not only feedback on their individual assignment, but also feedback on how the class had performed with the assignment overall that year and in previous years.

For several years, we invited actual WASH sector professionals to provide part of the formative feedback to students. Selected students would present their policy memos in class and argue for their proposed solutions. The WASH professional then evaluated the student's work, drawing upon their own professional experience. We found students really enjoyed and valued this close-to-practice approach, and we believe it provided students with realistic preparation for working in WASH sector.

6 Reflections on Teaching with MOOCs

Finally we offer short reflections on teaching this course online on Coursera as two MOOCs. During 2010 to 2018, teaching across U.S. and UK classrooms, we reached around 300 students. By contrast for the six years the material has been online to date, around 42,500 students have enrolled with a 7.5-percent average completion rate, meaning around 3,200 students have finished these MOOCs.[9]

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[8] https://www.youtube.com/watch?v=_Y1Kuq5NK_8.

[9] A highlight of running the MOOCs was that diverse learners from multiple countries enrolled. For the 2013 to 2014 run, students from 191 countries took part, with 42 percent from emerging economies and 40 percent female. Advertising the course via WASH sector networks and mailing lists, and having Global Water Partnership endorsement helped this uptake, and to reach emerging economies and learners outside major cities. From 2017 until late 2022, the courses still have 40 percent female students, ranging from 18 to 65+ years old. More than half the MOOC learners are from India, and 20 percent are from Africa, contrasting with Coursera typically having most learners from the United States and 5 percent from Africa. Around 57 percent of MOOC students are not currently in education, with 45 percent employed full-time and 40 percent already having a Masters degree. This suggests we reached educated professionals, perhaps some re-training while already in WASH-related roles.

Table 7: Examples of Policy Memo Assignments

Assignment Topic	Role Adopted by Student	Associated Learning Outcomes
Performance indicators to evaluate UNICEF's rural water supply and sanitation programs in Africa	Policy analyst in the office of the Chief of Water, Sanitation and Hygiene at UNICEF, leading an ex-post evaluation using at most four indicators.	Students think of simple indicators that work without baseline data and within a modest cost evaluation.
Reforming water tariffs in Egypt	Policy analyst advising Egyptian government on whether reforms are needed to current water tariff arrangements.	Students explore information treatments to convey to customers and policy makers whether current tariff structures need to be changed.
A sanitation policy for India	Policy analyst for a World Bank Water and Sanitation Program field office, proposing policy instruments to achieve the "Clean India" campaign.	Students assess previous experiences in India and other countries, and think about how different policy instruments interact in a given context.
Monitoring global WASH affordability	Policy analysts taking a fresh look at how the UNICEF/WHO Joint Monitoring Program monitors global WASH affordability.	Students critically reflect on costs of providing WASH in a context of climate change, and rising standards found in the Sustainable Development Goals (SDGs).
Re-nationalizing the England and Wales water industry	Policy analyst for the UK Regulatory Policy Institute reporting on possible benefits and costs of water sector re-nationalization to an All Party Parliamentary Water Group session.	Students assess evidence about the effects of ownership on economic and environmental performance of water utilities.

While the throughput from enrollment to completion is obviously lower than for a classroom setting, the MOOCs enabled us to reach an order of magnitude of more students. The MOOC format forced us to improve our class materials. Visuals needed to be clearer, and insights need to be presented in concise, easy-to-follow ways. We were also able to re-use the produced video materials in the classroom, and for students to watch before or after classes.[10]

Downsides are that the design of Coursera, like most MOOC platforms, limits control over the learning conditions of students. Greater numbers of learners also means significantly reduced contact with them compared to a classroom, on-campus course. For the first run of part one in 2014, it was a one-off course, and we had a team of 12 people (including ourselves), with five part-time teaching assistants. These teaching assistants were former students from the Manchester classroom version of

[10] We were also able to meet other course instructors at two Coursera conferences in 2015 and 2016, to share ideas about re-using MOOC materials in the classroom.

the course. The classroom experience enabled the teaching assistant to engage productively with students via message boards and forums inside Coursera. We also had some direct interaction with MOOC learners through email contacts. For the MOOC runs since 2017, these were opened for separate enrollment each week, and similar resources were not available to support them. We did not have teaching assistants, material could not be updated or revised, and we have had far less hands-on involvement over time.[11]

Similarly, producing the two MOOCs turned out to be much more work than we expected, involving a significantly expanded workflow compared to a typical classroom course. We also did not have the resources to update our MOOCs with newly recorded materials. Running MOOCs with consistently high levels of interactions with students would also cost more. We have no regrets about the work involved in producing these MOOCs, but instructors contemplating launching a MOOC should go in with “eyes wide open.”

7 Concluding Remarks

While running this course across a U.S./UK classroom and as MOOCs with a global reach, we tried to teach water economics and policy in ways that exemplified and embedded attitudes and working practices we wished students to take forward into their potential future careers in the WASH sector. We have also been able to distill eleven key messages that are present across the course materials, which we believe are relevant and useful for students to engage with. We aimed to teach water economics and policy in ways that encouraged active class participation with materials and exercises that were informed by practice. We also brought in WASH practitioners to take part in formative assessment of student assignments, to increase the quality and relevance of feedback they received, and to afford students insights into the future challenges of working in this sector.

Through the cases, videos, recorded lectures, debates, class cost calculations, policy memo assignments, and guest lecturers, we tried to stress the importance of not learning in the abstract, but through studying successes and failures of policy interventions around the world. We highly recommend considering these aspects when designing and running courses of this kind in the future. From the evidence of our classroom course, MOOC appraisals, and indications that the MOOCs were reaching working professionals, we believe these elements were also well received by learners. However, it should be noted that developing courses in this way involves mobilizing contributions from a diverse range of people and countries, and materials that may lie outside the scope of traditional university department organizations. It also requires cultivating over the years guest participants who become familiar with learning aims and intended outcomes of such a course.

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[11] Considering how to resource MOOCs long-term is therefore an important consideration. This includes planning what happens if instructors, as we both did, later change university positions. Our strategy here was to also upload our course materials to YouTube so they remain free to access. Part one is available here: https://www.youtube.com/playlist?list=PLO0Q0P_Y4YulwSmXupshcwVR798iNvdJ1; part two is here: https://www.youtube.com/playlist?list=PLO0Q0P_Y4Yunpl0i551N5zPQGgyX0BdQl. Some MOOC platforms, and university faculties, might not allow this, depending on their strategies (Thomas and Nedeva 2018).

Annex 1: Course Syllabus

The following is an overview of the 2022/2023 academic year syllabus for the Chapel Hill in-person class (a full syllabus is available upon request from the corresponding author). The course uses a two-part policy model, where in Sessions 1 to 6, typically taught over six weeks, students are introduced to key status quo conditions for water and sanitation access and provision in low- to middle-income countries. Sessions 7 to 14, taught over the following eight weeks, next invite students to critically reflect on a series of cases of actual policy interventions, using the understanding they have developed in the first part of the course.

Part 1: Understanding Status Quo Conditions

Session 1 – Introduction, Conceptual Framework, Ancient Instincts

- Introduction, Course Organization
- Student WASH experiences
- Conceptual Framework Discussion of course requirements
- Key Messages

Session 2 – Infrastructure Coverage, Dynamic Baseline, Climate Change

- Class discussion—questions about videos (MOOC materials watched outside class)
- Lecture: Forecasts of coverage, WASH SGDs: discussion of new targets and affordability
- Student-led discussion of two papers on economics of water affordability, with cases on Bangladesh and the United States

Session 3 – Water Vending, Corruption

- Class discussion—questions about videos
- Lecturer-led discussion of paper on the structure of water vending markets in Kathmandu, Nepal
- Class Debate No. 1 (USAID Aid to Haiti – Proposition: USAID should not invest in water and sanitation projects in Haiti at this time)

Session 4 – Understanding the Supply Side, Costs, and Technologies

- Class discussion—questions about videos (MOOC materials watched outside class)
- Lecturer-led discussion of paper who pays for water, based on life-cycle costs of water services among low-, medium-, and high-income utilities; also discussion of costs of water and sanitation services embedded in housing
- Discussion on condominial sewers

Session 5 – Understanding Demand for Improved Water and Sanitation Services

- Class discussion—questions about videos (MOOC materials watched outside class)
- Student-led discussion of paper on piped water adoption in urban Morocco
- Assignment No. 1 due: Student presentations of their assignments

Session 6 – Water Development Paths

- Class discussion—questions about videos (MOOC materials watched outside class)
- Student-led discussion of a paper on a multilevel perspective transition from cesspools to sewer systems (1840–1930) in the Netherlands
- Teaching Case No. 1 (Orangi pilot project)

Part 2: Policy Interventions

Session 7 – Planning Protocols, Sustainability of Rural Water Supply Projects

- Class discussion—questions about videos (MOOC materials watched outside class)
- Discussion of papers on evaluating waterpoint sustainability and revenue collection in rural Kenya, on handpump sustainability in Ghana, and demand-driven community managed rural water supply systems in Bolivia, Peru, and Ghana

Session 8 – Information Treatments

- Class discussion—questions about videos (MOOC materials watched outside class)
- Discussion of community-led total sanitation
- Class Debate No. 2 (The Human Right to Water – Proposition: The United Nations Declaration establishing a human right to water and sanitation is a big step forward and will result in many more poor households receiving improved WASH services in the future.)

Session 9 – Water Pricing and Tariff Design

- Class discussion—questions about videos (MOOC materials watched outside class)
- Discussion of papers on water and sanitation service delivery, pricing, and the poor in Nairobi, Kenya, and on the development path of water and sanitation tariffs and subsidies in China

Session 10 – Designing Subsidy Schemes to Reach the Poor

- Class discussion—questions about videos (MOOC materials watched outside class)
- Questions about a paper on choosing among pro-poor policy options in water supply and sanitation
- Student-led discussions of a paper on, and on water subsidy policies in Chile and Colombia, and on distributional impacts of water subsidy policy in Chile from 1998 to 2015

Session 11 – Changing Institutions: Privatization

- Class discussion—questions about videos (MOOC materials watched outside class)
- Assignment No. 2 due: Student presentations of their assignments
- Teaching Case No. 2 (Manila Privatization)

Session 12 – UK Privatization: the Regulation of Water Utilities

- Class discussion—questions about videos (MOOC materials watched outside class)
- Student-led discussion of a paper on the impact of the privatization of water services on child mortality

- Class debate No. 3 (Return to Public Ownership – Proposition: The private water utilities in England and Wales should be returned to public ownership.)

Session 13 – Case Study: Phnom Penh Water Supply Authority

- Class discussion—questions about videos (MOOC materials watched outside class)
- Teaching Case No. 3 (Ek Son Chan and the Transformation of the Phnom Penh Water Supply Authority)

Session 14 – Wrapping Up, Student Presentations of Assignment No. 3

- Class discussion—questions about videos (MOOC materials watched outside class)
- Assignment No. 3 due: Student presentations of their assignment
- Preparation for final assignment/exam

Annex 2: Example Policy Memo Assignment: Propose Four Performance Indicators to Evaluate UNICEF's Water Supply and Sanitation Programs in Africa

What role do you want me to adopt?

We want you to imagine that you are working as a policy analyst in the Office of the Chief of Water, Sanitation, and Hygiene at UNICEF.

What type of task do you want me to undertake?

The Chief wants you, in your role as policy analyst, to lead an upcoming ex-post (after the fact) evaluation of UNICEF's water supply and sanitation programs in Africa. She informs you that the forthcoming evaluation should use at most four performance indicators (criteria). She also explains that you should not assume that you have access to any reliable, accurate baseline data from households or communities before UNICEF started working in the African countries concerned.

What does my specific task involve?

Before the evaluation is done, the Chief wants you to write a four-page "policy memo" that you will submit to her. In your policy memo, you should propose the four performance indicators that you intend to use. Before you depart, the Chief wants to discuss with you the four performance indicators that you propose in your policy memo. The Chief wants you to be sure that your four proposed performance indicators (criteria) are both practical and measurable. She also explains that you need not be overly concerned with the resources required actually to conduct the upcoming evaluation. At the same time, the Chief is clear that the cost of the evaluation should be reasonable, and certainly the evaluation should not cost more than 5–10 percent of the total program cost. She emphasizes to you that this is not a research effort. This means it should be feasible to measure your four proposed performance indicators without needing teams of research scientists with PhDs.

What else should I consider?

Your four performance indicators should consider the fact that UNICEF water, sanitation, and hygiene programs are implemented in partnership with government departments, which UNICEF seeks to strengthen. Ideally your proposed performance indicators should be applicable to different levels of rural water and sanitation services (by which we mean public taps, hand-pumps, protected springs, yard taps, and connections inside the home for the exclusive use of household members, and improved pit latrines). If you believe that this is not practicable, then you should make this argument in your memo, and explain how the performance indicators you propose would change for different levels of service.

Please make sure to identify clearly each of your four performance indicators (criteria) and specify how you plan to measure them. Bear in mind that your suggestions will aid in the design of an evaluation effort to compile quantitative measures for comparisons across programs.

Annex 3: Example Final Exam

Instructions

Your task in this exam is to select one of the four "clusters" of questions below and have a short dialogue with ChatGPT ("Chat") about these questions. You are not limited to the specific questions listed in an option below that you choose. You can ask a follow-up question depending on ChatGPT's answer to your previous question, but you should not initiate more than 5 queries or requests. You can use any version of ChatGPT that you wish. You should then write a policy memo (maximum 2000 words) that critiques the answers you have received from ChatGPT. If for some reason you are unable to access ChatGPT, you should explain the circumstances that prevented you from accessing ChatGPT, and then simply answer the questions in one of the four options below.

Your critique should be based on your study of the materials in this course (readings, lectures, teaching cases, guest lecturers, assignments, etc.). Your policy memo should explain what you agree with, what you disagree with, and the reasons for your answers. You can also conceptualize your policy memo as a way to tell your supervisor "what ChatGPT should have said" i.e., what would have been a better ChatGPT answer given your own knowledge of water and sanitation problems in developing countries.

This exam is an "open-book", take-home exam. You can work anywhere you like and use any written sources you like, including course notes, case studies, publications, the internet, etc. However, no help may be received or given from other students (or anyone else) on this exam.
No questions will be entertained during the exam, nor will any clarification of the instructions or questions be offered. If you feel the instructions or any of the questions are ambiguous or unclear, please state how you choose to interpret the question and answer the question as best you can.

Select one and only one of the following four question clusters for your chat with ChatGPT:

Option 1: Household Water Use Behavior
- Write a 10,000-word essay on the main determinants of the quantity of water that household uses.
- How does the technology a household uses the affect the quantity of water a household uses?
- How do emotions affect household water use?

Option 2: Systematic racism and colonialism
- Is systematic racism a major reason that poor households in developing countries have poor water and sanitation infrastructure?
- Is colonialism a major reason that poor households in developing countries have poor water and sanitation infrastructure?
- Are system racism and colonialism the most important reasons that poor households in developing countries have poor water and sanitation infrastructure?
- What is the best approach to reducing system racism and colonialism in the WASH sector?

Option 3: Privatization
- Is privatizing a public water utility a good way to improve water and sanitation services?
- Can a water privatization help poor households obtain better water and sanitation services?
- What are the main problems that result from privatizing a public water utility?

Option 4: Water Tariff Design
- Is an increasing block tariff a good way to price residential water supplies?
- Are there any situations where an increasing block tariff might be inappropriate?
- Is an increasing block tariff a good way to charge businesses and industrial water users?

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Teaching and Educational Methods

Teaching Water Economics by Building Problem-Based Case Studies

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Abstract
Academic economists have many insights to contribute to water management at all scales. These contributions need to be placed in local institutional contexts and reconciled with insights from other disciplines if they are to affect policy, action, and evaluation. Case studies offer a useful way to organize different lines of thinking in the classroom or the field. This article reviews these factors—academic vs. practical perspectives; economic vs. other disciplines—and provides a framework for teaching water economics by building problem-based case studies.

1 Teaching and Understanding Complexity

> "*They're specialists, the whole lot of them, and they don't believe in a method of work which cuts into every field of science from botany to archaeology. They limit their own scope in order to be able to dig in the depths with more concentration for details. Modern research demands that every special branch shall dig in its own hole. It's not usual for anyone to sort out what comes up out of the holes and try to put it all together.*" —Heyerdahl (1950)

> "*If you're so smart, why ain't you rich?*" —McCloskey (1990)

> "*An expert knows more and more about less and less until they know everything about nothing.*" —Early 20th-century thinkers[1]

Economics is a powerful discipline that makes clear predictions about human behavior in specific circumstances. Since these circumstances do not hold in many instances of real life, there is a risk that economic insights are useless, confusing, or counterproductive. The quotations above illustrate the durability of a vexing paradox: too many smart ideas resulting in too few real-world improvements. The paradox indicates an opportunity—in fact, a dire need—to better match the supply of economic ideas to the demand for good ideas. Such an improvement will increase welfare for everyone.

In this paper, I discuss how case studies can improve the match between supply and demand for insights, on two margins. On the intensive margin, case studies help organize and focus economic insights to find useful solutions to existing problems. On the extensive margin, case studies raise new questions that deserve more attention from economists.

Note that I am using "case study" in the general sense of examining a particular area and situation. Case studies can take years to assemble, run for hundreds of pages, and involve a lot of data and deep analysis, but they can also be constructed in a short time with limited inputs and partial

[1] This saying evolved between 1911 and 1933 (https://quoteinvestigator.com/2017/10/25/more/).

analysis. Published cases tend toward the former, with "serious" characteristics;[2] classroom projects tend toward the later, with "superficial" characteristics. That said, it is difficult to define a bright line between superficial and serious, as one can clearly change to the other with additional time and effort. Although this paper focuses on the initial steps of building a case study—via a student project undertaken during a teaching term—it does not imply that such cases are without insight, opportunity for refinement, or potential publication.

Case-study building teaches water economics in three ways. First, case studies allow one to dive into rich but messy stories. Since water issues often depend on unique institutional characteristics, they are better suited to case study than abstract or general models.[3] Second, case studies naturally invite *x-disciplinary* perspectives and contributions, which can break through academic silos.[4] Third, case studies can be matched to teaching goals and constraints.

To "make the case for cases," I explore the boundaries between academic and practical perspectives on water (§2), argue that water issues deserve x-disciplinary treatment (§3), and explain how I use cases to teach a nonspecialist course in water economics (§4). My goal is to show how case studies can be used *not just* for exploring details in the classroom or reconciling academic perspectives *but also* for understanding real-world challenges—challenges that are increasing as climate change alters water cycles.

Before I get going, let me position this paper in the context of this journal. Economics is taught at many levels, from high school to PhD. Economics is used in an even broader range of settings. These patterns also apply to the teaching and use of water economics, so it is important to pitch ideas and techniques at the appropriate level and/or audience. In this paper, I am drawing upon my experiences teaching undergraduates as well as my interactions with policy makers, professionals, and the public. I am therefore going to describe how case studies can be used at any level, not just as a complement to academic textbooks. Readers (as teachers) should have no problem adding steps or constraints to encourage and challenge students of all backgrounds, disciplines and experiences.

2 Water Issues Are Real-World Issues

It takes time to understand water management. We all bring cultural, disciplinary, and institutional perspectives to water-as-a-topic, and we all need time to reconcile our perspectives. Cultural differences in language, history, and geography take time to identify, let alone master. Some institutions ("the rules of the game") are stable and fixed; others expand and contract with social trends (Coase 1998; Williamson 2000; North 1990).

Any course in water economics needs to consider local conditions and constraints that reflect and affect local water-managing institutions (Ciriacy-Wantrup 1969; Easter, Rosegrant, and Dinar 1999). This diversity means that case studies are relatively more useful in a water course. Case studies can help organize complexity into a narrative that the researcher and reader—or the student and teacher, or the academic and civilian—can follow, question, and understand. This accessibility is due to the way that case studies force consideration of multiple disciplines, acknowledgement of the messy details of history and institutional path dependency, and reliance on the practical sides of water management—all while focusing on a concrete example.

Local institutional diversity also means that academic ideas must be compared, conversant, and complementary to practical realities. Section 3 explores how to harness and reconcile academic

[2] For examples, consider Ostrom (1965); Loaiciga and Renehan (1997); Ehrhardt and Janson (2010); Reynaud (2013); Venkatachalam (2015); Sanders (2016); Donoso (2017); Zetland and Colenbrander (2018); and Elhadj (2022).
[3] Elinor Ostrom's PhD dissertation on groundwater management in one region of Southern California sprawls to 600-plus pages (Ostrom 1965).
[4] The "x" in "x-disciplinary" stands for cross-, multi-, trans-, and whatever future prefix academics attach to "-disciplinary." I will not attempt to clarify how they differ or which might be more appropriate for a given situation.

diversity; this section focuses on balancing academic and practical perspectives on water management.

Figure 1 relates academic and practical perspectives by placing the economics–x-disciplinary range on the x-axis and the academic–practical range on the y-axis. Although a topic might appear anywhere within the figure, I've divided the space into four boxes to highlight potential combinations, from academic economics (value, in theory) to practical x-disciplinarity (outcomes, in reality) on the diagonal and practical economics (proposing ideas) and academic x-disciplinarity (exploring complexity) on the off-diagonal.

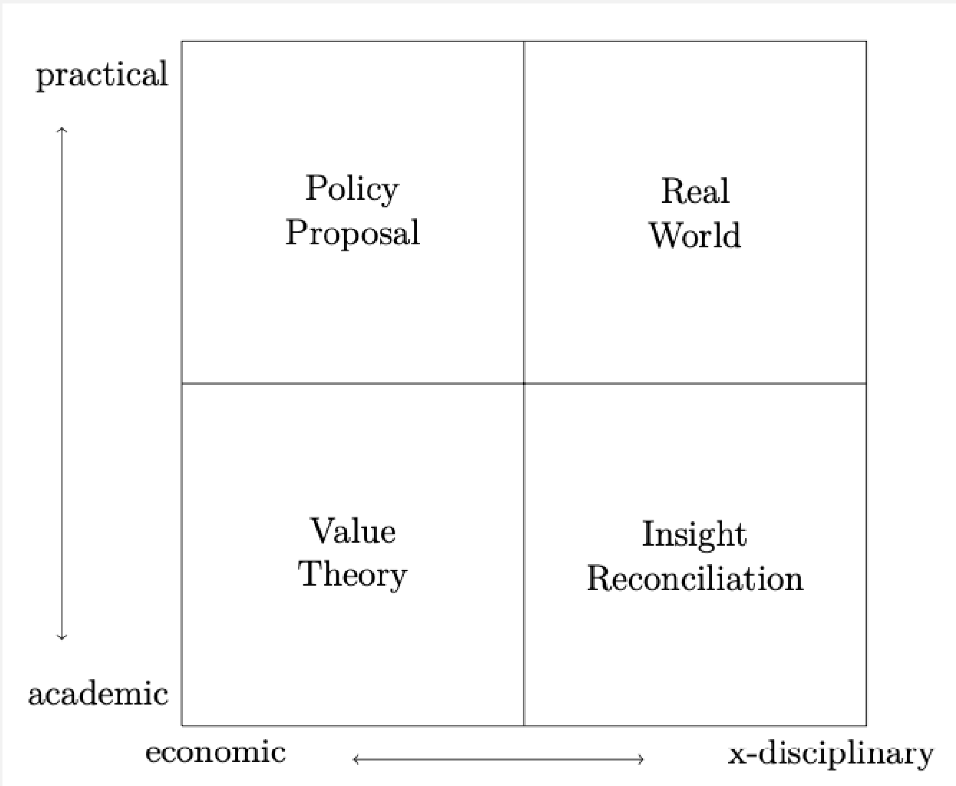

Figure 1: Different Perspectives on Water

Everyone knows, needs, and wants water. Such universality might seem a bug to those attempting to assess various perspectives, but I see it as a feature. The more people care about water policy, the larger our willingness and capacity to improve it. Water economists must play a role in these discussions, but they must also work with those who can contribute to discussions, design policies, and implement solutions. The rest of this section explores this academic–practical interface.

2.1 Differing Water Priorities

"Water" is a multifaceted topic. It is the focus of the sixth Sustainable Development Goal (SDG): "to ensure availability and sustainable management of water and sanitation for all." SDG 6, like the other sixteen goals, includes subtargets (eight in this case) to deal with water's complexity, from "provide safe and affordable drinking water" (Target 6.1) to "protect and restore water-related ecosystems" (Target 6.6). Water, like love or inequality, has many sides. Complexity prevents a quick or definitive study of water; caveats and dependencies abound.

Communities prioritize different uses of water. Poorer communities worry more about drinking water than environmental flows. Farmers focus more on irrigation; households on domestic supply. Richer consumers worry about mitigating climate change; the poor adapt. Too few communities—rich or poor—have political leaders who are able to keep their water systems in full repair, let alone adapt them to evolving needs. The big push for drinking water and sanitation that began roughly 150 years ago bequeathed massive benefits to generations, but that push is outside our memory—making it hard to motivate action and easy to accept decay.

Economists can play a useful role in explaining interdependencies, documenting successes and failures, and creating solutions that reconcile constraints, preferences and resources.

2.2 Tidy Theory Meets Messy Reality

There is an old joke about a drunk guy looking under a streetlight for his lost keys "because that is where I can see." Academics have a similar bias toward data, language, and institutions. If good water management practices could be copy-pasted anywhere, then we could study water in our neighborhood and generalize to the world, but we cannot and should not. Yes, we can explain the importance of marginal cost pricing or how to reduce risk with storage, but so could anyone paying more for less or digging a well. The challenge is to understand why marginal pricing is used (or not) or what steps are taken (or skipped) when balancing storage across seasons.

A delightful book, *Priests and Programmers* (Lansing 1991), contrasts local adaptive institutions to generalized deductive reasoning. Its author, an anthropologist, tells how World Bank experts ("programmers") told locals to ignore "inefficient" methods of cultivating rice that were codified in temple ceremonies. Long story short, yields rose briefly before crashing. The programmers had failed to understand see how local "superstitions" had internalized centuries of trial and error.[5] Economists need to start more conversations with "tell me why that is" instead of "do this."

That said, economists (and other academics) should continue to highlight fallacies and contradictions. An Ivory-Tower perspective might not capture the gritty reality of the streets, but it can help set goals and monitor progress toward them.

2.3 Inductive Search as a Complement to Deductive Prediction

Deductive reasoning moves from first principles to narrow conclusions through logical steps and assumptions. It is rational, abstract, and useful for investigating and testing ideas. Inductive reasoning begins with a situation and searches for patterns and choices that can explain observed facts. Inductive reasoning can be mistaken for just-so storytelling, but it allows for creativity, twists, and details that do not fit into deductive models. Both methods can help us understand water issues that have strange origins but familiar results (or vice versa). Since academics often use deductive methods, I will focus on how inductive methods can contribute to teaching water economics.

The inductive method begins with observed phenomena and tries to match them to new or known patterns, hypotheses, and theories. The Law of Demand, for example, suggests that an increase in the price of water will reduce quantity demanded, but we observe many cases in which quantity does not respond to a price change. These observations do not falsify the Law of Demand as much as encourage one to delve deeper—perhaps checking whether *ceteris paribus* assumptions actually hold. One such assumption—full information—is perhaps too strong in cases where one person decides water use and another sees the water bill, or when water is so cheap that a price increase ("50 percent higher!") seems to go unnoticed. Is that a case of zero elasticity, or does "salience" provide a better explanation? Salience would make sense if demand for drinking water goes from undefined (no behavioral response to price changes) to defined, meaning that the actor is paying attention—perhaps for the first time—to their water demand. The situation, in other words, is not one of "excessive" changes in quantity demanded but the *appearance* of the demand curve. Alternative

[5] Henrich (2015) explores this cultural-evolution dynamic for our species.

explanations like these matter if we want to understand water (mis)management, and authors such as Whittington (2016) show how traditional thinking trumps economic logic.

3 Water Is X-disciplinary

Economists working on water topics cannot go for long without drawing upon the ideas and expertise of other disciplines. Engineering, history, law, politics, public health, and many other disciplines study water issues that cross and ignore our tidy (academic) silos. For most economists, it is easier to borrow ideas from other social sciences than other disciplines, but there are plenty of exceptions to such provincialism—exceptions that might be driven by project funding, social networks, or sheer curiosity. No matter the reason, it is inevitable that we will need help from—and can offer help to—colleagues in other disciplines.

Such activity is often hard to justify when there are strong incentives to publish research in disciplinary journals. X-disciplinary cooperation in teaching, in contrast, is easier to justify when students expect applied insights and professional risk is lower (academics worry more about research, so there is more room to take chances in teaching). Although bureaucratic rules may inhibit cooperation, they can also encourage it—witness the endless calls for interdisciplinary collaboration.

Economists are late to the water game in comparison to engineers, lawyers, and scientists, but early in comparison with ecologists, ethicists, and psychologists. These different vintages can result in gate keeping (“we’ve known this for decades”), confusion (“we’ve always called it *y*; why do you say *x*?”), and conflict (“how dare you ignore our advice”), but they also provide an obvious opportunity to learn from the wisdom of elders and build on the energy of newcomers. It is a question of attitude—and most water people are excited to geek out with fellow travelers.

For those of us excited to learn from other disciplinary perspectives, case studies offer a convenient mechanism. Cases based on real-world questions are neutral to disciplinary boundaries, so they are less vulnerable to turf wars. Cases also present a focal point for asking questions and seeking answers that prioritize quality over purity. Cases—by virtue of involving practitioners—also force academics to focus on robust practicality over disciplinary obsession. And cases are eminently suited to organizing numerous perspectives that must be reconciled on many levels in order to build bridges toward new ideas and deeper understanding.

4 Teaching Water Economics with Case Studies

The importance of water management is increasing as climate change grows stronger because water is the vector through which climate impacts arrive—via storm, drought, sea-level rise, and so on. Demands for improved understanding and better policies need to be met with greater supplies of data and ideas from academics, economists among them.

Case studies provide an excellent framework for testing, rejecting, or adapting ideas. Cases can be scaled to local data, resources, and circumstances. Cases modeled on local conditions are also accessible to nonspecialists who can help with fact-checking, policy design, and— ultimately—action. Cases help people organize their data, ideas, and experiences into a story that anyone, regardless of their starting point, can relate to, which means they can be used to suggest questions, guide discussions, and further collective action. Students may struggle in the early stages of building a case study, but the wholeness of reality will eventually help them make connections. This characteristic explains why problem-based learning (PBL) works so well for teaching (Reimann 2004), and case studies are well suited to PBL environments.

These ideas and ideals work in the practical, policy, and professional worlds, but they also apply in the classroom, where the stakes are lower, the space for exploration is greater, and future problem solvers are learning valuable skills.

4.1 How Do Cases Contribute to Teaching?

Hands-on (first-hand) learning is more effective than "distant-handed" learning (Stein, Isaacs, and Andrews 2004; Henrich 2015).[6] Its effectiveness comes from the way in which learners need to reconcile facts, theories, and local institutions in a real-time process that will alter or create patterns of understanding. Since this process is directed at writing a case study that outsiders will recognize (and may use), it is less likely to be side-tracked by conflicting academic discourses.

Cases also benefit from students' intrinsic desire to understand a topic they have (typically) chosen to pursue. Their desire to understand will lead them to ask for interviews, read newspapers, or dig into archives. To understand those sources, they will learn techniques, test theories, and diversify their toolkit. They are more likely to go off the [disciplinary] reservation in their search, which will expose them—and others—to new and useful x-disciplinary combinations.

Perhaps the most useful aspect of teaching with case studies is the way in which they encourage collaboration between "town and gown" (practitioners and academics). Although there is a long history of either side accusing the other of missing the big picture, collaboration creates an opportunity to find common ground in a little case study picture. Since cases put more emphasis on "dirtbag pragmatism" than theological purity, they allow students to use an effective blend of tools (Rubin 2021).

One of my favorite papers in water economics (Loaiciga and Renehan 1997) was written by two geographers based on data provided by the Public Works Department of Santa Barbara (California). Their case study explains how higher prices and public communications reduced water demand by 46 percent in the short run (39 percent in the long run) during an extended drought in the 1990s. Their case, like most others, tells an accessible, compelling story of how various ideas were developed, tested, and then dropped or reconciled with other ideas and policies. Their case also works without the benefit (or delusion) of a *ceteris-paribus* analysis designed in a friction-free environment, which can lead to misleading conclusions. Vaux Jr. and Howitt (1984), for example, advised against investing in urban water security when water could be bought from irrigators in markets. Their faith in "assume a market and the water will come" looks foolhardy to anyone who has waited for decades for such markets to appear. Many Californian cities are now spending billions of dollars on infrastructure that markets were supposed to replace.

4.2 How Can Cases Be Used for Teaching?

Case studies come in many forms, so the teacher can decide on details.[7] Cases can, for example:

- Align with the course's ambitions and duration in detail, scale, and scope.
- Build on students' connections, culture, knowledge, and language.
- Help students understand the exceptions, strengths, and weaknesses of theory.
- Use available data and insights from other disciplines.
- Encourage students to interact with nonacademics, which can strengthen their inter-personal skills and professional development.

4.3 How I Use Cases to Teach

I teach a course on water scarcity to undergraduates in our teaching-oriented, honors program. In the course, "scarcity" refers to an inadequate supply of good quality water in comparison to human and environmental demands. Our class of around twenty students meets for two hours, twice per week

[6] Although definitions vary, I am using "first hand" in the sense of touching or doing something directly (e.g., irrigating a field). Second-hand learning comes from watching someone irrigate a field. One learns third hand by reading a farmer's irrigation journal. Fourth-hand learning occurs when reading a text book author's description of how farmers irrigate.

[7] Their more rigorous cousin, the analytical narrative, often includes game-theoretic models and testable hypotheses (Levi and Weingast 2022).

over the eight-week term.

The description of the case-study assignment in the syllabus explains its focus and goals:

> *During this course, you will research, write, and present a case-study paper on water scarcity affecting a major city and its political and hydrological surroundings.[8] Your case will help everyone understand water issues at different scales (local vs. regional), scopes (issues for farmers versus cities), and disciplinary perspectives (e.g., engineering and politics). You will explain how management evolves, succeeds, and/or fails for different stakeholders.*

In Week 2, students bring proposals for cities/regions to study. I discuss these proposals with the whole class to expose their varied interests, reconcile overlaps (e.g., two students choosing Cape Town), and suggest approaches (e.g., referring them to literature or experts I know).

During Weeks 2–5, they learn about their cases by answering the questions in Table 1 (graded pass/fail), which is on the next page.

They also learn through their own research (i.e., interviewing residents and local experts, collecting data from journalistic media and gray literature, and cross-checking their findings with the academic literature). The course reader—15–20 articles written by academics, journalists, and professionals—provides multiple perspectives for them to consider.

They write their case study after a few intermediate steps, i.e., writing a blog post on one aspect of water scarcity from their case study, writing a draft that is subject to anonymous (to them) review by two of their peers,[9] and presenting their cases to the entire class.

Although students are free to structure the case study in any way they want, the syllabus gives the following guidance, which I reproduce here (nearly verbatim) as a means of explaining the learning goals and grading rubric:

[8] "Scarcity does not just mean an empty reservoir. The poor living in slums have *economic scarcity*, which means they often lack the political power needed to get water supplies. Think of challenges and impacts at the macro- and micro-scale, respectively, that is, the big forces leading to under-supply and over-demand (macro) and then the individual or family-scale micro impacts of scarcity, in terms of sickness (mortality/morbidity), time spent collecting water, money spent to get clean water, etc." [This footnote is also in the syllabus.]

[9] The peer review gives the author detailed feedback, but it also exposes reviewers to other styles and techniques.

Table 1: Prompts to Help Students Learn about Their Cases

Week Number	Question Number	Prompt
2	1	Find an example of conflict over water allocation (e.g., water for irrigation or a river; water to one city or another) in your case-city's region and assess each side's claim to the water.
3	1	Find the regulator for your case-study city. (Municipal "public" utilities are usually overseen by people from city government; investor-owned "private" utilities are usually overseen by a separate commission.) Read the paperwork from a recent meeting on charges and services. What did you learn that is interesting?
3	2	Find your customer class for your cases study city. (Most residential customers are grouped according to the size of their piped connection, i.e., 0.5–0.75 inches or 15–20 mm.) Compare your service and water charges to those of other classes (multi-family, commercial, etc.).
4	1	Pretend you have no water at your home as it is a 5-minute walk away. Assuming you cannot go get your own water (for this question), how much would you pay someone to deliver 10 liters of water to your home each day? How much would you pay for a second delivery of 10 liters?
4	2	Find out if there are programs to help people who cannot pay their water bills in your case-study city. If there are, then how are they funded? If there are no programs, then what happens if people do not pay their bills?
4	3	Find a commodity crop that you consume often at https://www.wri.org/applications/aqueduct/food/. Check a package of that food in your home and find out if it is produced in a region facing water stress.
5	1	Identify a major project (treatment plant, network extension, dam, etc.) for your case-study city. Compare its cost to how it was (or will be) financed (e.g., bonds repaid by monthly service charges) over its service life.
5	2	Get a water quality report for your case-study city and compare the levels of allowed and measured contaminants in the utility's water.

Source: Author's course syllabus.

Your goal is to present a complete description that will help the reader understand the issues, even if solutions may be unrealistic or difficult to implement. I suggest (but do not require) the sections below. Word counts are suggested (adjust as needed), but the overall limit is 4,000 words.

Introduction: *Define the scarcity challenge(s), describe and quantify their impacts on the local community, explain why these impacts (and thus scarcity) must be addressed, and give a short summary of the causes you identified, and how you suggest they be addressed (250 words).*

Background: *Describe the city and its political and hydrological surroundings. Identify a timeline (history) of major events and outcomes reducing/increasing water scarcity. Your weekly exercises will contribute to this section (500 words).*

Data: *Use maps, tables, and figures to explore and explain the spatial, operational, fiscal, and sustainable dimensions of your case. For example, quantity of water consumed and prices paid by customer class; formal vs. informal water vendors; and share of water use by sector (agricultural, municipal, and industrial) as well as residential use (indoor/outdoor). Please use SI units (e.g., cubic meters of water) and always provide USD/EUR equivalents if you are using local currencies. Qualitative data (surveys, manager performance, regulatory activity) can also be useful. Also discuss what went right or wrong on collecting information on your case study. This will help me understand how easy/hard your research was for you (1,000 words).*

Analysis: *Explain how formal rules and informal norms (institutions) have led to current scarcity, recount history up to the current situation (perhaps go back to a time of abundance and then trace the emergence of scarcity), and show how hydrological, engineering, political, economic, and social forces interact, cooperate, or conflict to increase or reduce scarcity (1,000 words).*

Distribution: *Use a summary table or figure to explain the costs and benefits of scarcity and give 2–3 quantified impacts of scarcity. It will be useful to identify winners and losers, their power or leverage, and how they may (not) support change. You may want to draw lessons from other interactions of these groups (750 words).*

Recommendations: *Suggest a new way and/or evaluate existing attempts of reducing (quality/quantity) scarcity and the resulting adverse impacts. Consider the costs of various ideas and who will pay them. It is usually easier to start with a small improvement that can be expanded later. Discuss barriers to change and potential ways to overcome those barriers (500 words).*

Grading: *Your grade will be based on quality of writing and organization (25%), your analytical and institutional analysis (50%), and recommendations for addressing impacts (25%). You will get an A for a complete and clear analysis that improves on weaknesses in your presentation. Spelling errors, confusing structure, or missing or unjustified costs/benefits will lower your grade.*

Bonus points: *You can get a bonus of 0–10 percent on this grade for soliciting and receiving outside opinions on your case and/or recommendations. These outside opinions should be summarized in an annex that includes their name, title, and contact information (see me about anonymous sources). There is no guarantee that I will give points, but it is more likely if I see that you've engaged/learned from an expert.*

In sum, students need to explain the causes of scarcity and its evolution, estimate the costs and benefits of the current situation, describe potential policies or remedies to scarcity, identify barriers and complications that might prevent improvement, and reflect on what they learned in the process.

This course requires a lot of effort from students (an average of 12 hours per week outside of class) in the process of giving them a crash-course introduction to the political economy of water. Its case-study structure, in my opinion, aids greatly in helping students assimilate, organize, and understand a host of new ideas, theories, and facts.

Here are reflections from five students who recently took the course:[10]

> Student 1: "*Even though I have taken this class online, which made the class much less enjoyable and entertaining, I would say my situation was the best possible case for an online student. I was living right next to my case study, I could see the lake from my window, and my work allowed me to talk with farmers who are experiencing water scarcity.*"
>
> Student 2: "*Working on this case study was a long and demanding, yet very engaging and rewarding process. Discovering the history, present and future predictions on Mexico City's water situation—in numerous aspects—was genuinely fascinating.*"
>
> Student 3: "*I loved investigating the case of water scarcity in Guadeloupe. My favorite part was interviewing XX, who gave me a lot of insight when it comes to citizens' daily lives on the islands. I needed that information to better wrap my mind around what was going wrong in the region*."
>
> Student 4: "*Doing this case study on water scarcity in Antwerp really opened my eyes to the issue of water scarcity in Western Europe. I never realized that water scarcity could also be severe in places like Belgium, which is supposed to have a rainy sea climate.*"
>
> Student 5: "*Overall, I enjoyed working on this case. It was challenging to get a good overview as much of the data was scattered across websites, government and environmental reports, and academic literature. Moreover, the data was sometimes conflicting. However, there was enough data out there for me to get a feeling that I have a good idea of what was going on.*"

These students saw how their effort led to a deeper understanding of a complex topic. What is even more useful is how case studies, which help students explore real issues, also strengthen their research, interviewing, data analysis, writing, and other transferable skills. From a disciplinary perspective, the case study clarifies the intermingled roles of economics, politics, society, and the environment. Most important, this structure energizes students in their quest to understand more about the case they chose.

Good learning lasts longer than the school term, often for a lifetime. Students who are excited about their topics do not just learn more: They affect the people around them. They engage in policy and political discussions. And sometimes they change their career goals.

[10] Students have given me their written permission to include their comments in this paper.

4.4 Why Aren’t Cases Used More Often?

Professors often teach what they know in a way they are comfortable with, rather than what students should learn in a way that matches students’ learning styles. Case studies can make up for these weaknesses by allowing students to follow their own methods on topics they chose to focus on, but students need advice, corrections, and guidance.

Although we (professors) know that x-disciplinary work is better in many ways, it is hard to organize an x-disciplinary course—in terms of finding guest lecturers, grading assessments, and linking to subsequent courses. Case studies avoid many of these problems by encouraging students to find their own experts (academic or not) while holding them accountable for a clear analysis.

For students attending classes in multiple disciplines, this task is not as hard as it might seem. Students constantly reconcile different perspectives, methods, and epistemologies, which means they may be better prepared for cases than professors teaching in one discipline. The problem, in other words, is not that students cannot write cases, it's that professors don't ask them to.

5 From the Classroom to the Real World

Any course focusing on water is immediately complicated by the many ways in which water affects our lives. Such wide-ranging impacts call for a variety of approaches, which are hard to learn, let alone teach, in an academic setting. Even more important, these artificial, disciplinary boundaries rarely matter in nonacademic settings, so we need to help students manage them if they are to take useful lessons into the real world.[11]

Case studies help students explore real, local, and personal complexities. They push students to strengthen their research, interviewing, data analysis, and related skills. Cases put economics in context and reveal other influences affecting water management and use. Most importantly, cases motivate students to understand the complexities and seek answers to the questions they've asked.

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[11] Around 1 percent of OECD adults have doctorates. The U.S. share is 2 percent (OECD 2019).

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Teaching and Educational Methods

Teaching Water Economics in a Desert Environment

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JEL Codes: Q1, Q2 and Q5
Keywords: Demand management, supply augmentation, water markets, desalination, water energy-nexus

Abstract
Teaching water economics in a desert environment is less complex than in other environments. Economic methods dealing with the interaction between surface and groundwater, surface water pollution, water for nature, and hydropower are not in need in desert environments. The course focuses on demand-side policies such as quantity restriction, rate setting, technology adoption, and comparisons of policies oriented toward reducing water demand and addressing the wasteful use of water. Often adopting water-saving technologies have the ability to reduce demand without decreasing users' utility. We discuss the right of access to water and fairness. The course addresses the rationale for supply-side policies implemented in Gulf Cooperation Council (GCC) countries. We emphasize the environmental impacts and energy requirements of desalination as limits. Alternative sources of water for cities, such as the expansion of existing agricultural water markets to encompass trade between farmers and cities is explored. The course looks into the social impediments of treated wastewater recycling in farming. The course is taught since 2011 to undergraduate students in the form of lectures and lab work with the support of videos and flipped classroom. During the last weeks of the course, each student presents to the class a paper on the main issues addressed.

1 Introduction

Teaching water economics in a desert environment is less complex than in other environments. Rivers and surface water are absent in desert environments. Hence, all issues related to the interaction between surface and groundwater, surface water pollution, water for nature, and water for hydropower are irrelevant. Economic methods dealing with the above issues are not needed. Conventional renewable freshwater is in the form of groundwater found in relatively limited volumes spatially dispersed. Supply of urban water depends mainly on desalination, the nonconventional resource.

Traditionally in desert environments, the main source of water is groundwater. Life was organized around the springs, then horizontal wells called Qanats and Aflaj were developed hundreds of years before Christ (Jomehpour, 2009), and water flew by gravity from the aquifers to the oasis. There was no need of energy to abstract the water from the aquifers. However, the initial investment cost of drilling the horizontal wells was high enough and, in many circumstances, costed several human lives due to accidents from tunnel collapses on the workers (MRMWR, 2008). Water was scarce, and its management was of upmost importance. Water institutions were developed, and both common and private ownership was established. Access to water for basic human needs and for animals for local people and nonlocals was clearly established. Water distribution among economic sectors, priority of use, recycling, use of chemicals, and balancing of supply and demand within seasons and inter-annually were closely monitored (Zekri & Al-Marshudi, 2008). The event of the modern states in the 1970s, driven by the exploitation of hydrocarbons, led to a deep transformation of the economy and the water sector. Abundant and cheap energy led to the construction of tens of desalination plants in the Gulf Cooperation Council (GCC) countries to secure water for the booming economies (Reddy & Ghaffour, 2007). Water seemed unlimited, and supply was encouraged by a high demand. The increase in demand is due to the very low prices administered, population growth, immigration, concentration of populations in cities, and high income of the local citizens as well as by the stable profits desalination plants generate for private investors (Williams, 2022). The consequence is an erosion of the water management knowledge and culture accumulated over centuries. Urban areas became independent of the limited, if any, renewable sources of water and depended almost totally on desalination. Four out of six GCC countries, Bahrain, Kuwait, Qatar, and United Arab Emirates (UAE) have less than 20 m^3/cap/year of renewable water resources (Figure 1).

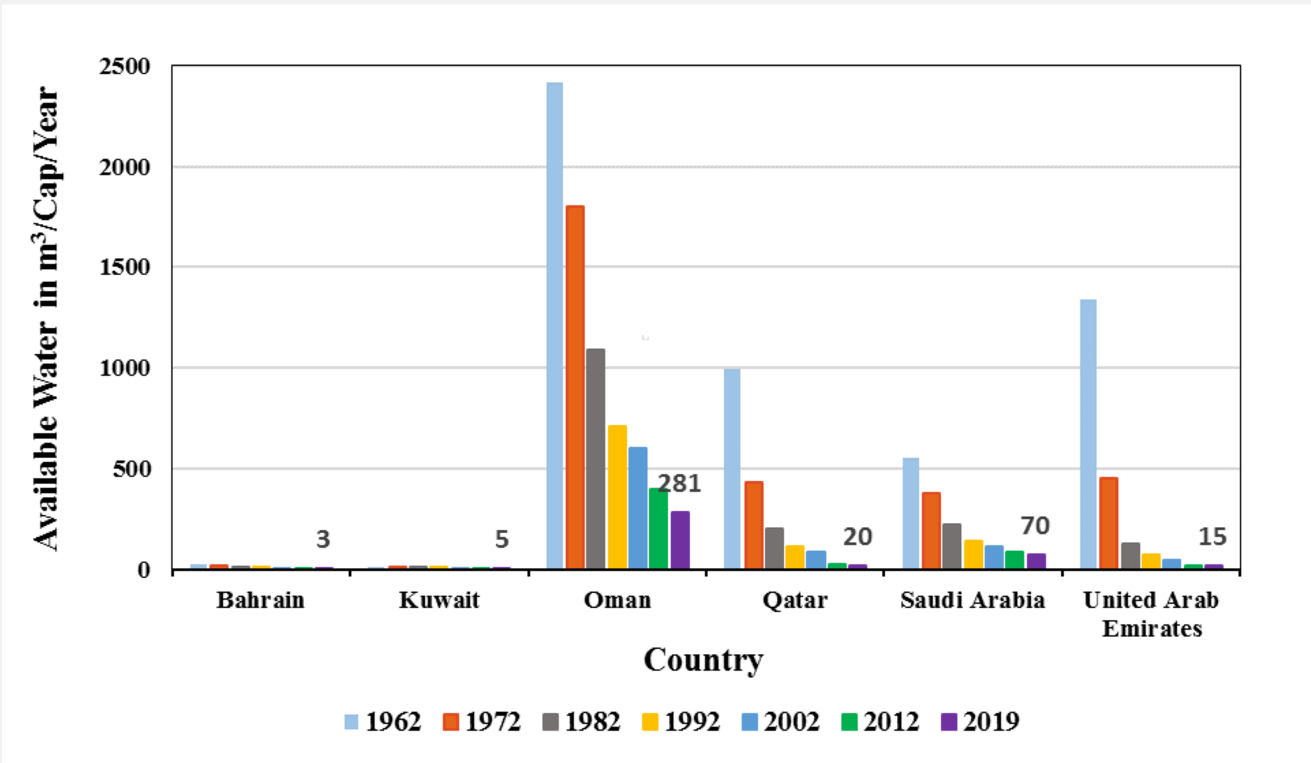

Figure 1. Available Renewable Water Resources for Gulf Cooperation Council Countries in m3/Cap/Year 1962–2019

Source: Based on World Bank data. https://data.worldbank.org/indicator

Although it is difficult to associate an exclusive desert climate to a whole country, such as the case of GCC countries, several other countries have large areas of inhabited hot deserts with no surface water. Figure 2 shows a map of countries with hot desert climate (BWh) and cold desert (BWk). A non-exhaustive list of these countries includes Algeria, Angola, Australia, Botswana, Djibouti, Chad, Egypt, Eritrea, Ethiopia, India, Iran, Iraq, Kenya, Libya, Mali, Mauritania, Mexico, Morocco, Namibia, Niger, Pakistan, Tunisia, Senegal, Sudan, South Africa, Syria, and United States (Las Vegas). Most of the countries with hot desert climate have parts of their territory under water stress and can benefit from this paper to develop similar courses.

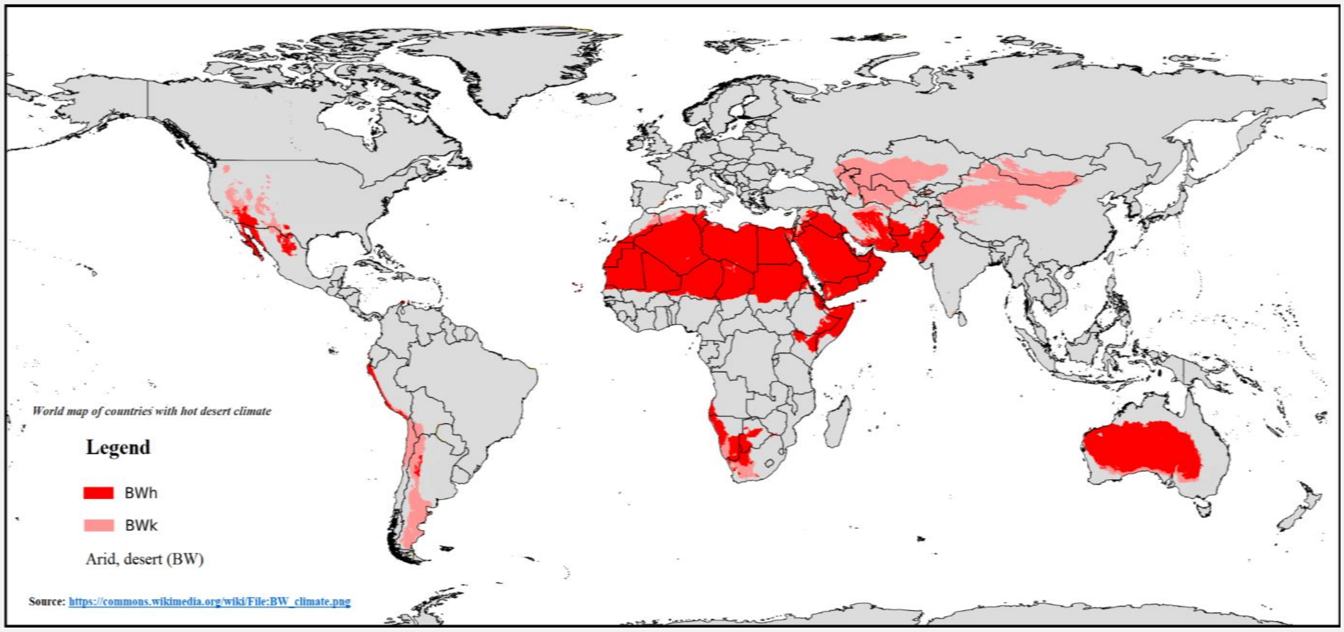

Figure 2. World Map Showing Countries with Hot Desert Climate (BWh)

Source: Lucioni, 2019

Supply augmentation through desalination has its own problems. The volumes of desalinated water in the GCC countries increased by 77 percent during the period 2010–2020 and went from 3,585 Mm3/year to 6,354 Mm3/year (Gulf Cooperation Council, 2020). Household water consumption is among the highest at the global level with 263 l/cap/day in Saudi Arabia and up to 500 l/cap/day in Kuwait, UAE, and Qatar (World Bank, 2022). The major environmental problem is brine, the hot high-salty water resulting from desalination. The rejection of brine back into the sea causes environmental impacts on the marine environment, which have been and still are ignored. Treated and sometimes insufficiently/untreated wastewater are rejected in natural channels causing groundwater degradation and seawater pollution. Although several courses in colleges of engineering and agriculture deal with water issues, the focus of such courses remains purely technical. Hence, these problems require an economic, policy, and social approach to complement students learning.

Water economics and policy in a desert environment is taught in Oman since 2011. It is a three-credits elective, taught at the undergraduate 3000 level in the form of lectures and lab work with the support of videos and flipped classroom. The course recruits students from the Department of Natural Resource Economics as well as students from the Department of Soils, Water, and Agricultural Engineering. The prerequisite for enrollment is “principles of economics,” a college required course. The maximum number of students allowed in this course is 30, but this limit has never been reached and often I have around 10–15 students. The course lasts for 15 weeks. During the last three weeks, each student presents to the class a scientifically published paper on the main issues related to the course. The students are graded on a 2-hour midterm (30 percent), 1-hour presentation to the class (30 percent), and a 3-hour final exam (40 percent). The students’ presentations encourage students to master self-learning, get used to life-long learning activities, apprehend water policies, and learn from other countries’ successful experiences. The students can gain extra marks to encourage participation in the debates and enrich the discussions. The eight chapters of the course are as follows: (1) Introduction to Water Economics and Policy; (2) The Fundamental Economic Theory Applied to Water; (3) Water Policy Analysis; (4) Demand Analysis; (5) Water and Wastewater Pricing; (6) Water and Economics in GCC and in Oman; (7) Water Pollution and Pollution Control; and (8) Water-Energy Nexus.

The course addresses the following six major issues: water scarcity at the global level and the supply versus demand options; managing domestic water demand via pricing, quantity restriction, and technology adoption to reduce and recycle water; managing agricultural groundwater in a context of aquifer over-abstraction and seawater intrusion; traditional water markets among farmers and their possible extension to encompass trade with municipalities, including treated wastewater; the water-energy nexus, desalination for agriculture; and the transition toward the use of renewable energy and environmental impacts of desalination. The course outline is found in Annex 1.

2 Water Scarcity at the Global Level

It is fundamental that students apprehend that water scarcity is a global problem and understand the physical and social characteristics of water. The report “Charting our Water Future” clearly summarizes the current and future supply and demand for water (2030 Water Resources Group 2009). The central idea is to highlight the challenges of supplying urban water and feeding the growing population without additional water and exploring the available options for doing so. The volume of rainfall received annually on planet earth does not change (Shiklomanov, 1998). At the local scale, annual rainfall changes, leading to uncertainty. The term no additional water refers to conventional water resources. Desalination is one of the solutions to scarcity, and it is the most expensive supply expansion method. Furthermore, desalination is possible only in case seawater or brackish water is available. For many landlocked countries around the globe, even desalination is not a solution since access to seawater or brackish water is not possible. In some other cases, access to the sea is available but still desalination is not feasible. A good example is Windhoek, the capital city of Namibia, which, having an arid climate, has been recycling its wastewater into drinking water since 1968. The city is 987 km away from the sea, making it extremely expensive to transport the water after desalination. Water is heavy, and its transportation and distribution requires heavy infrastructure and a lot of energy for pumping and pressurization. Simply said, humans cannot produce water, which is a natural resource. Humans can increase supply of fresh water by purifying nonconventional water resources and accelerating the water cycle. However, that requires a lot of energy; most of it is fossil fuel at the current state of knowledge, very expensive, and not affordable for most developing countries. In desert environments, rain is extremely scarce, and only 1 percent of the rain ends up in aquifers, while 70 percent evaporates due to the high temperatures. Evaporation is around 2,000 mm/year, which is 2,000 liters/m^2/year. The remaining 29 percent of the received rain ends up as surface run-off, and only a small part is captured into dams to enhance aquifer recharge given the topography and absence of deep valleys. The cost of supply increase through recharge dams is also quite high. Nonetheless, it remains less expensive than desalination in several cases, essentially if the negative externalities of desalination are taken into account.

3 Managing Domestic Water Demand

Domestic water demand in desert areas such as GCC countries is very high despite the acute scarcity of water. Hence, demand-side policies are a top priority in teaching water economics. Historically, people living in desert environments used to use water very efficiently at all levels adjusting to scarcity (Saeid et al., 2016). Utilities in the modern states supply water to households at very cheap rates, sometimes as low as \$0.08/m^3, representing less than 7 percent of the cost, as was the case in Saudi Arabia (McIlwaine & Ouda, 2020). The relatively high incomes of the citizens is another explanatory variable of the very high water demand in the region.

On another hand, there is considerable public resistance to water price reforms and a lack of advocacy from the public authorities on the total cost of water and the amounts of subsidies allocated to the water sector, which impeded reforms. In some Islamic countries, biased culture led to thinking that water should be free. Indeed, in general, the Islamic culture calls for a sane use of water. In Islam access to public water in rivers, springs, and streams, on which there is no property rights, is free, similar to any other natural resource that is not privately owned. However, most Muslim scholars agree that water delivered to households has gone through treatment, transportation, and pressurization, which represent added values that should be priced and that water can be even traded (Kadouri et al., 2000). Many citizens in GCC see low water prices as a way to distributing the oil rent. However, citizens ignore that subsidies for water benefit more the rich than the poor (Kotagama et al., 2017). Hence, water subsidization is a biased way to distribute oil wealth. This part of the course is essentially based on Griffin (2016, pp. 145-174), where students learn the fundamentals of economic theory applied to water, derivation of water demand functions, and comparison of urban water policies. The methods learned are applied to estimate the water demand function for Muscat city using the data by Kotagama et al. (2017) and exposure to new methods using data from water utilities with a large number of observations and linked to census data providing household characteristics (Baerenklau & Pérez-Urdiales, 2019; Boland & Whittington, 2000).

Estimating the cost of the water and rate setting is discussed prior to addressing the pricing methods (Griffin, 2016; Raftelis, 2005). The conflicts of objectives among the pricing criteria are highlighted (Garrick et al., 2020). Three major stakeholders have their say on water prices: utility managers, politicians, and water users. Cost recovery and budget balance is paramount for the utility managers. However, from an economic perspective, economic efficiency and balancing supply and demand are very important objectives to achieve through pricing. Policy makers are interested on equity and fairness issues. Recent pricing methods, made possible due to data management, go beyond the classical methods such as tiered block pricing. Available detailed data on household characteristics such as income, family size, and water use allow a better compromise between the fairness and efficiency objectives (Cook & Whittington, 2020; Dinar et al., 2015).

Water prices change rarely in GCC countries, and if ever, the objective is often to reduce subsidy and balance a utility's budget with no intentions to reduce demand (Zekri, 2020). The low oil revenue and public budget deficits, in recent years, triggered cutting down the water subsidies. Nonetheless, supply increase is the rule, and construction of new desalination plants is a major task of the public water authorities. We compare quantity restrictions and pricing policy using a policy matrix. The students learn the pros and inconveniences of each policy. A quantity restriction policy though looks easier to implement, is in fact very difficult to monitor, and requires extra monitoring costs. Houses are fenced in GCC countries, and it is not even possible to monitor a policy that obliges users to reduce outdoor water and garden irrigation. Implementation of a quantity restriction on a proportional basis might end up obliging efficient water users to further cut down their consumption resulting in high marginal benefit losses.

The course addresses the limitations of water conservation via the use of education programs and awareness rising. In a review paper on behavioral change for water conservation, (Sezer et al., 2017) identified only 12 studies out of 52 reviewed, having had field experiments lasting one year or longer. Most of these studies were carried out in developed countries (United States, Germany, Switzerland, The Netherlands, Australia, Japan, Spain, and Greece). The long-term effects of behavior change on water conservation are not conclusive. Out of three types of behavioral tactics: reflective, semi-reflective, and automatic, only the first two tactics were tested with water. Information campaigns often are used during periods of water stress, are combined with price incentives, and curtailment achieve temporary water savings but appear to be inefficient in achieving long-term water conservation. For countries depending on renewable water resources, reducing water demand in the long term might not be an objective, as this would influence water rates. However, for countries depending totally on desalination, as is the case of desert countries, the long-term decrease of water demand should be an utmost goal. Data driven allowing targeted personal messages based on smart metering/real-time information compares water consumption among users evokes a feeling of discomfort and leads to short-term savings while for longer-term behavioral change the literature is inconclusive. Sønderlund et al. (2016) have studied the effect of smart metering and information feedback on domestic water saving. They reported that behavioral change depended on the feedback information, its frequency, and granularity. Most importantly, their results show that water saving is more effective when feedbacks are combined with time-variable water prices (Zekri & Al-Maamari, 2020).

Domestic water demand depends heavily on the existing fixed appliances in the home (flush toilets, faucets, garden irrigation system). A successful strategy for water demand management and permanent demand reduction requires a combination of several tools: proper rate setting, water pricing, targeted subsidy, information to users, and technology adoption. Strong price signals are necessary but not sufficient. Additionally, water users need precise, short, practical, and timely advices on how to cut down water consumption and the type of technology to adopt. Recent technology developments, such as aerators, sensors, low flow faucets/showers, smaller dual flush toilets, and timer for garden irrigation or smart irrigation systems have the advantages to provide the same utility (comfort) while reducing the volume of water used. The adoption of automated/smart garden irrigation contributes also to saving the owner's time by eliminating the need to water the plants.

Quality precise information is very helpful in achieving demand cut down. It is possible to achieve a reduction of demand at no cost in some cases. For instance, inserting a filled plastic bottle of water into an existing flush toilet is cost free and reduces water use by 1.5 liters when flushing the toilet. It requires no investments nor plumbing costs. Hence, advocacy, awareness raising, and provision of precise advice improves adoption of cost-free or low-cost technologies. However, in many other cases water-efficient technologies are uneconomical compared to their less-efficient alternatives and require legal interventions as well. For instance, only low volume/dual-flash toilets should be allowed in the market; new residences should be equipped with at-home greywater treatment facility for water recycling in gardening. This is because it is much cheaper to install a grey water facility during the construction than retrofitting one (Zekri et al., 2021). Some countries are applying rebate programs to speed up household adoption of water saving technologies and facilitating the access to such technologies. Rasoulkhani et al. (2018), using an agent based modelling approach, showed that rebate programs increase by 50 percent the rate of adoption of expensive technologies. Similarly, (Pérez-Urdiales & Baerenklau, 2019) showed that rebate programs increased adoption to levels that would not have happened without the programs, both for indoor and outdoor technologies, and that the latter have also increased the adoption of unsubsidized water-efficient technologies.

4 Managing Agricultural Groundwater

4.1 Groundwater in Desert Environments

Groundwater is the only conventional water resource in desert environments, characterized by the absence of rivers and surface reservoirs. Some of the aquifers are nonrenewables, and their management should be similar to mining oil reservoirs. The renewable aquifers are most important and more challenging to manage. In desert countries, agricultural land is not a constraint while water is the major constraint for food production. Agriculture depends totally on irrigation; rain-fed farming is not possible. Supply of the urban water is from desalination plants, and the major users of aquifers are farmers.

4.2 Aflaj

Tapping groundwater was traditionally achieved through horizontal wells (Aflaj or Qanats) that preserved aquifers from over-abstraction (Figure 3). Aflaj and Qanats flows varied according to the water elevation in the aquifers, which in turn depend on rain and natural recharge. The annual/seasonal irrigated areas increase/shrink according to the flows. The abstracted flows are allocated among users through properly defined water rights. The modern state supplied electricity to the rural areas, often at

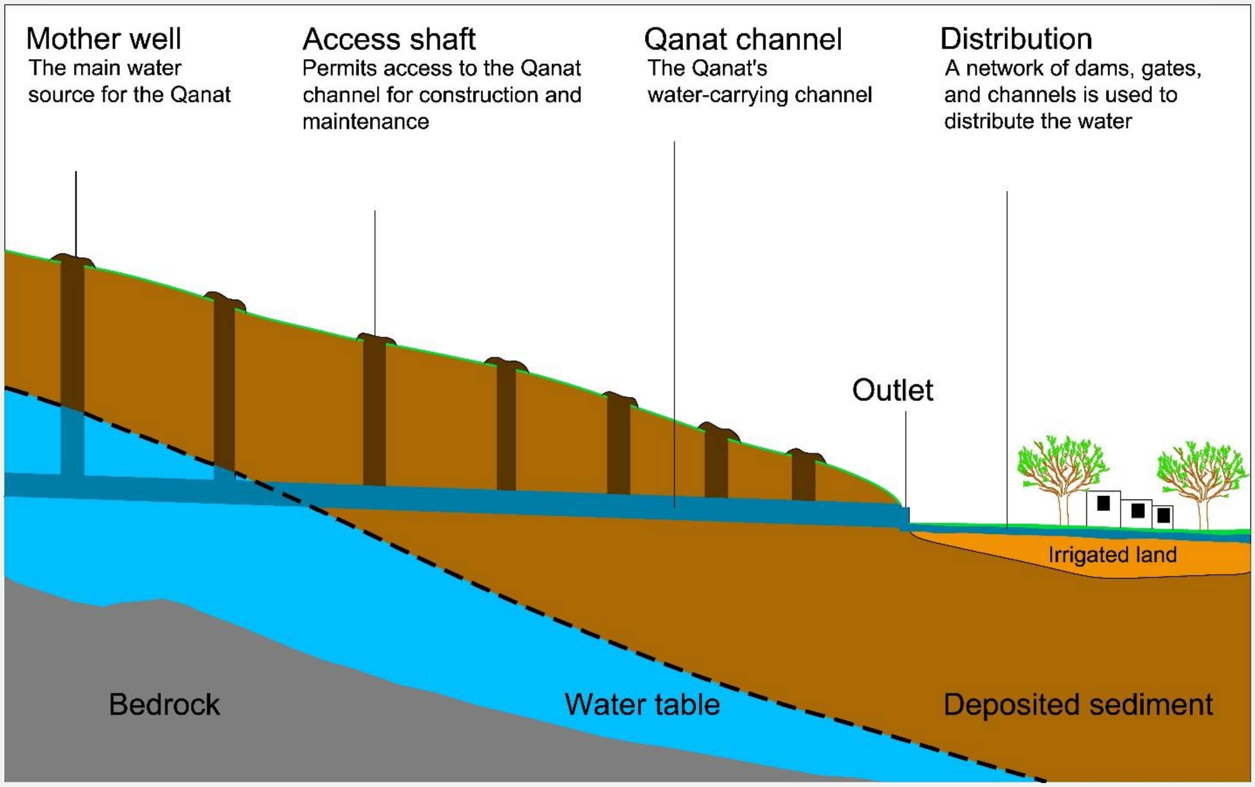

Figure 3. Falaj or Qanat Cross-Section System Tapping Groundwater

cheap prices. The public authorities encouraged the drilling of new wells and installation of electro-pumps aiming to increase food production and food security. Aquifers ended up being over-abstracted, and in the case of coastal aquifers, groundwater quality has become saline due to the seawater intrusion (Zekri & Al-Marshudi, 2008).

4.3 Aquifers Over-Abstraction

The major cause of groundwater over-abstraction, at the global level not only in desert countries, is the absence of water property rights or individual quotas. Aquifers were managed properly during centuries prior to the introduction of uncontrolled electro-pumps, which tap the groundwater without accounting for the natural recharge volumes. The course exposes students to the solution to over-abstraction from an institutional point of view in the form of allocation of property rights to the resource among the different users. The difficulties to monitor abstraction are a major cause of the implementation of such an approach. Hence, adoption of new technologies at an aquifer level are shown as an example to address the feasibility of the establishment of water quotas in combination with the installation of groundwater smart meters and online monitoring.

4.4 Managing Aquifers

The course exposes the students to the methodological approaches for an efficient use of groundwater. Dynamic optimization models, applying the Hotelling principle, coupled with aquifer simulation models such as MODFLOW are used to determine the optimal annual abstraction volume from an aquifer and agent-based modelling to allocate such volumes among users (Zekri et al., 2017). Sustainability implies cutting down the abstraction. Reduction of abstraction does have implications on wealth distribution, and the social and political issues are important. To attenuate the negative social impacts we recommend mechanisms to compensate farmers who will have to quit the business. The course addresses the groundwater quality, caused by over-abstraction. Indeed, when aquifers are located on coastal areas, the salinization of the aquifers is higher the closer the farmland to the sea. In oil-dependent countries such as GCC, farming is most often a secondary activity, making it easier to transition to a sustainable use of the aquifers as the social impacts are less acute and funds for compensation are relatively easier to find. Another way of compensating farmers consists of allowing land use change from agricultural to urban uses, avoiding any governmental payment to farmers to withdraw from groundwater pumping. Finally, the adoption of more efficient irrigation technologies, in the absence of water pricing or individual quotas, cannot resolve the over-abstraction issue. Farmers adopting the water-saving technology tend to expand the irrigated land and/or intensify the production within the same land within the seasons (Zekri & Al-Marshudi, 2008). An advanced theoretical explanation of the effect of irrigation technology subsidy and water pricing on groundwater pumping is found in (Wang et al., 2015).

4.5 Aquifers' Storage and Recovery

Aquifers are perfect nature-based storage facilities. Aquifers provide free storage capacity; protect groundwater from evaporation and to a certain point from pollution. Urban water security in the GCC countries is very low, and the building of concrete reservoirs results in a high cost per cubic meter stored. The over-abstraction not only results in the salinization of coastal aquifers, but it also reduces the aquifers' storage capacity through land subsidence. In addition to the allocation of water quotas, aquifers storage and recovery represents a formidable solution that enhances water security, avoids seawater intrusion, and protects the storage capacity. This course applies an integrated water management approach of desalinated water and groundwater and exposes students to the economic modelling of injection and abstraction of desalinated water and its benefits in an uncertain environment (Al-Maktoumi et al., 2021; Zekri et al., 2021).

5 Traditional Water Markets and Their Expansion

The second aspect related to aquifer management emanates from the use of the groundwater essentially to farming. Theoretically, water should be flowing first to those who are ready to pay higher prices for it, that is urban users. While traditionally in desert environments the top priority of groundwater is providing drinking water, the situation has been reversed. Water markets are a possible way to restore the priority of water use. Water markets among farmers are spread and still operational in rural Oman for instance. The existing water markets allowed securing roughly the necessary funds for a proper maintenance of the water infrastructure. Voluntary work, from the Aflaj (plural of Falaj) communities, supplied the labor force for the maintenance whenever it was necessary, and extra funding from the villagers during urgency was a common practice (Zekri & Al-Maamari, 2020). However, given the fact that the villages' domestic water depends no more on Aflaj, the voluntarism shown by households to restore a damaged channel of the Falaj is fading. Restoring the damaged channel was essential for survival (drinking, cooking, and hygiene). Currently, groundwater is almost exclusively used for farming, and the urgency for restoring the flows, in case of collapses, is no longer felt, as even farming is a hobby/secondary activity. This is partly a result of public interventions, bringing piped water, which is causing a slow degradation of Aflaj's infrastructure that has been preserved for millennia.

The majority of Aflaj are located quite far away from the coastal land, and many of them are in mountainous areas. Hence, the cost of transporting piped water until these rural locations is high both in terms of initial investments as well as in terms of operating and maintenance costs. It is an energy intensive process. In essence, the Aflaj water laws give utter priority of water allocation to the domestic uses. In the past, domestic uses were very small, compared to the agricultural demand, as households were allowed to take water from the sources but not to divert the source to their residences. There was no piped water in the villages, and farmers privately own groundwater. The creation of water markets between Aflaj (agriculture) and the cities increases the benefit of farmers and the city simultaneously and enhances the sustainability. Hypothetical, markets between farmers and the city are considered. Farmers, who are the water shareholders, can sell part of the Aflaj water to the city and buy tertiary/quaternary treated wastewater from the treatment plant. Aflaj water is of much higher quality than the treated wastewater; hence in the exchange, farmers will gain financially. The city, or water utility, will also gain since buying the water from Aflaj is much cheaper than buying and transporting desalinated water from faraway coastal areas. This allows recycling the tertiary/quaternary treated wastewater and sustaining the agricultural activity. The wastewater company can recover an important part of the treatment cost, which will enhance its financial sustainability. Most of the treated wastewater is currently disposed of in the Wadis (channels that are dry except in the rainy season) and is not generating any returns. Establishing the water markets require revising the water institutions to allow trade between farmers and the city. To facilitate such revision, students learn how to estimate the long run benefits to each party: city, farmers, and the treated wastewater company. While the estimation of benefits could facilitate water trade, a social approach to persuade farmers of the unsustainable current practices of supplying desalinated water and reviving the historical principles of Aflaj management would weaken any resistance against trade. In Muscat city, all parks and landscapes are irrigated from treated wastewater. Citizens are progressively accepting the treated wastewater re-use. Many agricultural products irrigated with treated wastewater, imported from Jordan and other countries, are sold in the GCC countries. Progressively the social resistance to treated water recycling is diminishing. The advantage of water markets, among cities and Aflaj, is that the farmers will be properly compensated through the transactions. Finally, not all groundwater will be transferred to cities as the demand is not that high. Hence, consumers looking for local agricultural products irrigated with fresh water will always find them.

6 Water-Energy Nexus, the Transition Toward the Use of Renewable Energy and Desalination for Agriculture

Desalination is an energy-guzzling process currently met by fossil fuels. Desalination is simply changing the scarcity from the water sector to the energy sector. For instance, Darwish et al. (2008) alarmed on the consumption of electricity and desalinated water in Kuwait and their high growth rates. They estimated that all of Kuwait's oil production will be used to produce water and electricity in about thirty years to satisfy demand. Although their estimations are based on constant technology assumptions, the desalination is causing stress on the energy sector. In Saudi Arabia, 3.4 million barrels of oil equivalent are burned daily out of which 10 to 20 percent are used for desalination as of 2010 (Rambo et al., 2017). Although the desalination technology did improve during the last decade, reverse osmosis, the most efficient technology, compared to multistage flash and multi-effect desalination, uses 3.5 to 5.0 kWh of electricity per cubic meter depending on the size of the plant and the salinity of the intake water. The supply augmentation of desalinated water increases the domestic consumption of oil and gas and reduces the revenue from the oil sector, the main source of income.

The use of renewable energies for desalination is still in its infancy and is applied at small-scale plants. Costs of desalination using renewables vary considerably according to the type of renewable energy used and plant capacity. For instance, for seawater reverse osmosis combined with photovoltaic solar power, the cost is 11.7–15.65 $/m^3$ (Bundschuh et al., 2021). Most of the innovations are undertaken at research centers and universities. Large desalination companies often benefit from a highly subsidized cost of energy that in turn discourages innovations for the transition toward renewables (England & Al-Atrush, 2022). Students are taught that West Australia enacted regulations, for new desalination plants, to use renewable energy sources (Knights et al., 2007); https://www.energymatters.com.au/renewable-news/em515/).

Small desalination units is a decentralized solution to water supply compared to the current highly centralized plants. Several options exist in the market for family level or village level. Solar stills are the simplest devices to desalinate water, utilizing direct solar radiation, for low capacity water supplying systems in remote areas. The solar still is based on the principle of evaporation and condensation process. Hydro-panels is a technology that produces water for houses or the village/district level. A hydro-panel is a combination of solar panels and a system that harvests water drops from the air (Ferwati, 2019). The costs of desalination are high but could be a good alternative for remotely located houses for drinking and cooking purposes only. Some of these options are available in the market, and prices vary from $0.0066 to $0.30 per liter (Zekri & Al-Maamari, 2020). Standalone systems represent new water supply systems for remote areas with dispersed population. In some circumstances, the savings on network connections make the standalone system profitable.

The course addresses the feasibility of desalination water for irrigation purposes. Very few farmers in the GCC have adopted small desalination units, often to overcome the salinity problem of the groundwater. The course goes beyond estimation of the costs and benefits to farmers. Students' attention is called on international trade of agricultural products, or virtual water, as an alternative to groundwater abstraction and desalination (Kajenthira Grindle et al., 2015; Ouda, 2014). In fact, given the economic openness of most GCC countries to international trade, desalination for irrigation has little room, despite the electricity price subsidy, except for hobby farms. Local products require substantial volumes of water due to the extremely hot environment and hence are not competitive with imports (Al Jabri et al., 2019). Finally, yet importantly, the desalination units place more stress on the electricity grid during summer's peak hours, and the negative impacts of disposal of the brine into the aquifers causes further degradation of the groundwater quality.

7 Environmental Impacts of Desalination

Often the water sector calls for a high initial investment cost followed by a very long pay-back period. This is quite different with desalination plants as they are capital intensive but their expected life is 20–30 years. These plants depreciate within a single generation and do not span to future generations like dams or water pipes. Hence, the appetite of the private sector to invest in desalination plants with long-term contracts (take-or-pay) with fixed prices labelled in hard currencies and volumes clearly specified and agreed on. Private companies are selected on one criteria: the lowest desalination cost. The negative externalities are not taken into account for the selection. This type of contract encourages a supply policy approach and discourages the desalination companies to cut down their negative impacts or even to innovate and find better solutions to the process of desalination in a way that it is less harmful to the marine environment. Fortunately, public authorities in developed countries are starting to realize that the environmental impacts are of concern. Recently in California, the Coastal Commission unanimously voted against the construction of a new desalination plant in Huntington Beach. The rejection was based on the negative impacts on marine life, the high costs to the water users, and the choice of the location and lack of near-term need of the water (Phys.org, n.d.).

However, the water authorities and desalination plants in the GCC countries are still behaving as if seawater in the Arabian Gulf is unlimited and the negative externalities are minimal. Although for each new desalination project, an environmental impact assessment is ordered, in reality the cumulative impacts of the different plants and other economic activities are never considered. Eight countries are bordering the Arabian Gulf. In addition to the pollution from desalination plants, the other economic activities are also contributing to the pollution among which the power plants, the oil industry, and transportation are the most polluting.

Most GCC countries withdraw seawater for their desalination plants from the Arabian Gulf or Red Sea. le Quesne et al. (2021) affirm that the environmental impacts caused by the brine disposal loaded with chemicals, used as anti-fouling and membrane cleaning, as well as the loss of marine life through seawater intake to the process are of high concerns in the Arabian Gulf. The desalinated volumes from plants based on the Arabian Gulf increased from 0.04 million m^3/day in 1970 to reach 21 million m^3/day in 2018. For every desalinated 1 million m^3 plants pump 2.3 million m^3 from the sea, as water feed intake. Hence, 1.3 million m^3 return back to the sea in the form of brine. The impacts of brine are essentially due to the high level of salinity; low level of oxygen content, chemicals, and total alkalinity; and high temperature. The average salinity in the Arabian Gulf reached over 39 parts per thousand (ppt), and it is predicted that it will rise to 70 ppt in low flashing and shallow embayment. The salinity of seawater in the east side of Qatar is already around 45 ppt, and for the west side it is 57 ppt, which is comparatively higher than the other regions. Reverse osmosis can tolerate a maximum feed water salinity of 70 ppt (Panagopoulos, 2021). Observe that the higher the salinity of the seawater, the higher the cost of desalination. Not only future costs of desalination will increase, due to higher energy requirements, but most importantly the predicted temperature increases, caused by the brine disposal, could lead to significant impacts on species persistence, biodiversity, fisheries productivity, and coastal communities (le Quesne et al., 2021). The sought economic diversification and the transition to an economy independent from fossil fuels will require the preservation of the natural capital (sea and marine environment), in the instance of the Arabian Sea, on which several economic activities (tourism, recreation, fishing, diving, etc.) rest. There is need for major changes to ensure the sustainable use of the Arabian Gulf. The cost of water does not take into account the negative externalities caused by brine disposal. There is an absence of studies valuing these environmental impacts. Most of the existing studies dealt with physical and biological impacts such as the water temperature increase, the salinity increase, bleaching of coral reef, and the loss of marine biodiversity (Campos et al., 2020; Ibrahim & Eltahir, 2019; Sezer et al., 2017).

Panagopoulos and Haralambous (2020) summarized several studies that addressed the reduction or the elimination of the brine. Among the solutions, several will only transfer the pollution problem to other resources, such as groundwater, surface water, or land. It is stressed that the evaporation of the brine is the least polluting method and the most expensive, with costs ranging between \$3.28 and \$10.04/m^3. Production of table salt is among the products considered. Every cubic meter of brine produces 70 kg of salts. If all brine in GCC countries is evaporated, production of table salt would exceed 2 million tons/day, which will find no market to absorb it.

The total elimination of brine disposal, by evaporation or other means, though environmentally very sound, is not currently economically feasible, as it will increase drastically the cost of desalination. Hence, chances for desalination plants to adopt the zero liquid discharge are remote. It will be hard for public decision makers, depending on desalination from the Arabian Sea, to agree on the future brine policy to adopt. At current state-of-the-art, the cost of brine disposal is three to ten times the cost of desalinating the water. How much of the brine disposal cost can be charged to water users remains a question. An important step in terms of policy is that in the future, contracts with desalination companies should consider the negative externalities as one more criteria in the selection process. This would encourage companies operating in the sector to speed up innovations and cut down the cost of brine disposal.

8 Conclusions

Teaching water economics in desert regions is oriented toward demand management policies given the acute water scarcity. Issues related to rate setting, water pricing, quantity rationing, and technology adoption are of prime importance for the management of urban water. Supply of desalinated water represents an important part of the GCC countries' public expenditures. The course addresses groundwater, the only renewable water resource, through the lenses of property rights, smart metering, and quota allocations as well as international food trade and/or virtual water imports. The course exposes the students to the limits of desalination as a source of fresh water and the environmental costs it generates. Supply of desalinated water depends on the availability and access to a brackish source or seawater.

The increased salinity of the Arabian Sea and the increase in the temperature of the seawater are a worry for the six countries depending on it as a source for desalination. The increase of the seawater salinity has a direct impact on the cost of desalination. The loss of marine life, biodiversity, fish diversity, and harvest all negatively affect the sustainability of the sea as a natural resource, which is supposed to be the basis for economic diversification in the region.

There is an urgent need of policy changes that would foster the transition toward the integration of renewable energies in desalination. Currently, the public water authorities select the private desalination companies on the least cost supply of fresh water. Minimization of the environmental brine impacts is equally important as the cost of water from a sustainability point of view.

The main messages from the course are the need to reduce water demand (reduce waste) to much lower levels, without causing a loss of utility or comfort. Pricing and quantity restriction are variables that water managers' control to influence users' water demand. The course discusses the issues of access of water to the poor, in developing countries, and of fairness in general. The students learn about new pricing methods that take into account the households' revenue and family size. The course strongly recommends the transfer of some of the agricultural water to urban uses, whenever economically feasible, through water markets and the recycling of the treated wastewater in irrigation. Policies that foster the transition from a supply side to a demand side are the core of the course.

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Teaching and Educational Methods

Solving Optimal Groundwater Problems with Excel

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Keywords: Coastal aquifers, dynamic optimization, Excel Solver, groundwater management, sustainable yield

Abstract

Welfare maximizing management of coastal groundwater requires a sequence of pumping targets, typically terminating with a constant withdrawal rate in the long run. In contrast, managing according to sustainable yield at best identifies the constant rate of pumping in the long run. We illustrate an accessible solution method, using Excel Solver to find the optimal transition paths of groundwater pumping, price, and head level and the corresponding solutions in the long run. The developed framework is applied to the Pearl Harbor Aquifer (PHA) in Hawaii using data from previous studies. Each step of the solution process is described, including setting parameter values and defining objective, variable, and constraint cells in Excel to facilitate successful replication of the results. Possible extensions are also discussed such as watershed conservation, protection of groundwater dependent ecosystems, and management of multiple aquifers.

1 Introduction

Groundwater depletion and degradation, exacerbated by climate change, are increasingly recognized as critical issues in many groundwater-dependent parts of the world. Over time a typical aquifer is recharged naturally from precipitation that infiltrates below ground and can also be recharged via irrigation return flow, due either to canal leakage or excess applied water not consumed by crops. The cost of withdrawing groundwater is a function of lift, or the distance between the water table and the surface. The relevant management problem is to determine how much groundwater to withdraw over time, taking into account whenever possible the interlinkages between the aquifer, the watershed, and groundwater-dependent ecosystems.

Groundwater resources account for 99 percent of Earth's freshwater,[1] yet only a fraction of this is accessible without exceedingly large pumping costs and without risking salinization or over-depletion. Groundwater provides for all the daily water needs for one third of the world's population and is the only source of freshwater for all human needs in many parts of the world, particularly in remote and dry areas (World Bank 2016). Groundwater provides a buffer to climatic variability, acts as storage during droughts, contributes to river flow, and supports near shore marine ecosystems. Global groundwater withdrawals have more than quadrupled in the last 50 years. This extraction uses significant amounts of energy, although because energy is often heavily subsidized, the true costs of groundwater extraction are misunderstood, unknown, or ignored completely. While resource economics provides the tools to make the full value of groundwater transparent, so far there has not been adequate coverage of this topic in textbooks and many classrooms, especially as compared to nonrenewable resources such as oil and coal, or renewable resources that traditionally command a tradeable price in the market such as fish and forest products. Without a clear understanding of the efficient extraction and pricing of

[1] For a more detailed accounting of the Earth's water resources, including ice and permafrost, see Water Science School (2018).

groundwater, students (and practitioners) are left with picking a long run target such as maximum sustainable yield (MSY) and an inevitably ad hoc and arbitrary approach path, which will further exacerbate the global water scarcity crisis.

While textbooks developed for undergraduate and graduate classes in natural resource economics provide complete coverage for exhaustible resources such as coal or oil, as well as full chapters devoted to renewable resources such as fisheries and forests, the chapter on water resources is typically focused on the difference between finding efficient allocations for surface water versus groundwater, with limited details provided for optimal groundwater extraction and pricing over time (Perman, McGilvray, and Common 2003; Field 2015; Tietenberg and Lewis 2020). In this chapter we provide what is currently missing in natural resource economics textbooks to facilitate understanding of the optimality conditions for groundwater resources.

To add more complete coverage of efficient allocation and pricing for groundwater resources, this framework was used in advanced undergraduate and master's level Ecological Resource Economics classes by one of our co-authors during her sabbatical teaching at Kobe University in Japan.[2] The derivation of the Pearce equation in conjunction with the Excel example facilitated clearer understanding of optimal allocation and pricing, especially since the chapter on water in the textbook used in the course (Tietenberg and Lewis 2020) followed a detailed discussion of the optimal price equation for nonrenewable resources but provided no corresponding explanation for renewables. Seeing the marginal extraction cost (MC), marginal user cost (MUC), and marginal externality cost (MEC) components of the Pearce equation in this manuscript helped the students clearly see the connection and differences compared to the same analysis of nonrenewable resources. This is an important and missing piece to many natural resource economics textbooks currently available. Without the Pearce equation provided in this chapter, learning outcomes regarding efficient allocation and pricing of groundwater were incomplete and imbalanced compared to more in-depth coverage of nonrenewable resources or renewables such as fisheries or forests. In particular, the explanation of the MUC reflecting the intertemporal opportunity cost of groundwater is a crucial but often underappreciated component in teaching groundwater economics.

In what follows, we focus primary attention on coastal aquifers, inasmuch as inland aquifers can be analyzed as a special case. A coastal aquifer can be thought of as a freshwater lens floating on denser underlying ocean water, where the volume of groundwater in storage depends primarily on the aquifer's boundaries, porosity, and head level (Figure 1). In particular, the greater the head level, the more water is discharged into the ocean, decreasing net recharge.

In many jurisdictions, including water-challenged states such as California and Hawaii, management of groundwater relies on the principle of sustainable yield (Roumasset and Wada 2010, 2013; Elshall et al. 2020). California's Assembly Bill No. 1739, Chapter 347 defines their "sustainability goal" as "the existence and implementation of one or more groundwater sustainability plans that achieve sustainable groundwater management by identifying and causing the implementation of measures targeted to ensure that the applicable basin is operated within its sustainable yield." The bill defines "sustainable yield" as the maximum quantity of water that can be withdrawn annually from a groundwater supply without causing an undesirable result. Hawaii's groundwater regulators also base groundwater management on sustainable yield, defined as the maximum extraction rate that can be sustained without "impairing" the aquifer. The Hawaii Water Commission then exercises some discretion in determining whether a proposed increase in extraction is too close to sustainable yield.[3] A number of other states in the United States are increasingly governed by similar types of regulations,

[2] A syllabus for the course is available in the online supplementary material.
[3] Hawaii State Water Code, Chapter 174c and L 1987, c 45, pt of §2; am L 1999, c 197 §6.

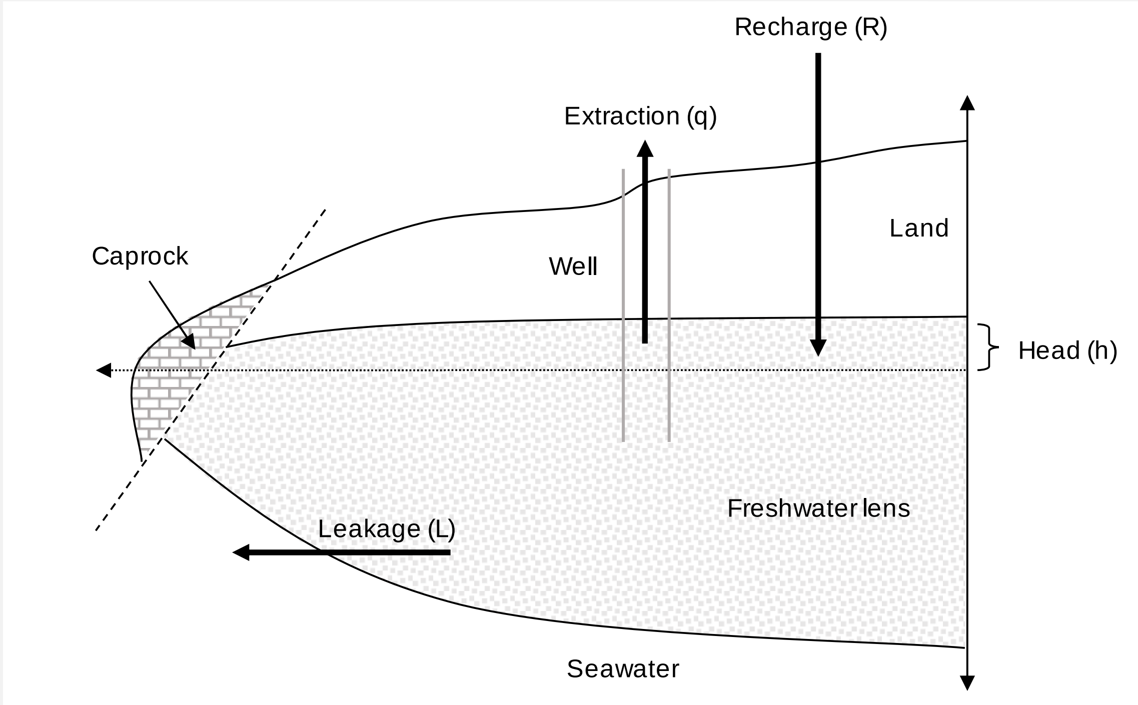

Figure 1: Cross-Section of Coastal Aquifer. Adapted from Roumasset and Wada (2012)

with Oregon defining "sustained yield" as "the amount of water that can be withdrawn from the groundwater basin annually without exceeding the long-term mean annual water supply to the reservoir"[4] and Arkansas and Louisiana both relying upon sustainable yield measures for groundwater management (Texas A&M University School of Law 2017).

The primary question for which resource economics was developed is how much to extract from a natural resource stock over time. The answer to the question is a vector. But California, Hawaii, and other jurisdictions relying on sustainable yield are implicitly searching for a scalar, as if one number could provide the answer for any number of years. Specifically, we seek the sequence of groundwater withdrawals over time that maximizes the present value (PV) of an aquifer. In some cases, the sequence of optimal withdrawals will converge to a single quantity to be extracted in the long run, called the "steady state" solution, which may or may not coincide with the stock corresponding to MSY stock. The objective of this paper is to set up a framework to solve for the optimal management of a coastal groundwater resource and illustrate how the extraction and price paths can be solved in a user-friendly and transparent Excel spreadsheet suitable for classroom use. We conclude by discussing possible extensions to the basic groundwater management problem to allow for additional challenges such as multiple water resources, consideration of linked groundwater dependent ecosystems, and improved recharge due to upstream watershed conservation.

2 Sustainable Yield Is Incomplete as a Management Strategy

Groundwater is typically viewed as a renewable resource in the sense that aquifers—subsurface layers of water-bearing permeable rock or sediment—can be replenished over time by groundwater recharge. The natural recharge rate, which is primarily determined by precipitation, is analogous to the biological

[4] This approach embodies two fallacies. First, the existing stock, which the strategy aims to maintain, may be either too high or too low. Second, the goal is to identify a constant extraction rate when consumer welfare may require lower amounts in early years.

growth rates that characterize other renewable resources such as trees and fish. An aquifer can also be recharged by irrigation return flow due to canal leakage and/or excessive application of water to crops, as well as by inflows from adjacent and more elevated bodies of freshwater. In the case of a coastal aquifer, even in the absence of pumping for aboveground uses, groundwater naturally discharges from the aquifer at the ocean boundary. The rate of submarine groundwater discharge (SGD) along the saltwater interface is a function of the groundwater stock, inasmuch as a larger stock creates a wider surface area across which groundwater can discharge, as well as more pressure at the interface. Thus, left unharvested, the groundwater stock grows due to natural recharge, and the rate of growth depends on stock-dependent SGD. With these resource characteristics in mind, the water manager's challenge is to determine how much groundwater to pump over time.

In the past, a common management recommendation by non-economists was to limit extraction of a renewable resource to a safe yield or sustainable yield. In the context of groundwater, the former constrains pumping by the amount of recharge, while the latter takes into account discharge as well, such that the constraint is based on groundwater capture (net recharge). More recently, groundwater management in many regions has evolved toward some form of sustainable groundwater management that accounts for hydrological, environmental, and socioeconomic consequences of pumping, while incorporating stakeholder participation and adaptive governance (Elshall et al. 2020). Although much more holistic than earlier approaches to groundwater management, recent efforts still often focus on what yield can be sustained in the long run without clear recommendations on how to approach said long run yield. Only by coincidence can this approach find the extraction path that maximizes the contribution of groundwater to the general welfare.

In contrast, resource economics poses the question: "What is the approach path that maximizes the contribution of an aquifer to consumer welfare?" In the remainder of this paper, we discuss, in simple terms, the welfare maximization problem and provide an example of how to find the optimal approach path using a framework developed for Excel's Solver.

3 Optimal Extraction Is Sustainable But Not the Other Way Around

This section begins with an intuitive derivation of the governing equations for the groundwater management problem. Although not used directly in the Excel application, we provide what is currently missing in natural resource economics textbooks regarding the optimality conditions for groundwater resources, couched in relatively simple marginal benefit and marginal cost terms, for students who may be unfamiliar with dynamic optimization methods.[5] We then provide an approach to solve the standard groundwater management problem using Excel Solver. The section concludes with an application to the Pearl Harbor Aquifer (PHA) in Hawaii.

3.1 Intuitive Derivation of the Governing Equations

The standard resource economics approach to groundwater management is to maximize the PV of net benefits generated by the aquifer. The solution specifies both the optimal steady state stock level and the optimal approach path to that long run target. Although the optimal steady state level may be very close to or even coincide with the constraint specified by other groundwater management approaches, the rate of optimal pumping is typically not constant over time. Moreover, the corresponding groundwater stock level may follow an increasing, decreasing, or nonmonotonic path toward the steady state.

While there are an infinite number of candidate sequences that can potentially solve the maximization problem, we can narrow down the possibilities by imposing an *equation of motion* for the aquifer stock, which describes how the quantity of the groundwater stock (h) changes over time in response to pumping decisions in every period. The analytical solution to the water manager's problem requires a dynamic optimization approach such as optimal control, which requires proficiency in

[5] More rigorous mathematical equations describing the optimization problem can be found in the Appendix.

differential equations. To promote accessibility, we provide an intuitive derivation of the necessary condition for maximum welfare instead. We then explain and illustrate how to use Excel Solver to obtain numerical solutions.

We start with the simplification wherein SGD is zero (e.g., an inland aquifer), and the recharge rate is very low (effectively zero over the management horizon of interest). In this case, groundwater can be treated as a nonrenewable resource and the derivation proceeds accordingly. As with many other problems, optimal extraction is governed by the *Nike rule of economics*: *Just do it until marginal benefit equals marginal cost*. In this case, it is convenient to consider the marginal benefit and cost of "waiting," that is, postponing harvest of the marginal unit by one period. The marginal benefit of waiting is $\dot{p}$, that is, the capital gain from selling at next period's price. The marginal cost of waiting is the foregone interest from harvesting today instead of one period later, that is, the real interest rate times the net price or $r(p\text{-}c)$. Dividing both sides by r and adding cost to both sides yields

$$p_t = c(h_t) + \frac{\dot{p}}{r} \tag{1}$$

Equation (1), called the "Pearce equation," says that groundwater should be extracted in every period until the marginal benefit of extraction is equal to the MC plus a second term $\frac{\dot{p}}{r}$, which is referred to as MUC.[6] The MUC is the loss in PV that would result from an incremental reduction in the resource stock.[7] If equation (1) were not satisfied, there would be an opportunity to increase PV welfare by reallocating pumping over time. For example, if the left-hand side of equation (1) was less than the right-hand side for some period t, welfare could be increased by reallocating excess pumping into the future. That is, the discounted capital gains of leaving some of the groundwater *in situ* would exceed the marginal benefit of pumping that water in period t.

The simple Pearce equation (1) can be extended to the more general renewable case by expanding the MUC term. For a renewable groundwater resource, the "extra benefit of waiting" is determined by how much the net recharge of the aquifer, valued at the net price, changes in response to a marginal increase in the groundwater stock. Now the condition that the marginal benefit of waiting must be equal to the marginal cost of waiting is given by:[8]

$$p_t - \mathrm{c}(h_t) = \frac{\dot{p}}{r} + M(h_t) \tag{2}$$

Because both net recharge and unit extraction cost are functions of the head level in this case, they show up in the second component (M) of the MUC expression. There are now two competing effects of extraction: (1) reducing the stock increases future pumping costs, but (2) reducing the stock also reduces SGD and hence increases net recharge. Solving the management problem using the Pearce equation ensures that this tradeoff is accounted for and that the resulting solution maximizes PV. However, as discussed in the following section, using the Pearce equation directly to numerically solve real-world groundwater optimization problems can sometimes be challenging. The remainder of the paper describes a relatively simple alternative approach using Excel's Solver.

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[6] We call this the "Pearce equation" in honor of David Pearce, e.g., Pearce and Markandya (1989). The full Pearce equation is P = c + MUC + MEC, where MEC is the marginal externality cost, for example, the pollution cost of a resource such as coal.

[7] For a demonstration that the lost PV from mining the marginal unit of a nonrenewable resource is $\frac{\dot{p}}{r}$, see Pongkijvorasin and Roumasset (2007).

[8] See the Appendix for a more detailed discussion about the components of $M(h)$.

3.2 Numerical Solution Strategies: Back to the Future, Forward to the Future, and Solver

The problem is now how to operationalize the theory so that students can solve for the optimal extraction path, given aquifer parameters and demand over time. While solution methods for nonrenewable resources and fisheries are well known, for example, the Excel solutions in Conrad (1999), there are no comparable methods for groundwater economics available in any textbook. Even in advanced articles that use the Excel method for groundwater economics, space limitations have precluded a complete exposition suitable for students.

Different algorithms can be devised to solve the groundwater extraction problem described above. In this section, we discuss two options that directly use the necessary conditions for the optimal control approach. The first solution algorithm starts at the future steady state and works back to an ever less distant future. If demand for water is growing over time, we can be sure that a backstop resource, an abundant but costly alternative such as desalination, is eventually implemented in the steady state, and thus the steady state efficiency-price will be $p^* = c_b$, where c_b is the unit cost of desalination. It will then also be possible to solve for the optimal steady state head level h^* by setting $\dot{h}$ and $\dot{p}$ equal to zero in the equation of motion and the Pearce equation (2). We do not, however, know the time T, at which the efficiency price path optimally reaches c_b. Therefore, the first step is to guess T. The Pearce equation with $p_T = p^*$ and $h_T = h^*$ will then tell us the value of p_{T-1} along the candidate optimal path. Once p_{T-1} is determined, h_{T-1} can be generated using the equation of motion. This process can be repeated until $t = 0$ (the initial period), at which point the h_0 generated by the candidate path should be compared to the actual initial head level. If the candidate and actual initial values match, then the solution is optimal. If not, the guess for T must be adjusted, and the process repeated until the initial conditions match.

An alternative approach is to guess the initial efficiency price and iterate forward. With the initial head level h_0 given, a guess for the initial efficiency price p_0 allows us to determine the head level in the next period using the equation of motion, as well as the efficiency price in the next period using the Pearce equation (2). This process can be repeated until the price reaches the optimal steady state price p^*. Recall that we can solve for h^* and p^* by setting $\dot{h}$ and $\dot{p}$ equal to zero in the equation of motion and the Pearce equation. If the head level reaches h^* by the time $p = p^*$, then the initial guess for p_0 was correct, and the candidate paths are optimal. If not, then the guess for the initial price should be adjusted, and the process repeated until the terminal conditions are satisfied.

3.3 An Alternative Approach Using Excel's Solver

For relatively simple groundwater optimization problems, Excel's Solver can be used to find the PV-maximizing paths without using the Pearce equation directly. There are three types of cells required to complete a Solver evaluation: (1) objective cells, (2) variable cells, and (3) constraint cells. In the context of groundwater management, the objective cell contains the PV of water consumption—this is the value to be maximized. The setup should also include two columns of variable cells, one each for the quantity of groundwater pumped and the quantity of desalination, where each row represents a time period, that is, the first row includes control variables for $t = 1$, the second row includes variables for $t = 2$, and so forth. Lastly, a vector of constraint cells should be added that incorporates the equation of motion for the groundwater stock. Note that the initial value for the head level h_0 should be included in the first constraint cell, and an initial guess for candidate solution values should be filled in for the variable cells. When Solver is selected in Excel, a dialog box will pop up asking the user to "set the objective" (objective cell) "by changing variable cells" (variable cells), "subject to the constraints" (constraint cells). Once the appropriate cells are selected, the user should also ensure that "max" rather than "min" is selected and choose one of three solving methods from the pulldown menu. Clicking "Solve" instructs Solver to adjust the values of the control variable cells, subject to the constraint cells, until the PV in the objective cell is deemed a maximum.

Although the numerical solution using Solver is relatively straightforward, there are a few caveats to keep in mind. First, because the length of the control and constraint vectors are chosen before the optimization takes place, this approach is more suited for finite time horizon problems, that is, problems for which the number of management periods is predetermined. Nevertheless, the infinite time horizon solution can be approximated by rerunning the simulation for longer and longer time horizons until the terminal values are not sensitive to the extension.

3.4 Pearl Harbor Application

Using the PHA on Oahu, Hawaii, as a case study, we provide a step-by-step example of how to apply the Excel Solver method described above. Model assumptions including parameter values are largely drawn from Burnett and Wada (2014). We provide as a supplement to this paper an Excel spreadsheet containing all of the equations and parameters we describe below, along with the maximized solution paths for our two demand cases.

In the case of Pearl Harbor, freshwater can be extracted (q) via pumping wells, but it can also discharge (L) naturally through low permeability caprock (coastal plain deposits) that bounds the freshwater lens along the coast (Figure 1). As the head level (h) declines, the fresh water lens gets thinner and begins to mix with the ocean water below it. At some point, *hmin*, any further extraction would yield water saltier than the environmentally prescribed maximum allowable concentration.[9] Note that since extraction could otherwise continue, thereby increasing net recharge further, net recharge is still a decreasing function of the head level at *hmin*.

We define the period-t benefit (B_t) as the area under the inverse demand curve for water up to the total quantity consumed (Q_t) in period t. The demand for water is modeled as a constant elasticity function: $D(p_t, t) = \alpha e^{gt} p_t^{\eta}$, where g is the growth rate of demand, η is the demand elasticity, and α is a coefficient calculated using actual pumping and price data. The inverse demand curve is then $p_t = ((Q_t/\alpha)e^{-gt})^{(1/\eta)}$. Values for the demand parameters α, η, and g, are assigned to cells B2, B3, and B4, respectively, in the Excel spreadsheet (Figure 2).

The total quantity of water consumed in period t is the sum of the quantity of groundwater extracted (q_t) and the quantity of desalinated water (b_t), that is, $Q_t = q_t + b_t$. When it is optimal to use the backstop resource, total quantity is determined by the backstop price:

$$Q(p_t = p_b) = \alpha e^{gt} p_b^{\eta}, \tag{3}$$

where $p_b = c_b + c_d$. Values for the unit cost of desalination (c_b) and the unit cost of distribution to end users (c_d) are assigned to cells E4 and E5, respectively, in Figure 2. For each period, the total quantity (that would be) demanded at the backstop price is calculated in cells (D9:D108). Following equation (3), in period 1, for example, D9 = $B$2 * (($E$4 + $E$5) ^ $B$3) * (EXP($B$4 * A9)). Note that for the case with zero demand growth, this value remains constant over time. The optimal desalination quantity in each period is determined in cells (E9:E108) according to the following criteria: if $q_t \geq Q(p_b)$, zero desalination is optimal; if $q_t < Q(p_b)$, the optimal quantity to desalinate is $Q(p_b) - q_t$. The formula for period 1, for example, is E9 = IF(B9 > D9, 0, D9 - B9).

Recalling that the total quantity of water demanded is the sum of the quantity of groundwater extracted and the quantity of desalination, we can now go back to the inverse demand curve, which will be used to generate the efficiency price path (C9:C108). As a starting point, the efficiency price in period 1 is C9 = (((B9 + E9) / $B$2) * (EXP(-$B$4 * A9))) ^ (1 / $B$3) in Figure 2. In subsequent periods, the efficiency price changes in accordance with changes in the optimal quantities of extracted groundwater and desalination.

[9] For the United States, the Environmental Protection Agency sets this limit at 2 percent of ocean salinity.

	A	B	C	D	E	F	G	H	I	J
1	water			cost			head			
2	alpha	107.40		beta	0.00137		R	220		
3	n	-0.25		e	272		h0	17.10		
4	g	0.00		cd	3.39		hmin	15.125		
5	r	0.03		cb	8.46		gamma	78.149		
6	q-cutoff	20								
7										
8	time	q	p	Q (p = pb)	b	C	h	l	hdot	PVNB
9	1	77.2	3.75	57.89	0.00	3.74	17.10	73.40	0.32	5,006
10	2	77.2	3.75	57.89	0.00	3.74	17.42	76.20	0.31	4,858
11	3	77.2	3.75	57.89	0.00	3.74	17.74	78.94	0.30	4,715
…	…	…	…	…	…	…	…	…	…	…
108	100	77.3	3.74	57.89	0.00	3.73	23.84	142.43	0.00	257
109							23.84		TPVNB	160,971

Figure 2: Excel Spreadsheet for the Case of Optimal Groundwater Management with No Demand Growth

The remaining piece to consider in the objective function is the unit cost of groundwater extraction, which is specified as a linear function of lift:

$$c_q(h_t) = \beta(e - h_t) \tag{4}$$

where e is the ground surface elevation of the well, $e - h_t$ is the the distance groundwater must be lifted to the surface, and β is a coefficient calculated using actual pumping cost and lift data.[10] The extraction cost coefficient and elevation values are specified in cells E2 and E3, respectively, in the Excel sheet (Figure 2). As was the case for desalinated water, we want to include the cost of delivering the pumped water to end users (E4). The unit cost of groundwater, inclusive of distribution, is calculated for each period in (F9:F108). Following equation (4), for period 1, the Excel formula is F9 = $E$4 + ($E$2 * ($E$3 - G9)). Because the extraction cost is a function of the head level, we next have to characterize the change in head level over time.

As previously mentioned, the relatively simple hydrology of the modeled aquifer is represented by an equation of motion that describes how the quantity of the groundwater stock (h) changes over time in response to inflows and outflows of water in every period. Outflow from the aquifer is composed of extraction (what we are trying to solve for) and leakage or SGD. Like unit extraction cost, leakage from the aquifer is a function of the head level in every period, although in this case the relationship is assumed to be quadratic:

$$L(h_t) = 0.24972h_t^2 + 0.022023h_t \tag{5}$$

Leakage is calculated for every period in (H9:H108). Following equation (5), period 1 leakage, for example, is determined using the formula H9 = (0.24972 * (G9 ^ 2)) + (0.022023 * G9). Inflow is determined by an exogenous rate of recharge (H2). Putting everything together, the change in head level in every period ($\dot{h}$ or "hdot" in Figure 2) depends on the constant rate of recharge, the quantity of groundwater extracted (B9:B108), the amount of leakage (H9:H108), and a head-volume conversion factor (H5):

$$\gamma \cdot \dot{h} = R - L(h_t) - q_t \tag{6}$$

Following equation (6), the first period $\dot{h}$ value is calculated using the Excel formula I9 = ($H$2 - B9 - H9) * 365 / $H$5. Note that the change is multiplied by 365 to convert annual units to daily values. Finally, the head level in each period $t + 1$ is calculated as the head level in the previous period t plus $\dot{h}$. Thus for $t = 1$, h_2 is calculated using the formula G10 = G9 + I9.

With all of the economic and hydrologic variables and parameters now accounted for, the final step before applying the Solver optimization is to define the objective of the maximization problem. For each period, the present value net benefit (PVNB) is equal to the area under the inverse demand curve (B), net of extraction and desalination costs, discounted at rate r (B5):

$$e^{-rt}\left[B(q_t + b_t) - c_q(h_t)q_t - c_b b_t\right] \tag{7}$$

Following equation (7), PVNB for period 1, for example, is calculated using the following Excel formula: J9 = ((((((EXP(-$B$4 * A9) / $B$2)) ^ (1 / $B$3)) * (($B$3 / ($B$3 + 1))) * ((B9 + E9) ^ (($B$3 + 1) /

[10] More generally, the exponent for the lift term need not be equal to one, particularly when considering management of multiple wells simultaneously, because in that case, pumping may be shifting to (more costly) higher elevation wells as the aquifer is drawn down over time. For our purposes, we assume that the need for more wells at higher elevations occurs so rarely that the extraction function is approximately linear.

$B$3) - ($B$6) ^ (($B$3 + 1) / $B$3)) - ((B9 * F9) + (E9 * ($E$4 + $E$5)))) * EXP(-$B$5 * A9))), where the formula for the area under the inverse demand curve has been substituted for B. Note that a minimum quantity or choke price is required to ensure that the area under the demand curve is finite; in this case *q-cutoff* is set at 20 units (B6). The total PVNB or TPVNB over the entire planning horizon is then J109 = SUM(J9:J108).

To solve the groundwater optimization problem, start by opening the "Solver Parameters" dialog box (Figure 3). The TPVNB cell ($J$109) should be set as the objective, and the "Max" option should be selected. Next, Solver requires the user to specify which cells to change to find the solution. For this problem, the objective is to maximize TPVNB by "changing variable cells" $B$9:$B$108 (the groundwater extraction path). For many standard problems, it may be sufficient to check the box "Make Unconstrained Variables Non-negative," but in this particular case, there is a minimum allowable head level (*hmin*), below which pumped groundwater would have unacceptably high salinity levels. Therefore, the following constraint is specified: $G$10:$G$109 > = $H$4. Note that to avoid an undesirable terminal effect where *q* is very high at *t* = 100 (resulting in *h* < *hmin* at *t* = 101), the

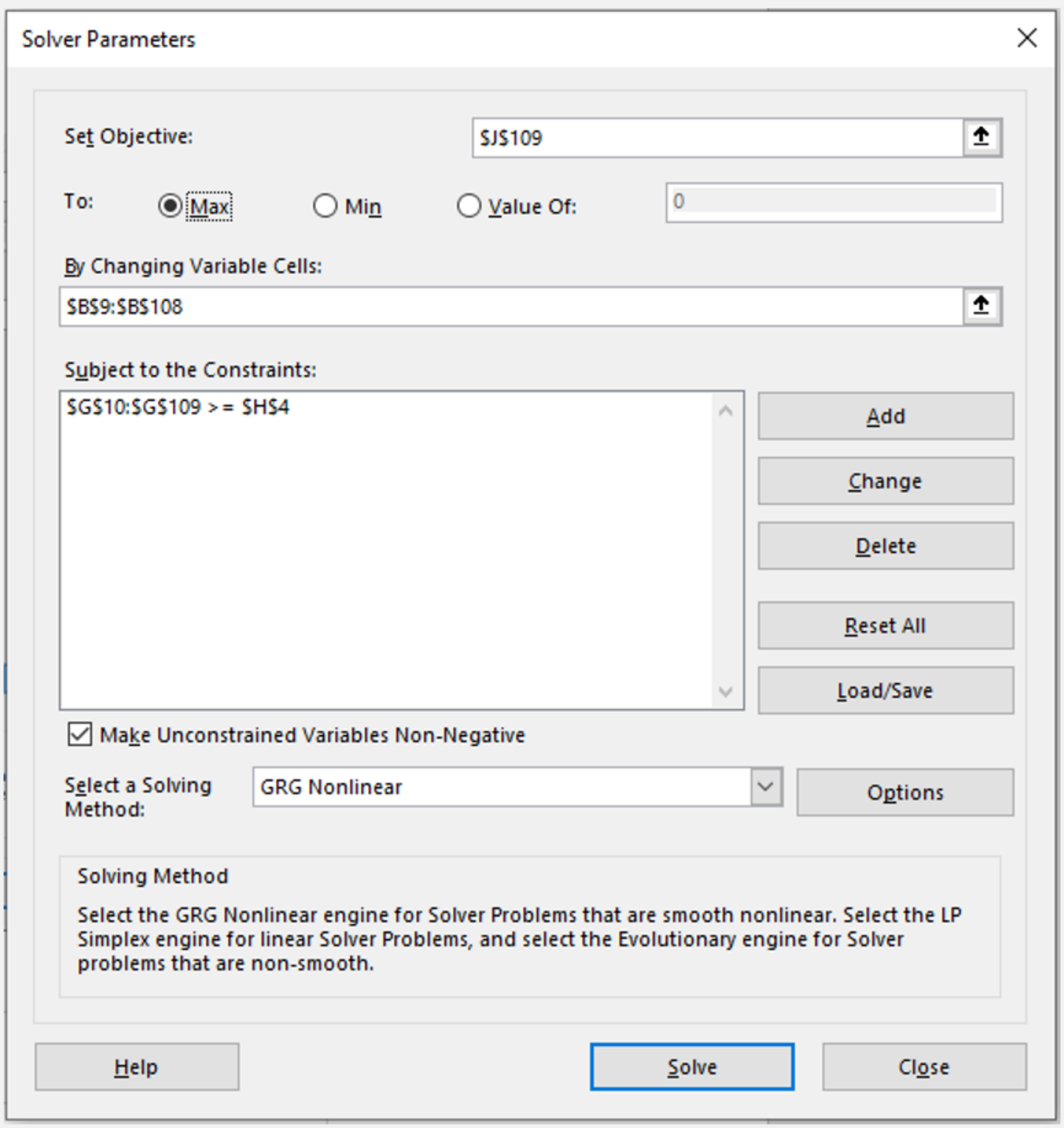

Figure 3: Solver Parameters Dialog Box for the Groundwater Optimization Problem

constraint is maintained from period 2 to 101. As previously discussed, Solver offers a few different solving methods. Here, the GRG Nonlinear method is appropriate. Once all of the parameters are specified, clicking “Solve” generates a solution.[11]

To test the robustness of the simulated results, sensitivity analysis can be performed by adjusting one or more of the parameter values in rows 2–6. The results for the case of 2 percent annual water demand growth are presented in Figure 4. Although the only parameter value adjusted in this case is in cell C4, the entire trajectories of groundwater extraction (B9:B108), efficiency price (C9:C108), desalination (E9:E108), and head level (G9:G108) are different from the no demand growth case in the optimal solution. The optimal paths of these key variables are plotted in Figure 5 for comparison. For the no growth case, the optimal head in the long run is higher than *hmin*, the head level corresponding to MSY, to economize on future extraction costs. Instead of conserving for the purpose of postponing desalination, you are conserving to earn a sustainable dividend from lower extraction costs. Growing demand guarantees that you eventually use desalination, in this case a little after 60 years. The backstop puts a ceiling on the efficiency price. Extraction is constant at MSY in the long run, and demand growth is entirely served by increasing desalination.

In the early (roughly 40) years, optimal extraction is below MSY, allowing the head to increase. Thereafter extraction is above MSY (optimal overdraft) until the head is drawn down to its steady state level (at year 64). From Figure 5, it is clear that the optimal trajectories of q and h are much different from the cases where extraction is set to maintain the current head level or to the level (*hmin*) that corresponds to MSY.

We can also see from columns C and F in Figure 4 that the efficiency price always exceeds MC along the optimal path, including at the steady state. This means that the common practice of setting p equal to extraction cost will induce consumers to waste water (use more than optimal).[12] We encourage teachers and students to get a feel for the optimality of this case as well as the no demand growth solution by trying slight deviations from the optimal exaction path in the Supplementary Excel worksheet (which contains the complete optimal solution for the 100-year time horizon for both cases) to see directly consequences of departing from the optimal path.

4 Extensions to the Basic Coastal Groundwater Management Problem

4.1 Interior Aquifers

The solution for the PHA can be emulated for any coastal aquifer. Since an internal aquifer is a special case of a coastal one, albeit with leakage (SGD) = 0, the Solver approach described can also work for that case. For cases of very low demand growth, however, the number of periods needed for convergence may be impractical. For such cases, the user can redefine the period length, say to 5 years (with the corresponding adjustment of the discount rate).

The spreadsheet-solution method can be also extended to include interlinkages between groundwater and upstream/downstream resources as discussed below.

[11] For the simple case illustrated below, the solution is not sensitive to the choice of initial values so long as they do not violate a constraint. For example, the method will still work even if initial extraction is set to zero. One strategy is to use the actual extraction rate as the guess for initial extraction.

[12] In the steady state, net recharge is entirely consumed and supplemented with the backstop resource. This means that a royalty is earned on the extracted water, but not from the backstop.

	A	B	C	D	E	F	G	H	I	J
1	**water**			**cost**			**head**			
2	alpha	107.40		beta	0.00137		R	220		
3	n	-0.25		e	272		h0	17.10		
4	g	0.02		cd	3.39		hmin	15.125		
5	r	0.03		cb	8.46		gamma	78.149		
6	q-cutoff	20								
7										
8	time	q	p	Q (p = pb)	b	C	h	L	hdot	PVNB
9	1	78.3	3.83	59.06	0.00	3.74	17.10	73.40	0.32	5,447
10	2	79.9	3.83	60.25	0.00	3.74	17.42	76.15	0.30	5,749
11	3	81.5	3.84	61.47	0.00	3.74	17.72	78.78	0.28	6,067
...	...	...	...	...	...	...	...	...	...	...
108	100	162.5	11.84	427.72	265.18	3.74	15.12	57.46	0.00	822,499
109							15.12		TPVNB	16,727,613

Figure 4: Excel Spreadsheet for the Case of Optimal Groundwater Management with Demand Growing at 2 Percent Annually

Figure 5: Optimal Trajectories for Groundwater Extraction, Desalination, Total Water Consumption, Efficiency Price, and Head Level for the Cases of 0 Percent and 2 Percent Annual Demand Growth

4.2 The Watershed

In the basic groundwater optimization model, we took recharge as exogenously given. More generally, recharge depends on the quality of the upstream watershed. Without maintenance expenditures, the watershed will tend to depreciate, often due to invasive species. Investment in watershed management can maintain a given quality, for example, through fencing and species removal, or improve the watershed condition, say by replanting. This relationship can be simply represented as $R(N)$ where R is the rate of recharge, and N is the quantity of watershed capital. The latter changes over time according to:

$$\dot{N}_t = I_t - \delta N_t \tag{8}$$

where I is the addition to watershed capital via investment and δ is the depreciation rate. The problem is to solve simultaneously for groundwater extraction and investment in watershed capital. The condition for optimal groundwater extraction is prescribed by the same Pearce equation (2) given previously. The condition for optimal watershed investment is again determined by the Nike condition. In this case, "just do it" refers to generating recharge. The marginal benefit thereof is the “shadow” price of water. Its marginal cost is the cost of increasing N by one unit divided by the marginal recharge from N, that is,

$$\frac{c_I(r+\delta)}{R'(N_t)} = \lambda_t \tag{9}$$

where c_I is the cost of investing in a unit of N, r is the real interest rate, and λ is the shadow price of water given by both its net price and MUC.[13] In this case, extending the basic groundwater optimization problem detailed in the previous section would require values for the recharge function parameters, as well as the depreciation rate and unit cost of investment. Investment in watershed capital for every period would also need to be included with groundwater extraction as control variables for the maximization problem, and the watershed capital itself should be tracked in every period, given that it enters the MUC in the Pearce equation via the recharge function. An example of joint watershed and groundwater optimization can be found in Wada, Pongkijvorasin, and Burnett (2020) for the Kiholo aquifer on Hawaii Island. A similar approach could be taken for the PHA using watershed conservation data from, for example, Bremer et al. (2021).

4.3 Groundwater Dependent Ecosystems

In the case of the isolated aquifer discussed previously, the SGD was important for calculating net recharge but any environmental effects of SGD were not considered. In general, SGD can change the concentration of nutrients in nearshore marine locations (e.g., bays and estuaries), and these effects can be either beneficial or harmful. In particular, SGD tends to lower the salt concentration and can support a valuable ecosystem that thrives in brackish water. On the Big Island of Hawaii, brackish water supports a native seaweed species that is sought after for local dishes (e.g., “poke bowl”) and is the foundation for a marine food web that supports invertebrates and other marine life (Duarte et al. 2010). SGD is a decreasing function of groundwater stock or head level. This means that in addition to MUC, groundwater extraction imposes the additional cost of reduced environmental benefits to the nearshore marine ecosystem.

A similar approach can be used to extend the basic groundwater optimization model for Pearl Harbor to include consideration of groundwater dependent ecosystems (GDE). Understanding of two key relationships is required. First, the relationship between SGD (l) and nearshore salinity (s) is given by:

$$s_t = f\big(l(h_t)\big) \tag{10}$$

The second relationship is between nearshore salinity and some biological measure of the valued groundwater dependent ecosystem such as the growth rate of seaweed (x):

$$x_t = w(s_t) \tag{11}$$

If the resource manager’s goal is to maintain GDE growth at or above a target level, then a constraint can be added to the standard optimization problem: $x_t \geq \underline{x}$. One can then derive a modified Pearce equation, wherein the MUC term is dependent on how fast x increases with h (the first derivative of equation (11) with respect to h), inasmuch as extraction decisions today affect future head levels, which in turn affect the trajectory of SGD and ultimately the valuable GDE (Wada et al. 2020). The Excel sheet for the standard groundwater optimization problem

[13] See for example, Roumasset and Wada (2015) for a less heuristic derivation.

(Figure 2) need only be slightly modified. Two columns would need to be added to track salinity (equation 10) and seaweed growth (equation 11) over time, and an additional constraint would need to be specified in the Excel dialog box (Figure 3) to bound seaweed growth from below. In general, if SGD has a beneficial effect on the GDE under consideration, we expect optimal extraction to be somewhat lower, leading to a higher head level in the long run and correspondingly higher SGD.

4.4 Multiple Aquifers

In our base case, we considered a single aquifer with a uniquely corresponding demand for water. In some situations, however, demand may be serviced by multiple aquifers. In that case, the water manager must decide how much to withdraw from each. Drawing from energy economics, we know that optimal extraction from different sources (e.g., oil and coal) is governed by the principle of least-cost-first. Unlike extracting different grades of the same resource, however, full marginal cost (FMC) cannot be ordered by c alone, but by c + MUC.[14] In the case of groundwater, a renewable resource, the MUC for each aquifer is determined by characteristics unique to that aquifer, and the least-cost-first principle requires comparison of the FMCs.

On Oahu, an example is provided by the Honolulu and Pearl Harbor aquifers. Consumption is recorded in the Honolulu and Pearl Harbor "districts" making it tempting to manage the two aquifers independently according to their respective demands. But since the two systems are connected by pipes, this would be a mistake. The PHA has a lower FMC because of its faster leakage. The cost of extracting from the PHA is correspondingly lower because lowering its head level means less SGD flows to the ocean. Thus, the optimal extraction profile is to first extract from PHA until either its MUC rises to equal that of the Honolulu Aquifer (HA) or MSY is reached at the minimum head level. In the application in question, it turns out that the latter comes first. The optimal sequence is then to service the joint demand from only the PHA until head is reduced to *hmin*, where net recharge is also maximized. Thereafter only net recharge is withdrawn from PHA, meaning that the balance of demand is met by the HA, which eventually reaches MSY as well. In subsequent periods, any excess of demand comes from the backstop resource, desalination.

This extension requires separate sets of hydrological parameters characterizing each aquifer. That means two head level trajectories and two extraction paths would have to be tracked over time, where the change in head level (*hdot* in the Excel sheet) for each period is governed by

$$\dot{h}_i = R_i - L_i(h_{it}) - q_{it} \tag{12}$$

for aquifers i = 1,2. However, the general solution strategy remains unchanged: vary the control variables (extraction from each aquifer, desalination) subject to the head constraints ($h_{it} \geq hmin_i$ in every period t for aquifers i = 1,2) to maximize the total PVNB, which in this case includes consumption benefits of water drawn from both aquifers and desalination.[15]

5 Conclusion

We have detailed how renewable resource economics is applied to the problem of welfare maximizing groundwater extraction and shown how to obtain a numerical solution with Excel. The optimal path of groundwater pumping is typically not constant over time in transition to that steady state. In contrast,

[14] For a single resource, the MUC for different grades is the same. There is only one resource price so $MUC = \dot{p}/r$ is the same for different grades. Therefore, the principle of least FMC degenerates to the Herfindahl condition of least-extraction-cost-first. For different resources, which have different resource prices, that does not follow, and we need to use FMC instead (Chakravorty and Krulce 1994). In the case of water, there is only one water price, but the MUCs of different aquifers are typically different.

[15] We recommend using either using actual values for initial guesses or obtaining independent solutions for the resources and using those to set the initial guesses for the combined resource system.

management strategies that specify a target pumping constraint (safe yield, sustainable yield, etc.) are incomplete, in the sense that they usually do not describe the approach path, which may be fast, slow, or even nonmonotonic. The method also provides the corresponding paths of efficiency prices. By equating marginal prices to efficiency prices, a water authority can implement the efficient extraction program.[16]

In the illustration for PHA, optimal extraction, for the base case of 2 percent demand growth, is well below MSY for most of the first (roughly) 40 years, more than MSY for the next (about) 24 years, and then equal to MSY beyond that. Not only does MSY deplete the aquifer too fast, but it squanders the potential gains from early conservation. The results are even stronger for the case of zero demand growth. Optimal extraction is constant over time and well below MSY, implying large welfare losses from extracting at the MSY level.

Through the basic groundwater management example presented here, along with the possible extensions such as watershed conservation, protection of groundwater dependent ecosystems, and the management of multiple aquifers, it should be clear that while optimal water management is sustainable, management strategies that primarily aim to sustain the resource at a desired level are not likely to be optimal. It should be noted that while the examples presented in this paper focus on characteristics of the groundwater resource and direct water consumption, incorporating additional environmental and socioeconomic considerations does not change the conclusion that optimal water management is sustainable but not the other way around.

The solution method detailed and illustrated here can also be adapted to inland aquifers. The archetypical inland aquifer (e.g., Burt 1966) is a special case of a coastal aquifer, wherein discharge is zero. Moreover, recharge is constant except when the aquifer is so near its maximum capacity that it cannot absorb the full amount of recharge. For this case, both discharge and recharge growth can be suppressed so long as the absorptive capacity is not a limiting condition in the optimal solution. While this sounds very much like a nonrenewable resource, some components of the M term in equation (2) do not approach zero. This means that the efficiency price remains above the extraction cost even in the long run. While students should be able to navigate the Excel spreadsheet provided in the supplementary materials, we recommend the instructor demonstrate the example provided in the chapter with the selected parameters as an in-class exercise as a starting point. Students can then try alternative formulations developed by the instructor as take-home exercises, including the extensions described in Section 4. While the tool is designed to allow for such extensions, adding multiple state or control variables to the application may require additional Excel add-ins not required to run the basic groundwater model.[17] We recommend that instructors test extensions such as linked watersheds, aquifers, or marine habitat impacts with the standard version of Excel to investigate which add-ins may be needed before assigning these more complex models to students. Even without students engaging in these more complex exercises, it will be useful for them to see that solving for optimal extraction from an isolated aquifer is at best a first approximation of the solution when groundwater is part of an ecological system.

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[16] Since efficiency prices are above extraction costs, charging the efficiency price for all consumption units will generate a revenue surplus. One way to return the surplus to consumers is by charging inframarginal block prices below the FMC.

[17] These Excel add-ins provide optional commands and features for Excel. By default, all add-ins are not immediately available in Excel but typically many are free, especially with the standard university licenses. Add-ins require installation and in some cases activation, typically from the File/Options menu depending on the version.

Appendix: Maximization Problem and Optimality Conditions

Mathematically, the dynamic optimization problem is as follows:

$$max_{q_t,b_t} \int_0^\infty e^{-rt}\left[B(q_t + b_t) - c_q(h_t)q_t - c_b b_t\right] dt \tag{A1}$$

where B denotes the benefits of water consumption, and c_q and c_b are the unit costs of groundwater pumping (q) and a backstop resource (b) such as desalination, respectively. For those without a calculus background, this may look scary, but it is just a way of adding up the discounted benefits and costs from now on. The water manager may choose to supplement groundwater pumping with desalination, an abundant but costly alternative called a *backstop* resource. Note the subscript t for the variables q and b, which indicates that the solution requires selecting values for the choice variables (also known as "control variables") in every period until the end of the planning horizon. That is, the planner must choose the complete approach paths (i.e., not just values for the current period) for q and b that maximize PV. The discount factor (e^{-rt}) converts the net benefits accrued for each period t into PV terms.

While there are an infinite number of candidate sequences that can potentially solve the maximization problem (A1), we can narrow down the possibilities by imposing an *equation of motion* for the aquifer stock. For a single-cell coastal aquifer, the change in groundwater stock over time is described by the following equation:

$$\gamma \cdot \dot{h} = R - L(h_t) - q_t \tag{A2}$$

The head level (h) or distance from mean sea level to the top of freshwater lens is an index for groundwater volume. The change in head level over time, denoted as $\dot{h}$, is converted to change in volume by a constant conversion factor γ. Recharge (R) is assumed exogenous, and leakage (L) out of the aquifer via SGD is a function of the head level. In the discussion that follows, we suppress γ for simplicity and interpret $c_q{}'(h_t)$ as the change in unit cost per volumetric unit of groundwater stock.

We start with the simplification wherein SGD is zero (e.g., an inland aquifer), and the recharge rate is effectively zero over the management horizon of interest. In this case, groundwater can be treated as a nonrenewable resource. The marginal benefit of waiting is $\dot{p}$, that is, the capital gain from selling at next period's price. The marginal cost of waiting is the foregone interest from harvesting today instead of one period later. Extraction is optimal when the marginal benefit is equal to the marginal cost of waiting:

$$p_t = c(h_t) + \frac{\dot{p}}{r} \tag{A3}$$

Equation (A3), called the "Pearce equation," says that groundwater should be extracted in every period until the marginal benefit of extraction, $p_t \equiv B'(q_t + b_t)$, is equal to the MC plus a second term $\frac{\dot{p}}{r}$, which is referred to as MUC. The MUC is the loss in PV that would result from an incremental reduction in the resource stock. If equation (A3) were not satisfied, there would be an opportunity to increase PV welfare by reallocating pumping over time.

The simple Pearce equation (A3) can be extended to the more general renewable case by expanding the MUC term. For a renewable groundwater resource, the "extra benefit of waiting" (postponing the marginal unit extracted until next period) is: $\frac{\mathrm{d}}{dh}[(p_t - c_q(h_t))F(h_t)]$, where $F(h_t) \equiv R - L(h_t)$ is the net recharge function (more generally the net growth function of the resource). Now the condition that the marginal benefit of waiting must be equal to the marginal cost of waiting is given by:[18]

$$p_t - c_q(h_t) = \frac{\dot{p}}{r} + \frac{\left[p_t - c_q(h_t)\right]F'(h_t)}{r} - \frac{c_q'(h_t)F(h_t)}{r} \qquad (A4)$$

Because both leakage and unit extraction cost are functions of the head level in this case, they show up in the MUC term. The second term on the right-hand side of (A4) is negative because $F'(h_t) < 0$. That is, there is actually a benefit of extraction because of the increased net recharge. The third term is positive because the higher the water table, the lower the unit extraction cost, that is, $c_q'(h_t) < 0$. Note that the first term in the MUC goes to zero ($\dot{p} = 0$) as we approach the steady state solution in the long run, but that the entire MUC can remain positive.

[18] This follows Pearce and Turner's (1990, p. 255) derivation for a generic renewable resource. Equation A4 can also be rewritten as: $p_t = c_q(h_t) + \frac{\dot{p}-[R-L(h_t)]c_q'(h_t)}{r+L'(h_t)}$. See Burnett and Wada (2014) for a detailed derivation.

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Teaching and Educational Methods

Simulating a Water Market: An In-Class Activity to Compare Market Efficiency under Various Institutions and Relative Advantages of Agents

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Abstract
Water markets are a public policy tool that can help to allocate water to its highest value uses, creating more efficient outcomes. This paper presents a classroom simulation that exposes students to some of the practical ramifications of establishing a water market and the outcomes that result. The activity has students role-playing as various businesses that require water for operation and assigns initial water endowments to some of the agents. Students must buy and sell water on a market and attempt to maximize their individual welfare. The students gain a deeper understanding of the welfare gains from water markets and learn how a lack of information and negotiating power can create inefficiency.

1 Introduction and Background

Water management is a complex problem that requires simultaneously managing uses to households, agriculture, industry, recreation, ecosystem services, and more (Young and Loomis 2014). Water is often allocated inefficiently because it is frequently under priced, leading to overconsumption (Creel and Loomis 1992; Timmins 2003). Water rights are often established according to traditional allocation methods that do not encourage conservation or sustainable use and prevent or restrict trade (Hutchins and Steele 1957; Donohew 2009). Groundwater is often extracted to fill the need, but as aquifers are depleted, new management policies will be required (Gibbons 1986; Dalin, Taniguchi, and Green 2019; Pauloo et al. 2020). Climate change will likely exacerbate these issues because drought is expected to become more prevalent, and water is to become more scarce (Palmer et al. 2008; Mukheibir 2010; Kahil, Dinar, and Albiac 2015; Mehran et al. 2017).

Water markets are a tool that have been proposed to help alleviate these issues (Hartman and Seastone 1970) that Olmstead (2010) has reviewed. They allow low-value users to sell their water to other entities with high-value uses, improving economic efficiency. These benefits are especially pronounced during low supply periods. Various locations around the world have established water markets. Grafton et al. (2012) found that establishing a water market in Australia's Murray-Darling Basin created gains from trade exceeding $2 billion per year and that the potential benefits in the U.S. West of expanding water transfers exceed $175 million per year. Schwabe et al. (2020) report that California had $3.9 billion of water exchanged from 2008 to 2019, but this accounted for only 2 percent of use in the state. The adoption of water markets in new locations is likely to provide economic benefits and alleviate future scarcity issues (Loch et al. 2013; Leonard, Costello, and Libecap 2019; Garrick et al. 2023).

Water markets do have some drawbacks. Most notably, increasing the price of water is likely to place financial burdens on low-income households, particularly people experiencing poverty in low-income countries (Venkatachalam 2015; Grafton, Horne, and Wheeler 2022). Additionally, water markets can increase price uncertainty and introduce risk to users (Zuo, Qiu, and Wheeler 2019).

Another concern is that externalities can be present when there is no market presence for instream flows (Griffin and Hsu 1993). Despite the potential gains highlighted in the U.S. West, Colby, Crandall, and Bush (1993) found significant price dispersion in the U.S. West water markets and that information flows and linkages may be insufficient to allow prices to converge, especially in locations with few potential market participants.

Teaching university students about water markets provides a good opportunity to use an in-class simulation to enhance student learning. Water economics is often toward the end of an environmental and natural resource economics course. At this point in the course, the analytical difficulty of the material on water economics and water markets is less difficult than in other portions of the course. However, several of the nuanced aspects of water markets and the difficulties presented when practically implementing water markets are not obvious from the theoretical classroom material. Students are familiar with retail settings, where buyers are price takers within a market and decide what quantity they will purchase at the set price. Water markets typically function as negotiation, ask/bid, or auction-based markets. Many students have little or no practical experience with these market institutions, and several students have expressed significant learning from active participation in price negotiations.

Several simulation activities and games are available online for principles of microeconomics classes to demonstrate the laws of supply and demand. Software-based economic simulations are available online, such as economics games (economics-games.com), MobLab (moblab.com), and econ class experiments (econclassexperiments.com) that cover competition, markets, externalities, game theory, and more. Mashayekhi et al. (2006), Gold and Gold (2010), Kvasnička (2014), and Riley (2020) have also developed computer-based activities that cover supply and demand and the function of markets.

Two components differentiate this water market simulation from standard market simulations. The first is that supply is represented by a fixed total quantity constraint with the endowment of water rights to specific agents rather than a production function. Second, the market functions through private negotiation for determining prices and quantities. Third, students have an implicit tendency to try to lower the cost of water. Experience running the simulation has shown that students are more hesitant to charge efficient (high) water prices than "widgets" in a principles of microeconomics course, likely due to the necessity of water for basic human needs. Participation in the simulation reinforces to students that active water markets can support essential human needs while increasing economic efficiency. This activity focuses on face-to-face peer interaction and does not include software or computer augmentation. Students must negotiate and trade during class time, similar to activities on barter trading (Karpoff 1984), supply and demand (Lin 2018), land conservation (Dissanayake and Jacobson 2016), and ecosystem services (Abidoye, Dissanayake, and Jacobson 2021).

The in-person nature of the activity can improve student outcomes by reducing student passivity (Senthamarai 2018), motivating students, and improving critical thinking skills (Laal and Ghodsi 2012). Additionally, Eppich and Chang (2015) found that in-person debriefing can promote professional collaboration and practical decision-making. Farolfi and Erdlenbruch (2020) have developed a class activity that illustrates the common-pool dilemma aspect of water management. The activity presented in this paper uses a setting where water rights are established, avoiding the common-pool dilemma, and focuses on how trading can increase the welfare of market participants.

This paper introduces an in-class activity that simulates a water market. The simulation is targeted at a "300" level environmental economics or environmental and resource economics course. At this level, the student will have completed a principles of microeconomics course and an introductory calculus course as prerequisites. However, they will not necessarily have completed an intermediate microeconomics course where they have applied calculus in an economics setting. This simulation has been conducted in an undergraduate, 300-level environmental and resource economics at the University of Oregon and in a master's level environmental economics course at Duke University's Nicholas School of the Environment. The simulation is conducted as part of the unit on water economics, generally placed toward the end of the course so that students are already familiar with marginal analysis from other units already covered. The students should be familiar with problems that involve two or more agents and understand how to compute the marginal benefits (MB) or marginal costs (MC) given total benefits or costs. They should recognize that to find an efficient outcome they must set marginal costs and benefits equal to each other and solve for equilibrium quantity and price. The simulation presented here gives costs and benefits in tabular form, similar to the Chapter 18 exercise in Harris and Roach (2017). The scenario handouts could be readily modified to give the costs and benefits in a functional form for use in classes where students are comfortable with differential calculus.

2 Learning Objectives

There are two broad categories of learning objectives for this activity: (1) Gaining a deeper understanding of the material presented in the class and (2) Demonstrating the practical functioning of a water market and showing how the practical application can deviate from theoretical results derived in lectures and homework. The second category is not germane to many environmental economics courses. However, the simulation demonstrates results that economists have observed and verified empirically. Menkhaus, Philips, and Bastian (2003) have found that private negotiations disadvantage sellers (particularly small sellers) compared to open auctions. Kristensen and Gärling (2000) found that irrelevant anchoring information influenced negotiated offers and prices. Bazerman, Magliozzi, and Neale (1985) established that under negotiation, a market converges toward a Nash equilibrium with experience, but that initial outcomes are not at the Nash equilibrium. Students will find these insights useful as they embark on their careers and consider the application of the knowledge they have gained in the classroom.

The following list includes these objectives and some potential additions that could be included if desired.

- Homework problems and lecture examples have demonstrated how to solve for efficient equilibrium outcomes with information on all participants. In practice, buyers do not have information on seller costs, and sellers do not have information on buyers' preferences. Market transactions help reveal this information over time, and during this transition, the market typically has some deadweight loss.
- Understanding that inefficient outcomes can result in a market setting, even when other factors discussed in the course are absent. There are no externalities, property rights are established, and it is not a common property or public good. However, private negotiation and the initial market phase, where agents must learn other parties' preferences, costs, and benefits, will push the market toward an inefficient outcome.
- Even though the simulation will likely not lead to an efficient outcome, it will lead to welfare gains compared to a situation where no trading is allowed.
- Understanding that markets typically reach an efficient outcome only after some time has passed. Markets typically require time for buyers and sellers to observe prices and price variability before an efficient equilibrium can be reached. Over time, the price will move toward the price that will allow the fixed supply to meet demand.
- Recognizing that market power and negotiating power can alter the dynamics of a market and favor certain agents in the market.
- Reinforcing how uncertainty plays a role in market outcomes—fixed prices or taxes create quantity uncertainty, while fixed quantities (as demonstrated in the simulation) create price uncertainty.

- The activity can be repeated with the same values to allow students to observe the market approaching a more efficient outcome over time. When implementing a second round, the instructor should record the prices and quantities from trade for the initial market on the blackboard but complete both rounds before conducting the debrief. Typically adds 5 minutes to the activity.
- The activity can be repeated with different water supply values (included in the accompanying spreadsheet) but with the same costs and benefits. This round will confirm students' understanding of how resource shortages impact a market by raising the price and reducing consumption. This demonstrates some of the impacts of drought and reinforces concepts from a unit on renewable or nonrenewable resources. Similarly, record prices and quantities from the previous round(s), but complete this round before conducting the debrief and discussion. This typically adds 10 minutes to the activity.

3 Simulation Description

The water energy nexus has received considerable attention over the past two decades, as well as This section describes the process of running the simulation. Appendix A includes a copy of each handout, and Appendix B includes copies of the text shown on PowerPoint slides displayed during the simulation. This simulation has been run during the lecture on a day when a homework assignment is due that includes a structurally similar problem (included in Appendix B) with two agents. Completing the homework question before the simulation ensures that the students are familiar with calculating marginal costs and benefits, that they should set MB = MC to find the solution, and that Price = MC at the solution. The major difference between the simulation and their homework is (1) they have information about their own costs and benefits but do not know anything about other agents' cost or benefit functions, and (2) there are five agents, increasing the complexity through multiple trading possibilities, and establishing an efficient outcome is more difficult. Table 1 outlines the simulation and the expected time that will be needed.

3.1 Pre-Simulation Setup

Divide the class into five groups of approximately 3–4 people and assign each group to be an agent. The collection of five groups will form a market. Larger classes will have multiple, noninteracting markets. There should be a clear delineation between markets to ensure that they are not buying and selling with the wrong market and that information is not being shared between the markets. The simulation has been run successfully with up to 70 students and three simultaneous markets.

Give a handout to each group that will assign them an "agent" (municipality, hay farm, berry farm, beverage plant, and textile factory). Each agent is given their total costs or benefits in table form. Then, they calculate MB/MC in table form by subtracting the current row from the previous row and dividing by the difference in usage. Within each market, two agents have a water endowment who will be the sellers. Two sellers are included to alleviate the potential for monopoly power. The two sellers have not colluded in prior experiences running the simulation. However, there is potential for astute groups to engage in monopolistic or monopsonistic behavior with the limited number of participants.

3.2 During the Simulation

Give students approximately 15 minutes to complete all transactions. During the simulation, I answer questions that help clarify instructions but defer most questions that ask about a solution technique. I will refer the students to the relevant homework question and reiterate that this is conceptually similar, but that they only have information on one agent and must negotiate with other groups. A question that typically comes up early in the simulation after groups have successfully computed the MBs is, "Where

Table 1: Outline of the Components of the Simulation and Their Requisite Time

Activity Component	Approximate Expected Time	Comments
Initial Instructions	5 minutes	Reviewing announcements or homework questions at the beginning of class may be useful. Assigning groups and providing instructions to latecomers will encumber the activity.
Group Setup	5 minutes	The time taken will depend on the group assignment method.
Simulation Phase 1	15–20 minutes	Prior experience has shown that the groups take 15–20 minutes to conclude their negotiations. Giving people a 5-minute warning at 15 minutes may be helpful to encourage them to wrap up. If all negotiation has concluded, end this phase.
Simulation Phase 2 (optional)	5 minutes	Repeating the simulation with the same supply quantity, costs, and benefits will likely see an equilibrium closer to efficiency that requires less negotiation time. Prior experience has shown that the initial simulation results in a low price and volume of water traded. This phase will likely see a higher price with greater volumes traded, leading to a more efficient outcome.
Simulation Phase 3 (drought scenario, optional)	10 minutes	Repeating the simulation with new supply values will require less time than the first round but more than the second. The efficient price is higher than in the standard simulation. The negotiated price(s) are likely to increase, reflecting the supply shortage and student learning.
Debrief and Discussion	10–15 minutes	Allow time for questions relating to the simulation or the simulation's application to the class material.

are the MCs that I should set these equal to?" resulting in a need to guide them to negotiate and begin trade with other groups.

3.3 Post-Simulation Debrief and Discussion

After completing the simulation, record each agent's outcome and write them on the classroom blackboard. At the beginning of this portion of the simulation, let students know that classes rarely or never find an efficient outcome for all five groups in the market to set them at ease with sharing their results. During this phase, it is critical to make students comfortable with the learning process and not to be concerned that they "got it wrong." Try to be gentle and humorous during this portion of the simulation and avoid critical comments.

The most common outcome observed is that the price of water is lower than MB/MC, indicating that more trade should occur and that the price of water should be higher for an efficient outcome. Most markets will not have multiple prices, which leads to some discussion points to reinforce the learning objectives.

First, discuss the differential price. Why did some agents pay more? Typically, some sellers will have multiple transactions at different per-unit prices. Ask them why they sold at lower prices if higher prices were available.

Second, bring up the solution technique used throughout the class to solve problems of setting MB = MC. Then identify 1–2 groups where the price they bought/sold at is higher than their MB or MC and discuss their specific outcome. Ask how their profit would change if they bought or sold one more unit of water at the same price and show that they could have increased their benefits. Often the buyers note that sellers would only sell them more water by increasing the price of all previous units, an outcome that would lower their benefits. In that case, choose the seller as the second group to analyze and see if their benefits would have increased from being willing to sell more.

Then discuss some of the learning objectives and discuss how the activity demonstrates some results covered in class and how the actual markets do not always achieve some of the results derived analytically.

- In class lectures and homework problems, cap-and-trade markets have a single clearing price and generate an efficient outcome. Discuss how negotiation and market power can prevent an efficient outcome. Also, discuss how markets tend to approach more efficient outcomes as time progresses and the agents learn, but that market changes, perhaps due to drought, reduce or reset this learning. Show a slide that shows price evolution for a real market, such as Figure 1 in Rimsaite et al. (2021), Figure 7 in Brown (2006), or Figure 1 from Hitaj and Stocking (2016).
- Quantity instruments, such as cap-and-trade programs that have been discussed earlier in the course, create price uncertainty. This is comparable to the simulation they have just finished, where the total water supply is fixed. Discuss verbally how a simulation with a slightly different setup, a fixed price, would result in an uncertain quantity consumed. In a practical setting, a fixed price would lead to uncertain instream flow remaining and the potential for overuse.
- In previous simulations, the sellers typically do not wish to sell efficient quantities of water. Relate this to the endowment effect (Kahneman, Knetsch, and Thaler 1991) many students have seen from a behavioral economics course or unit in a different class.
- A final point for discussion is equity concerns. A common outcome in prior simulations has been that the municipality does not maximize its total welfare/profit. They sell less water than would be efficient to ensure their citizens have access to plenty. Discuss the idea that the high MB at low quantities represents critical water uses such as drinking, sanitation, and cooking. The low MB at high quantities could represent nonessential uses such as watering lawns and washing cars. If the municipality in the simulation sold a low quantity of water, this likely resulted in low agricultural output. In a practical setting, this would result in higher food prices. While the simulation simplifies reality, the trade-off between agriculture and urban use is a tangible public policy issue.

Some caveats can be mentioned during the simulation or the debrief to elucidate some areas where the simulation deviates from actual water markets. These include:

- The simulation includes the municipality as the primary water seller. In practice, municipalities are often purchasing from agricultural water rights holders (Shupe, Weatherford, and Checchio 1989; McLane and Dingess 2013).
- The simulation abstracts away from other costs that must be incurred in practice. The cost to treat and distribute water in residential and commercial settings is particularly important for

water economics. The end-user price of municipal water can be significantly higher than the price required for the initial purchase (Varela-Ortega et al. 1998).
- The simulation does not account for differential water quality requirements. Agricultural water supply will generally require treatment before use in a city or a beverage plant.

4 Conclusion

This paper includes an in-class simulation to engage students in how water markets function. The activity has students play the role of economics agents who require water for their business or operation, and students must trade with each other to maximize their net benefit. This activity reinforces many of the concepts learned in an environmental or natural resource economics course on water economics. Also, it presents some of the barriers that prevent or impede the practical implementation of markets in public policy.

No formal assessment has been conducted to assess the impact of the activity. However, multiple students self-reported in the comments of their course evaluation that they found the active participation to be beneficial or helpful in improving their understanding of water markets, that the activity helped them understand how the application of the course material to actual policy can be difficult, and that it was a highlight of the course. No comments to date have self-reported that the activity was a negative experience. However, as this was not asked directly on the evaluation, it is possible that some students have a negative opinion but did not express it.

There are some pitfalls that the instructor should avoid while implementing this activity. First, the students need to be prepared for the simulation by having a foundational understanding of marginal analysis and how to use it to solve for economically efficient outcomes. They should also understand the concept of water markets and how they function, i.e., this activity is not recommended for the first class on water markets as an introduction to the concept. Second, the instructor must provide a balance of assistance. If too much solution assistance is given, the students will learn less than if they arrive at the solutions with their group. However, the instructor should guide any groups that are unsure how to progress during the simulation.

This activity aims to aid the instruction of an environmental economics, resource economics, or agricultural economics course that includes a unit on water economics. However, the simulation could be applied to other classroom settings where simulating a market establishment would benefit student understanding and aid student engagement.

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Appendix A – Group Assignment Sheets

Group A: Municipality
You are the city council for Hydroville. The city owns the property rights for 20 acre-feet (af) of water. You must provide water for the citizens of your town. The water is used by the citizens for residential and general commercial purposes (drinking, washing, landscaping, etc.). The marginal benefits are decreasing due to the citizens placing a higher value on drinking than on washing and landscaping. You can use all 20 af for your city or sell some of the water to other users.

The table below lists the marginal benefit of the water to the citizens of your town.

Water Used (af)	Total Benefit	Marginal Benefit
0	0	
2	200	
4	380	
6	540	
8	680	
10	800	
12	900	
14	980	
16	1,040	
18	1,080	
20	1,100	

Names of group members:

For each group you are trading with, record the group, the quantity of water sold, and the price per af.

Provide a brief (2–3 sentences) explanation of how you arrived at the amount(s) that you bought or sold.

Group B: Hay Farm

You are the owners of a family hay farm. You have installed gutters on the farm buildings that collect 2 acre-feet (af) of water for yourself. You have the option of installing an irrigation system to the river that will allow you to participate in the market for $20. This will allow you to sell your 2 af on the market, or it will allow you to buy additional water.

You produce hay that you can sell on the market for $10 per bale. Assume you have no costs other than water.

Hay Produced (bales)	Water Used (af)	Total Benefit	Marginal Benefit
0	0		
16	1		
30	2		
42	3		
52	4		
60	5		
66	6		
70	7		
72	8		
72	9		

Names of group members:

Are you choosing to install the irrigation to allow you to buy and sell water?

How much water are you buying or selling, and what is the price per af?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Group C: Berry Farm

You are the managers of a berry farm. You own the property rights to 10 acre-feet (af) of water by virtue of owning property next to the river. You can use your water to grow berries. You can install a drip system for $100 that will reduce your water usage by 2–3 for all amounts of berries produced. You can buy or sell water on the market. Berries sell for $4 per pound on the market.

The table below represents the number of pounds of berries that you can grow. Assume you have no costs other than water.

Berries Grown (pounds)	Water Used with No Irrigation (af)	Water Used with Irrigation (af)	Total Benefit	Marginal Benefit
0	0	0		
25	3	1		
45	6	2		
60	9	3		
70	12	4		
75	15	5		
75	18	6		
70	21	7		

Names of group members:

Are you choosing to install the irrigation system?

How much water are you buying or selling, and what is the price per af?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Group D: Textile Factory

You are the management team for a textile factory. The water you use in the factory to clean and cool equipment ultimately becomes wastewater and is unavailable for reuse. You have the option of two different production processes: one that uses more water and one that uses more labor. You do not have any prior rights to water, so you must buy the water you use. Choose a production process and the amount of water.

The table below represents your two production processes.

Revenue from Textiles ($)	Water Used by Process A (af)	Labor Costs from Process A ($)	Water Used by Process B (af)	Labor Costs from Process B ($)	Total Benefit	Marginal Benefit
0	0	0	0	0		
540	2	100	1	1,000		
960	4	200	2	2,000		
1,260	6	300	3	3,000		
1,480	8	400	4	4,000		
1,620	10	500	5	5,000		

Names of group members:

Are you choosing process A or process B?

How much water are you buying or selling, and what is the price per acre-foot (af)?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Group E: Beverage Plant

You own a beverage plant. You require water to make your beverages and to clean and cool plant equipment. You are the farthest downstream, so you have access to two water markets. You can obtain water from this market, or from another water market that has a fixed price of $90 per acre-foot (af). You cannot sell water from the other market because you do not have a way to transport it upstream.

The table below represents the water input required to produce beverages. You can sell your beverages at a price of $15 each. Assume you have no costs other than water.

Number of Beverages Produced	Water Used (af)	Total Benefit	Marginal Benefit
0	0		
8	1		
15	2		
21	3		
26	4		
30	5		
33	6		
35	7		
36	8		
36	9		

Names of group members:

Are you buying water from this market or from the alternative market at $90 per af?

How much are you buying or selling, and what is the price per af?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Appendix B – Slides and Graphics Presented

B.1 Slides during the Simulation

The following text should be presented before the simulation has begun, and before the handouts have been distributed. Phrases set aside with square brackets [] should be modified to include information specific to your course. Include details on the first bullet that instruct the students on how their groups will be determined (random assignment, find their own partners, etc.). I prefer assigning the groups randomly to encourage discussion with students they do not typically work with, but allowing them to form their own groups will save time.

- We will be conducting an in-class simulation. [Instructions on how to form groups]
- You will be assigned some details on the costs, benefits, revenues, etc., regarding the operation of your business or agency.
- This simulation is similar to [question #3] on the recent homework. The primary difference is that you only have information on your own operations and must negotiate with the other parties.

The following text should be displayed as the simulation is beginning. I provide oral instruction over these points as the simulation is beginning and leave them up as a quick reference for the students during the simulation.

- Your group must decide the level of output that you are going to produce.
- You should obtain the correct amount of water for the output that you choose.
  - For some groups, this will require buying water.
  - Some groups will be able to sell water to other groups.
- Your goal is to maximize the profits/benefits of your business.
- For each transaction with another group, you should record the amount of water sold and the price per acre-foot (af).

B.2 Actual Water Market Data Figure

I show this figure on a slide as part of the debrief, such as Figure 1 in Rimsaite et al. (2021, p. 5). The data is from transactions in a nine-state water market sample that includes AZ, CA, CO, ID, NM, NV, TX, UT, and WA. The figure shows some volatility that can likely be explained by drought conditions such as the simultaneous price increase to leases and transfers in 2003. It also shows some price variability where lease price increases in 2006, but the transfer price remains level, indicating there is likely to be some other cause.

Appendix C – Other Class Materials

C.1 Sample Course Outline

Table C1 presents the timeline of an environmental and resource economics course that is suited for this activity that shows the context for the activity. This timeline is for a 10-week quarter-length class. The schedule would require some modification for a semester-length or a condensed summer course.

Table C1: Example Timeline of an Environmental and Resource Economics Course	
Class Day	**Topic**
Week 1 Class 1	Introduction to environmental economics and review of principles of microeconomics
Week 1 Class 2	Externalities I: Markets and market failures—positive and negative externalities
Week 2 Class 1	Externalities II: Computation of equilibrium given supply, demand, and externality and welfare analysis
Week 2 Class 2	Pollution Management I: Introduce a model of polluting firms, and solve the model with command-and-control (quota) policy
Week 3 Class 1	Pollution Management II: Solve model with taxes and cap-and-trade; examine welfare implications of different policies
Week 3 Class 2	Pollution Management III: Discuss implications of uncertainty with the policy instruments; discuss the real-world application of policy; review for Midterm
Week 4 Class 1	Midterm I
Week 4 Class 2	Common Property Resources I: Description of types of goods, and example solved of market outcome and efficient outcome for a common property resource
Week 5 Class 1	Public Goods and Discount Rates: Theory of public goods and example solved to find market equilibrium and efficient outcome for a public good; introduce discount rates
Week 5 Class 2	Resource Allocation over Time I: Description of how economics uses dynamic models for resource allocation over time; review discount rate, and show how it enters dynamic economic models; introduce two-period model (simplified overlapping generation model) and solve for resource allocation
Week 6 Class 1	Resource Allocation over Time II: Conclude solving the two-period model; discuss extension to infinite time horizon; discuss how changes in parameters such as discount rate, demand in period 2, and uncertainty will change the allocation across time
Week 6 Class 2	Resource Allocation over Time III: Discuss the application of model results to real-world situations, the Hotelling's rule, and the Hartwick rule; review for Midterm II
Week 7 Class 1	Midterm II
Week 7 Class 2	Valuing the Environment: Total economic value, type of value; begin methods used to quantify nonmarket benefits; cost of illness, replacement cost, and travel cost model
Week 8 Class 1	Valuing the Environment: Conclude methods used to quantify nonmarket benefits; hedonic pricing, stated preference methods; introduce cost-benefit analysis, and solve dynamic cost-benefit example. **Homework assigned with problems over material from Week 7 Class 2 to Week 8 Class 2 Due Week 9 Class 1.**
Week 8 Class 2	Renewable Resources I: Discuss the real-world application of models developed earlier in the course to fish, surface water, and wildlife
Week 9 Class 1	Renewable Resources II: **Water market activity**. **Homework on renewable resources and valuing the environment Due.**
Week 9 Class 2	Nonrenewable Resources I: Discuss the real-world application of models developed in the course for mining and minerals; solve an example of recycling vs. virgin resource use of a mineral.
Week 10 Class 1	Nonrenewable Resources II: Discuss the real-world application of models developed in the course for groundwater and fossil fuels; cover the transition from fossil fuels to renewable energy and other energy and electricity trends
Week 10 Class 2	Climate Change and Review: Discuss how the topics covered relate to and interact with climate change; review for Final
Week 11	Final

C.2 Sample Homework Problem

The following problem is a sample problem that has been included on the homework assignment due the day that the water market activity is conducted. This problem gives students familiarity with the solution technique that they will need to use for the in-class activity. Students have also completed other problems that require them to convert total benefits/costs/product to marginal values and set those equal to find the efficient solution such as Harris and Roach (2017) exercises 4.1 and 13.2. This problem is assigned after covering different methods that have been used to assign water rights in lecture, so the students must recognize that prior appropriation assigns the water right to the earliest settler, and that who is upstream is not used. The solution is included in *italics*.

There are two farmers that have settled and built farms along a river. Jack settled and established his irrigation in 1954, and Kate settled and established her irrigation in 1960. Kate is upstream from Jack.

Acre-Feet of Water Used	Total Benefit to Jack	Total Benefit to Kate	Marginal Benefit to Jack	Marginal Benefit to Kate
1	100	150	*100*	*150*
2	180	270	*80*	*120*
3	240	360	*60*	*90*
4	280	420	*40*	*60*
5	300	450	*20*	*30*
6	300	450	*0*	*0*

a) Complete the table by computing the marginal benefit to each farmer.

b) If there are 15 acre-feet (af) of water available, if water is not tradeable, and if water rights are given by prior appropriation, how many units of water will be used by each farmer?

   Both farmers would use 5 af. There is no scarcity constraint with this level of supply. Both farmers get zero MB from a 6th unit of water, so they would not bother.

c) If there are 7 af of water available, if water is not tradeable, and if water rights are given by prior appropriation, how many units of water will be used by each farmer?

   Jack has the water right by prior allocation, so he will use the same 5 af as in part (b). However, this leaves only 2 af for Kate.

d) If a water market is established and if water is tradeable, how many af of water will be used by each farmer when 15 af are available, and what price will water sell at?

   With no scarcity constraint, establishing the water market will not change the outcome. Same as part (b) where both farmers will use 5 af. With no actual sales, the price is zero.

e) If a water market is established and if water is tradeable, how many af of water will be used by each farmer when 7 af are available?

With 7 af available, there is a constraint to supply, and water trading provides an opportunity for greater benefits. Find the allocation where the marginal benefits are equal, and the total amount used is 7. By inspection, this occurs at 3 af for Jack and 4 af for Kate. Water will be sold at their mutual marginal benefit price = $60 per af.

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Teaching and Educational Methods

Water and Economics: Why We Need and Ought to Teach Water Economics in the Modern Economics Curriculum

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Abstract
Water scarcity and the availability of good quality water are major challenges facing many regions globally, and these topics warrant attention in economics; a discipline that studies the allocation of scarce resources. Integrating water resources into the economics curriculum is essential for students to understand water-related issues, water distribution, and the implications of current water management policies on the future. Although water economics is covered by some institutions in the United States and around the world, the coverage is mostly limited to basic economic theories and applications, with little attention paid to the broader issues pertaining to water. We provide an examination of the current state of water issues coverage in undergraduate and graduate courses across various institutions in the United States. A novelty of our investigation lies in analyzing how water topics are addressed at institutions located in different water-stressed regions. Additionally, we present several pedagogical approaches that are currently being applied to water economics teaching. This study also proposes innovative teaching interventions that incorporate water topics into the economics curriculum and, in doing so, enhance students' understanding of basic economic theory, analysis, and real-world implications.

1 Water and Economics

Many regions around the world are facing challenges related to both water scarcity and water quality, and the impacts of these challenges are increasing as climate change and population density issues worsen. The World Resource Institute estimates that a quarter of the world's population face extreme water stress (Hofste et al. 2019). Major cities around the world are encountering water crises known as "Day Zero" (the day when there was no water available to deliver through a system) or are at risk of running out of water (BBC News 2017; Chapman 2019; Sengupta 2019). The growing global trend of urbanization, coupled with worsening climate change issues, is likely to result in more water stress and exacerbate water-related challenges.

The severity of water shortage is especially apparent in the agricultural sector (Connor 2015; Campbell et al. 2017). The resulting consequences are crop yield reductions and threatened global food security (Cook, Ault, and Smerdon 2015; Zhao and Running 2010). Further, water scarcity and degradation of water quality have an enormous impact on public health. A World Health Organization (WHO) report estimates that improved water supply alone could reduce diarrhea-related morbidity incidence by 6 percent to 25 percent (World Health Organization 2004). The burgeoning problem of water scarcity also has implications regarding human rights and international laws and conflicts. Drought and depleting water detected by satellite imagery in and around Iraq and Syria have been attributed as contributing factors in inciting wars and human displacements (Madani, AghaKouchak, and Mirchi 2016; Eklund and Thompson 2017; Selby 2019). The tension over transboundary water resources among countries in the Himalayan region and disputes over the Nile River are also a consequence of increasing water shortages (Ranjan 2019; Pemunta et al. 2021). The water crisis issue has, therefore, garnered much public and political attention, influencing many policies globally. The United States Clean Water Act of 1977 and the Water Quality Act of 1987 are examples of such efforts. The socio-ecological nature of water issues around the world requires multidimensional approaches to confront an inevitable crisis, and as such, water is a critical topic that needs to be covered in economics curricula.

The inclusion of water in the economics curriculum can have a multifaceted approach. In his book The Wealth of Nations (1776), Adam Smith described his observation of the Diamond-Water Paradox: "Nothing is more useful than water: but it will purchase scarce anything; scarce anything can be had in exchange for it. A diamond, on the contrary, has scarce any value in use; but a very great quantity of other goods may frequently be had in exchange for it." As the topic of scarcity is at the heart of the traditional economics curriculum, water economics is presented to students in introductory courses, often through Smith's Diamond-Water Paradox, to lead the discussion on scarcity. Similarly, the example of water can be applied when introducing marginal analysis to identify optimal water pricing, consumption, and distribution. Water scarcity can also be used to introduce topics in public health economics. For example, using water quality as an input of health in the Grossman framework (Grossman 1972) can help demonstrate the relationship between water quality and health status theoretically and empirically. Subsequently, students can perform the economic analysis of calculating the health cost associated with water quality reduction. Moreover, this opens the door for policy implication discussions such as subsidies within infrastructures, cleanliness practices, and taxation at the producer level to account for the negative externality.

Given the magnitude of the water crisis problem and its far-reaching impacts on various sectors, there is a dire need for courses (and programs) focused on water economics. Although teaching applications of microeconomic theory on water allocation could help students understand the basic framework of water resources management, the importance of broaching the broader significance of water resources must also be considered in these courses. Furthermore, considering the interdisciplinary nature of the subject, it is essential for students pursuing water economics to develop a deeper understanding of water resources and approach problems concerning water resources not just from an economic perspective, but also from other disciplinary perspectives.

The objective of this article is to assess (1) the current state of how water issues are covered in undergraduate and graduate courses across different institutions in the United States and (2) how modern pedagogical approaches are being applied to water economics teaching. To achieve the objective, we take three steps: (1) conduct a web examination of water economics courses in the United States with a text analysis of course syllabi, (2) review and categorize novel teaching methods and strategies pertinent to water economics and present evidence-based examples, and (3) detail novel teaching strategies on multiple course examples across different institutions and disciplines. Our contributions are twofold. First, we provide a comprehensive review of water economics courses taught across different U.S. institutions dictated by regional necessity. We present concrete examples of the courses from U.S. research and liberal arts institutions that cover water topics both at the undergraduate and graduate levels. A novelty of our presentation includes using text analyses to analyze how water topics are covered at institutions located in different water stress regions in the United States. Second, we provide teaching methods and strategies pertaining to water economics and how it could be integrated into the modern economics curriculum. We also provide a set of suggested sample course syllabi which vary by regional water stress levels.

2 Investigation of Water Economics Courses in the United States: A Text Analysis

To obtain a comprehensive view of water economics courses taught in the United States, we begin by conducting an online examination of such courses. Considering the potentially vast number of institutions that offer courses in water economics in the United States, along with data availability constraints, we limit our sample to syllabi that can be obtained online by searching for the phrase "water economics courses" (see Appendix A1 for details).[1] We anticipate the identified courses and institutions to encompass a wide range of U.S. universities and colleges due to this broader online examination approach for sample institutions. We also expect the identified institutions to span over U.S. regions with different levels of water stress. Following the Water Resource Institute (Hofste et al. 2019), Figure 1 shows the map of U.S. states classified into five levels of baseline water stress, including extreme stress, high stress, medium-high stress, low-medium stress, and low stress. Generally, the U.S. Southwest faces much higher water stress compared to the rest of the country, with New Mexico experiencing extremely high water stress.

The online examination identified 25 water economics courses taught by 24 institutions across 19 states in the United States. Table 1 provides a summary of all the courses concerning the course level (graduate vs. undergraduate), the department in which the course is cataloged (economics vs. non-economics), and the institution and state where the course is offered. In terms of teaching levels, there are 17 undergraduate courses, 6 graduate courses, and 2 cross-listed between graduate and

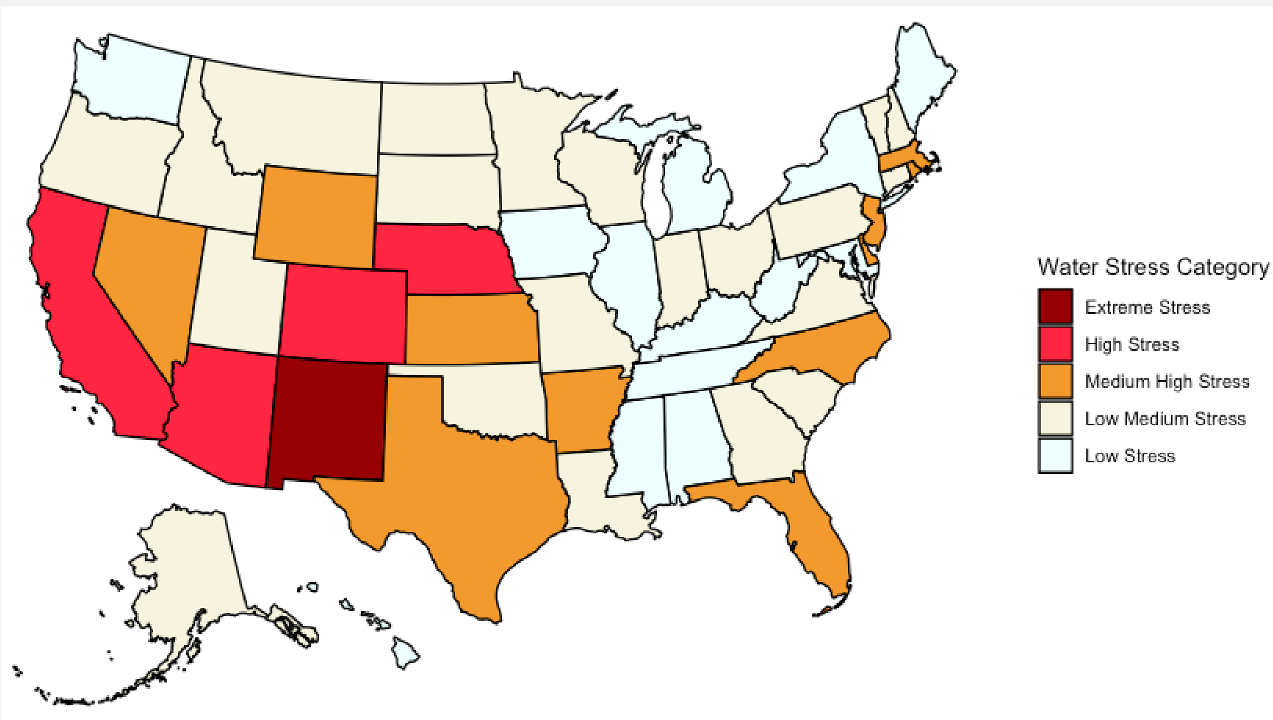


Figure 1: Regions Characterized by Different Levels of Water Stress in the United States

Data Source: Water Resource Institute (Hofste et al. 2019).

[1] Our online examination of water economics courses taught in the United States is not necessarily encompassing and does not include all types of courses and institutions because a course can be offered at an institution but cannot be identified via search engines.

Table 1: List of Water Economics Courses from an Online Survey across Regions with Four Levels of Water Stress (High, Medium High, Low Medium, and Low)

Course	Undergraduate/ Graduate	Department	Institution	State
		High-Stress Regions		
EES 270: Water Economics	Graduate	Environmental Studies	California State University	CA
Econ 267: Economics of Water	Graduate	Economics*	UC San Diego	CA
EEP 162: Economics of Water Resources	Undergraduate	Agricultural Economics*	UC Berkeley	CA
AREC 479: Economic Analysis of Water, Food, and Environmental Policy	Undergraduate	Agricultural Economics*	The University of Arizona	AZ
ENVS 129-01: Water Policy in the Western United States	Undergraduate	Environmental Studies	San Jose State University	CA
AREC 342: Water Law, Policy, and Institutions	Undergraduate	Agricultural and Resource Economics*	Colorado State University	CO
AEEC 575: Economics of Water Resource Management and Policy	Graduate	Water Science and Management	New Mexico State University	NM
CEE 173: Urban Water	Undergraduate	Civil Engineering	Stanford University	CA
		Medium-High-Stress Regions		
ECON 615: Water Resource Economics and Policy	Graduate	Economics*	University of Nevada, Reno	NV
397W: The Economics of Water Policy	Undergraduate	Resource Economics*	University of Massachusetts Amherst	MA
AGEC4720: Water Resource Economics	Undergraduate	Agricultural and Applied Economics*	University of Wyoming	WY
WATR 2350: Topics in Water Resources	Undergraduate	Department of Mathematical, Physical, and Engineering Sciences	Texas A&M university	TX

Table 1 continued.

Course	Undergraduate/ Graduate	Department	Institution	State
GEO/NRS/EEC 234: Introduction to Water Resources	Undergraduate	Environmental and Natural Resource Economics*	The University of Rhode Island	RI
EEC430: Water Resource Economics	Undergraduate	Environmental and Natural Resource Economics*	The University of Rhode Island	RI
AEB 2451: Economics of Natural Resource Use	Undergraduate	Food and Resource Economics*	University of Florida	FL
		Low-Medium-Stress Regions		
AAEC/FREC 4464: Water Resources Policy and Economics	Undergraduate/ Graduate	Environmental and Natural Resources	Virginia Tech	VA
Econ 3466E: Environmental Economics	Undergraduate	Economics*	University of Connecticut	CT
GEOG 467/567: International Water Policy	Undergraduate/ Graduate	Geology	University of Oregon	OR
ENV 865: Water Resources Institutions and Policies	Graduate	Environmental Studies	University of Wisconsin–Madison	WI
Econ 322: Environmental/Natural Resource Economics	Undergraduate	Economics*	College of William and Mary	VA
		Low-Stress Regions		
EAS 501: Water Resource Economics	Graduate	Environmental and Sustainability	University of Michigan	MI
ESWS 325: Principles of Water	Undergraduate	Environmental, Soil, and Water Science	West Virginia University	WV
Econ 349: Environmental and Natural Resource Economics	Undergraduate	Economics*	Rhodes College	TN
CEE 433: Water Technology and Policy	Undergraduate	Civil Engineering	University of Illinois at Urbana–Champaign	IL

Table 1 continued.

Course	Undergraduate/ Graduate	Department	Institution	State
Envr 322: Water Policy	Undergraduate	Environmental Studies	University of Puget Sound	WA

* Indicates courses offered by Economics or Applied Economics departments.

undergraduate. For departments, any courses offered by the Departments of Economics, Agricultural Economics, Environmental and Natural Resource Economics, and Food and Resource Economics are categorized in the economics category. All other courses, including those offered by the departments of Environmental Studies, Civil Engineering, Sustainability, Water Science, and Geology, are classified in the non-economics category. Among the 25 courses, 13 are cataloged in economics departments while 12 are in non-economics departments, indicating that departments other than economics also teach water topics with an emphasis on economic aspects.

The information on the institution and the state in which a course is offered, combined with Figure 1, allows us to group these courses into four subgroups based on water stress levels. While Figure 1 shows five levels of water stress, we combine both extreme stress and high-stress levels into one category “high stress” to balance the data sample, as New Mexico is the only state experiencing extremely high water stress. Consequently, we use four levels of water stress for our analysis: high stress, medium-high stress, low-medium stress, and low stress, as illustrated in Figure 2. According to Table 1, there are eight courses listed in the high-stress regions, seven courses in medium-high, five courses in low-medium, and five courses under the low-stress regions. Furthermore, these courses span both graduate and undergraduate levels across various departments. For instance, there are four courses listed by economics departments in high-stress regions, six courses in medium-high-stress regions, two in low-medium-stress regions, and one in the low-stress regions. The fact that these identified courses cover a wide range of U.S. universities and colleges and span different departments and water stress regions justifies our inclusive online examination approach.

To explore whether courses taught in different water stress regions focus on local water issues and how they do so, we conduct text analyses of the syllabi for all courses listed in Table 1. While a comprehensive course syllabus (that includes the course objective, description, topics, grading, schedule, etc.) was not available for each course, we were able to extract the course objective, course description, and learning outcomes from each identified syllabus. Using the extracted course objectives, course descriptions, and learning outcomes, we perform several text analyses to gain insights into qualitative patterns from the words in different groups of syllabi. The analyses are carried out in two categories: (i) analysis of the course syllabi based on the water stress regions, and (ii) analysis of the course syllabi based on economics and non-economics disciplines (see Appendix A1 for detailed steps of the text cleaning and analysis). We present our results using word clouds, which are commonly used for visualizing unstructured text data to gather new insights on trends and patterns from the words used.

Figure 3 displays the word clouds of the top forty words used in the course objective and description sections of the syllabi across the different water stress regions. A cursory glance at the word clouds in Figure 3 suggests that the coverage of topics in high-stress regions differs from low-stress regions. It appears that courses in high-stress regions emphasize words like “urban,” “groundwater,” “rights,” and “law” when teaching water-related topics (Figure 3a and 3b). In contrast, in low-stress areas, words such as “river,” “management,” and “human” appear more frequently (Figure 3c and 3d).

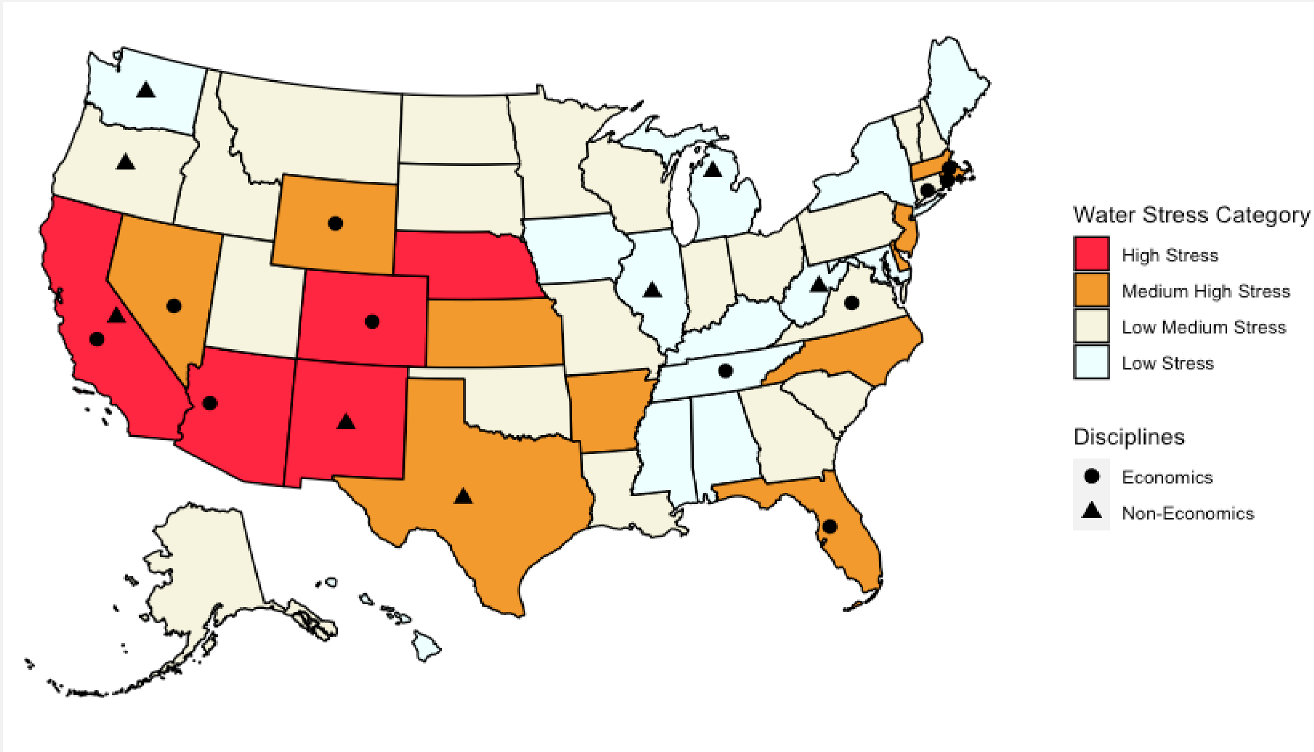


Figure 2: Regions and Disciplines Characterized by Different Levels of Water Stress in the United States

We obtain further insights on word usage by combining the information from the word clouds with the distribution of specific words. Table 2 shows the percentage count of select words used in the syllabi across the four water stress regions. The values of each word in Table 2 were normalized by using the count of that word over the total count of all words in the syllabi (i.e., course objectives and the learning outcomes) in each water stress region. If we look at the word frequency in Table 2 alongside the results of the word cloud in Figure 3, the emerging pattern becomes more evident.

Higher occurrences of words like "water" and "management" in both high- and low-stress regions are evident from the U-shaped relationship in Figure 4. This relationship suggests that courses in both high- and low-stress regions place a bigger focus on understanding water management issues. However, the topic of water management is likely to differ significantly between the two regions. The occurrence of words such as "urban," "groundwater," "management," "law," and "rights" in the high-stress region (Table 2) could indicate an interest in understanding and investigating the management of urban water scarcity within the context of water rights and water laws. On the other hand, words such as "river," "human," and "market" are more prevalent in the low-stress region (Table 2). Examining these words alongside the graph in Figure 4 suggests a focus on water management from water quality, flood management, and market perspective.

When we look at the course list in Table 1, it is apparent that the number of water-focused courses offered by economics departments is higher in the high-stress region, and this number gradually decreases as we move toward the low-stress regions. While there are fewer water-related topics taught by economics departments in the low-stress regions, the number of water economics courses taught in non-economics disciplines is higher in these areas. Similar to the earlier text analysis carried out on the four water stress regions, we also explore the common words used in the syllabi on economics vs. non-economics disciplines. Figure 5 displays word clouds of the top forty words used in the economics and

(a) High Water Stress Region

(b) Medium-High Water Stress Region

(c) Low-Medium Water Stress Region

(d) Low Water Stress Region

Figure 3: Word Cloud of the Top Forty Words in Syllabi in Each of the Four Water Stress Regions

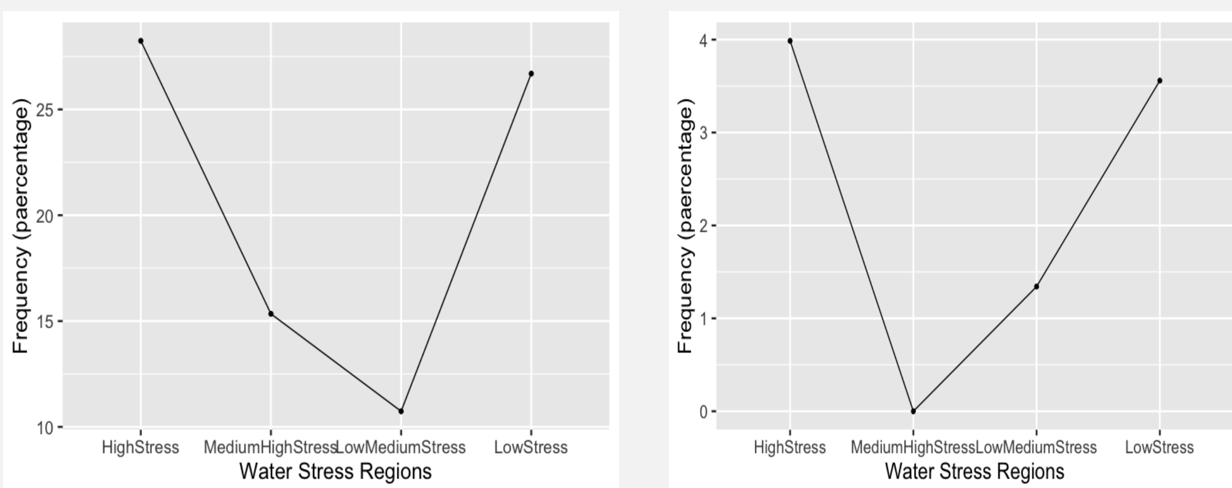
Note: The size of each word indicates the frequency—large-sized words occurred more frequently than small-sized words.

non-economics disciplines. While words such as "water," "economics," "resources," "policy," and "management" are used somewhat equally in both economics and non-economics disciplines, there are certain words more pronounced in either the economics or non-economics disciplines. For instance, words like "allocation," "supply," "valuation," and "markets" are entirely missing from non-economics disciplines. Likewise, words such as "governance," "agricultural," "social," "urban," "river," and "federal" seem to be used more in the non-economics disciplines.

To summarize, the text analyses reveal consistent patterns of differing content taught in the different water stress regions, as well as variations in content between economics and non-economics disciplines. These findings suggest a need for the economics discipline to provide a more holistic understanding of water-related issues by incorporating not only the economic dimension of water, but also the policy, governance, sociological, and anthropological aspects of water use. One way this could be possible is by instructors from different disciplines (e.g., economics and environmental studies) co-

Word	Word Frequency			
	High-Stress Regions	Medium-High-Stress Regions	Low-Medium-Stress Regions	Low-Stress Regions
Water	28.23%	15.34%	10.73%	26.69%
Economics	8.30%	10.22%	8.05%	4.98%
Urban	4.31%	0.00%	0.00%	0.00%
Management	3.98%	0.00%	1.34%	3.55%
Rights	2.32%	1.13%	0.00%	0.00%
Law	1.99%	0.00%	0.00%	0.00%
Quality	1.99%	1.13%	0.00%	3.55%
Supply	1.65%	1.70%	0.00%	0.00%
Allocation	1.66%	2.84%	0.00%	0.00%
Pollution	0.00%	2.27%	1.34%	0.00%
Demand	0.00%	1.70%	0.00%	0.00%
Market	0.00%	0.00%	4.02%	2.13%
Governance	0.00%	0.00%	4.02%	0.00%
Public	0.00%	0.00%	2.01%	0.00%
Human	0.00%	0.00%	0.00%	1.77%

Table 2: Percentage Count of Select Words Used in the Syllabi across Different Water Stress Regions



(a) Percentage of the Word "Water" **(b) Percentage of the Word "Management"**

Figure 4: Percentage of the Word "Water" and "Management" across Water Stress Regions

(a) Economics **(b) Non-economics**

Figure 5: Word Cloud of the Top Forty Words in the Economics and Non-Economics Disciplines

teaching a course on water-related topics. While the differences in content between economics and non-economics disciplines are interesting to observe, our other findings are more intuitive and seem to arise from relevant water issues and needs in these regions. If we look at the actual syllabus of the courses, topics like "water law and water rights," "groundwater," "agricultural water and water pricing," "property rights," "water markets," "water supply and demand," "urban water use," "water quality," "water conservation," "investment analysis," "optimal groundwater management," "river basin management," and "interjurisdictional conflicts," etc. are dominant in the high-stress area. These contents occur less frequently as we move from high- to the low-stress areas. Topics like "water quality," "managing freshwater resources," "environmental impact of water use," "non-market valuation of water quality," and "exploring the importance of water to biological processes" are common in low-stress areas. Based on these observations, we provide in Appendix A2 a set of suggested sample course syllabi for teaching water economics in economics departments that varies by water stress levels.

3 Review of Teaching Methods and Strategies in Water Economics

Next, we review novel teaching methods and strategies used in water economics classes, including those listed in Table 1 and additional courses from a general literature review. Economics teaching has been improving from the traditional "chalk and talk" pedagogical approach to a more interactive environment approach. Educators are now exploring alternative teaching methods and strategies in the discipline of economics to offer a diverse learning environment to the students and engage them in real-world economic issues (Truscott, Rustogi, and Young 2000; Becker, Becker, and Watts 2006; Roach 2014). We have reviewed and categorized these novel teaching methods as they relate to water economics, with pertinent examples in three pedagogical approaches: active learning, experiential or community-based learning, and inquiry-based learning. Focusing on water economics, while it is not as widely formally taught in class, we find a few examples of teaching water economics using one or more of these three approaches.

3.1 Active Learning

Using case studies as a teaching and learning methods has been proven to be an efficient method in improving academic performance in economics courses (Habasisa and Hlalele 2014). Student performance is further enhanced when case studies are combined with opportunities for students to collaborate and engage in small group discussions with their peers (Smith and MacGregor 1992; Monaco 2018; Liverpool-Tasie, Adjognon, and McKim 2019). In the subfield of water economics, with interdisciplinarity as one of its major characteristics, active and collaborative learning can be a practical approach to foster group activities and enhance students' communication and outreach skills. An example of such an approach is evident in the Water Resource Economics (AAE 4800/6800) offered at the University of Georgia, where students worked on the tri-state water dispute case and participated in a three-day "mock negotiation" session with students from Florida and Alabama on the A.C.F. (Apalachicola-Chattahoochee-Flint)/A.C.T. (Alabama-Coosa-Tallapoosa) tri-state water dispute case (Jordan 1999). In these mock negotiation sessions, students represent different interest groups to negotiate a water allocation formula between the states of Georgia, Florida, and Alabama. With this active learning practice, students have the advantage of both theoretical and applied methodologies.

Collaborative learning is a common type of active learning in which students exchange opinions and new information by relating prior knowledge (Smith and MacGregor 1992; Monaco 2018; Liverpool-Tasie et al. 2019). In addition to case studies, visual aids such as TV shows and movies also support teaching economics and fostering collaborative learning (Al-Bahrani et al. 2016). Leung and Nakagawa (2021) provide an example of showing the movie Lord of the Flies for an introductory microeconomic course. The learning objective is to guide students in identifying the economic concepts that have been applied in the movie. Educational videos on Youtube about water market rights can also be instrumental in the classroom while teaching water rights and water conflicts. In the subfield of water economics, with interdisciplinarity as one of its major characteristics, collaborative learning can be a practical approach to foster group activities and enhance students' communication and outreach skills.

3.2 Experiential or Community-Based Learning

Experiential learning is a pedagogical approach that provides students an opportunity to understand classroom-acquired knowledge better through the experience of real-world situations. This learning approach also aims to engage higher education students in the community. An illustration of this point is the Water Resources Economics (ECON 484/673) course offered at the University of Waterloo, which includes a trip to the region of Waterloo's wastewater treatment plant located in Kitchener, Ontario. During the trip, students learn the details of the treatment plant's construction, operation, and maintenance, helping students connect the theory on water management learned in the classroom to the real-world case of Waterloo's wastewater treatment plant. Furthermore, the University of Wisconsin–Parkside started university-community partnership in the mid-1990s. Their economics community-based learning brownfield project provided the information for environmental economics and econometrics courses to examine the economic impacts from the neighborhood park and the two brownfields (former industrial sites). In this way, economics students taking relevant courses learned firsthand that abstract economic theories and models can be applied to real-world problems, and can yield results that affect people's lives (Kaufman and Cloutier 2004). Furthermore, specific to water economics, the study of the relationship between water quality and health issues can benefit communities and enhance the learning experiences of students.

Another such case is the research agenda around "participatory action research" and "experiential learning" developed by the American University of Kuwait for students to develop their knowledge and skills by working on water challenges in Kuwait (Aljamal, Speece, and Bagnied 2016). The program includes economics students' direct participation in projects on assessing the cost structure of water production, pricing strategies, and water demand management.

In economics teaching, community-based learning is applied in various regions, aiming to engage higher education students in the community. Community-based learning can also provide an efficient learning experience for sustaining economic development in disadvantaged communities. The potential for positive impacts by virtue of community-based learning, especially among disadvantaged groups, has important implications for issues related to water. According to an article in Forbes (Ewing-Chow 2021), there exists a racial divide in access to clean tap water in the United States. This experiential and community-based learning technique, which is interdisciplinary in nature, could allow students to engage in their local communities and promote development efforts.

3.3 Inquiry-Based Learning

Inquiry-based learning is a teaching method that encourages students to ask questions and investigate real-world problems, and by doing so attempts to elicit curiosity among students. By developing a problem-solving environment in the classroom, students are actively engaged in the learning process and are given the opportunity to explore their natural curiosities. At the undergraduate level, Course-Based Undergraduate Research Experiences (CURE) programs can be highly successful in promoting engagement in water economics research. Students learn several foundational skills necessary for research within the context of water economics research. With a research question given, students can, either individually or in a group, work on their own to find and prepare data, perform analysis, and find the answer. This "hands-on" experience can feed curiosity and enhance the learning experiences of students. For instance, Water Economics (EES 270) at California State University utilizes the inquiry-based approach for understanding water economics concepts and encourages the ability to analytically apply these concepts to real-world problems. This is accomplished through various instruments such as written exercises (e.g., reading responses), quantitative exercises (e.g., problem sets), and holistic analyses (e.g., case studies).

Figure 6 summarizes the topics of water economics courses, the course levels at which water economics needs to be taught, and the teaching methods that can be applied in teaching water economics. With our online survey of the term "water economics course" and the text analysis of the syllabi, we recommend that topics such as water scarcity and water quality are important topics in economics courses. Water topics can be taught interactively as our examples show, and should be taught at all levels of higher education. For general economics courses, raising questions about water scarcity and quality can lead students to develop their interests in and attention to this daily natural resource. The following section presents examples of how water can be taught in different economics courses and levels.

4 Innovative Examples of Teaching Water Economics

While section 3 gives the essence of different strategies and teaching methods at different levels, the authors detail strategies in this section on multiple course examples across different institutions and disciplines that the authors have taught where water economics has been embedded. Along with the detailed strategy of each course we have taken, we also delineate them with the teaching methods described in Figure 6. Table 3 presents a brief overview of the courses, and later we explain in detail the courses and teaching strategies.

Although the contents of economics classes at the undergraduate and graduate levels are different, the objective of educating students at both levels is the same, which is to enhance their learning and developing capabilities. While a graduate-level course is more complex and technical, both graduate and undergraduate courses aim to prepare students to work independently and conduct effective research. That being said, we also observe the difference in educating undergraduate students versus graduate students. One of the differences between undergraduate students and graduate students is learning motivation. More undergraduate students are still exploring their interests. Providing more guidance and triggering their interest in economics, especially water economics, can be the main goals when we integrate the topic of water into economics education. Meanwhile, undergrad courses need to be more structured, while grad courses can allow more autonomy and flexibility. Undergraduate and graduate students also differ based on their career goals. However, economics educators should still prepare both undergraduate and graduate students to achieve their own career

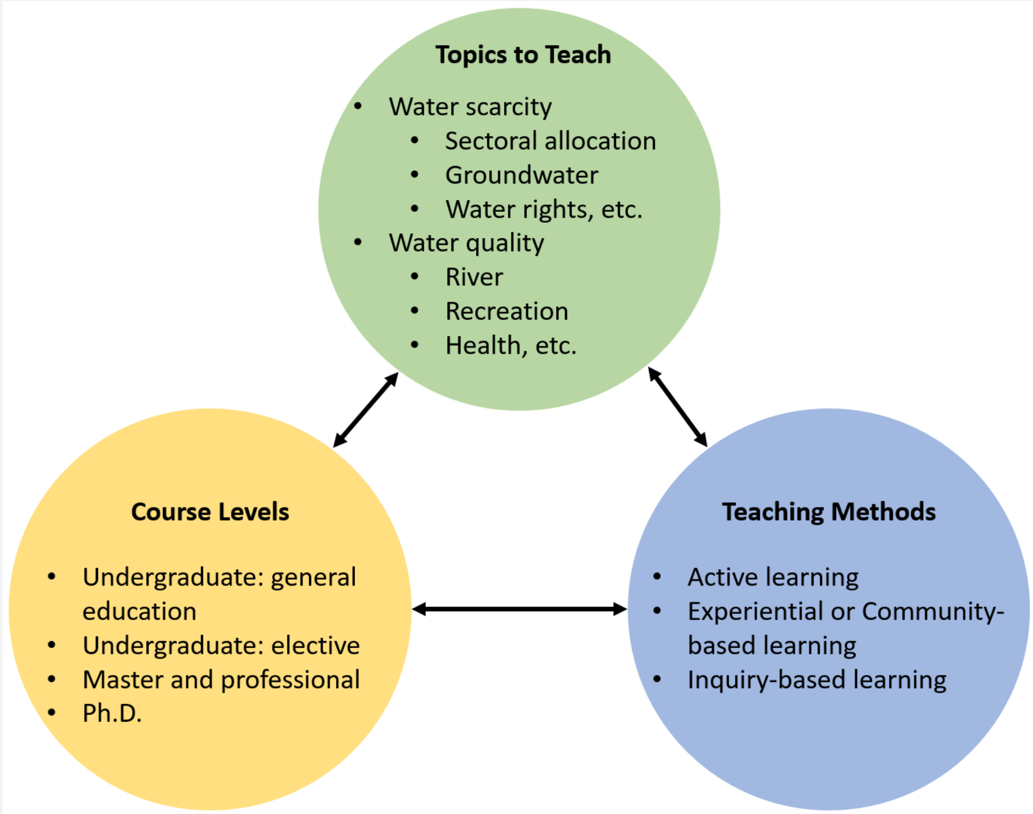


Figure 6: Potential Topics to Teach, Course Levels, and Teaching Methods in Water Economics

goals. Some undergraduate courses, like at the University of Arizona[2], adopt seminar-type classes to encourage students to learn deeper and practice their knowledge, while some graduate water courses welcome undergraduate students to participate for credit, like several courses of the Water Resources Program at the University of New Mexico (UNM).

In the following sections, we present cases showing interactive learning examples at both the undergraduate and graduate levels. Though there are some dissimilarities in terms of the content and structural design between undergraduate and graduate courses, the inherent objective is the same.

4.1 Examples of Undergraduate Teaching

We begin by looking at the introductory economics course (ECON 2120 Microeconomic Principles) at UNM, which focuses on sustainable water resources to facilitate active and inquiry-based learning in an inclusive environment. Why water? Because economics is the study of the allocation of scarce resources and New Mexico is the only U.S. state identified by the World Resource Institute as facing extreme water stress (Hofste et al. 2019), incorporating a teaching module on how to optimally manage scarce water resources in New Mexico and the Southwest is a natural fit. For UNM, with nearly 40 percent of the incoming students being the first in their family to go to college, adding a module on water that relates to their everyday life significantly helps with their learning. The course design consists of three parts. The first part of the course is dedicated to understanding the foundational tools of economics including the demand and supply framework and efficiency. The second part of the course focuses on firms' pricing, production decisions, and the role of antitrust authorities. The final part of the course examines the social issue of water scarcity and water resources management within the framework of economic

[2] https://economics.arizona.edu/undergraduate/bs-environmental-water-resource-economics

Table 3: Courses across Institutions with Different Teaching Methods Used by the Authors

Course Level	Course Name	Institution	Teaching Methods
Undergraduate (General education)	Microeconomic Principles (Econ 2120)	University of New Mexico (UNM)	Active and Inquiry-Based Learning
Undergraduate (Upper level)	Natural Resource Economics (Econ 433)	State University of New York (SUNY), Binghamton	Active Learning
	Environmental Economics and Policy (Econ 359C)	College of Saint Benedict and Saint John's University	Active Learning
	Environmental and Natural Resource Economics (Econ 335)	Fort Lewis College	Active Learning
	Problem-Based Learning Using Data Analytics (Econ 369*)	University of New Mexico (UNM)	Experiential/Community-Based Learning
	Economic Development (ECB305)	Gordon College	Active Learning
Graduate Level	Water Resources II (ECON545)	University of New Mexico (UNM)	Active and Experiential Learning
	Applied Environmental Economics (ECO 526)	Northern Arizona University	Active and Inquiry-Based Learning

Note: * Indicates that the course is also available for graduate credit.

analysis in the geographical Southwest. In this last section students apply the economic models they have learned in the first two parts. Specifically, they examine how our economic and political institutions have allocated water in the past (focusing on sources of inefficiency) and how they might improve on its allocation in the future (focusing on potential remedies and opportunities for institutional reform). Students also share their personal experience with water scarcity, learn about why sustainable water resources is one of UNM's Grand Challenges, and discuss how water management in New Mexico and the Southwest can be improved in the future. A unique component of the course is to offer students entry-level water economics research engagement as a part of the UNM Expanding Course-Based Undergraduate Research Experiences (ECURE) program. After water pricing is introduced as a source of water allocation inefficiency, students are guided to participate in two types of inquiry-based ECURE activities. First, they research and collect data on the historical and current tap water rates in their cities and communities. Then, they read and critically review relevant peer-reviewed journal articles. Examples of these ECURE activities as well as a performance-based assessment are provided in Appendix A3. Through these ECURE activities, students learn several necessary foundational skills.

Moving to upper-level courses, we introduced the topic of water resource allocation in environmental and resource economics at different institutions (Econ 433: Natural Resource Economics at SUNY Binghamton; Econ 359C: Environmental Economics and Policy at the College of Saint Benedict and Saint John's University; and Econ 335: Environmental and Natural Resource Economics at Fort Lewis College). We adopted a combination of active and inquiry-based learning in these courses, and the content of water resources is typically covered in five class periods. The water resource module began with discussions of background information on the hydrological cycle and water scarcity issues in the United States and around the world. A larger portion of the focus was then devoted to understanding the theoretical and empirical analysis of surface and groundwater sources. The theoretical analysis of water allocations was carried out using graphical and basic mathematical analysis (algebra and calculus), where students first learned the statically efficient allocation of surface water use with multiple competing user groups. Then, the course moved to the dynamic allocation of groundwater resources. Once students were taught the theoretical nature of water allocation, the next two class sections were dedicated to carrying out an empirical analysis of a static and dynamic scenario using Microsoft Excel. In Excel, students worked with a solver to determine and graph the optimal allocation of groundwater sources under various constraints such as constant versus increasing marginal extraction costs and under the assumption of availability of a substitute resource versus when substitute resources are not available.

While the theoretical and empirical analysis on the water resources topic focused only on the static and dynamic allocations, students were also separately introduced to the concepts of non-market valuation approaches using contingent valuation, hedonic valuation, and travel-cost approaches, all of which could also be employed to investigate water resource issues when students worked on their final projects. After completing the theoretical and empirical analysis, students were introduced to potential sources of inefficiencies in water resource allocation around the world, as well as different water pricing structures. The class section ended with discussions on potential remedial policies, and case studies were used to aid these discussions. For example, the coping mechanism of water security for Tucson, Arizona (Tietenberg and Lewis 2018) was discussed to highlight the supply of water in the face of severe scarcity. Another example was the mechanism of water rights trading among different parties, which was shown on the Water Colorado website (Water Colorado 2019). These case studies increased students' understanding of the water markets, current water crises, and the future of water supplies in the United States. Finally, students were introduced to the empirical application of theoretical understanding and presented what they had learned. By doing a group presentation on their assigned group project, students also experienced the phase of disseminating their project outcomes to the public.

One surprising outcome of these courses has been that each year at least a few students choose to continue working on their class topics even after the completion of the course, and sometimes these topics get converted into the students' capstone projects or honors theses. At the College of Saint Benedict and Saint John's University, during the Econ 359C course in Spring 2021, one student used a hedonic valuation approach to estimate the economic value of Mille Lacs Lake in Minnesota as their final project for the course. The student showed interest in continuing to expand on this topic even after the course was completed. Although the original class paper evolved to a different topic, the student was able to write a research paper that became the student's honors thesis, titled "Effect of the Mississippi River on Property Values in Anoka County: A Hedonic Price Analysis" (Parisi 2021). Overall, the approach of introducing students to a natural resource topic such as water by integrating theoretical models with empirical exercises in Excel, and ending with discussions on policies, has allowed the students not only to develop an appreciation of the role of economics in understanding environmental issues, but has also given them the tools and ideas necessary to complete capstone courses and theses.

Along with the theoretical approach in the above-mentioned courses, we have used empirical techniques to teach water economics to undergraduate students in a set of courses at UNM. These courses, all named “Problem-Based Learning Using Data Analytics” but with different course numbers in different semesters, use primary survey data to communicate real-world challenges pertaining to water resources, particularly in the context of a developing country. The overarching objectives of these undergraduate courses have been to teach the importance of water resources by showing the linkages between water, public health, and behavior through real-world data and rigorous empirical tools. The first course in this series, Econ 451: Problem-Based Learning Using Data Analytics, which was an upper-level undergraduate course offered in Fall 2016, exemplifies this. In the class, undergraduate students analyzed primary household survey data on the Danda River in Nepal collected in Summer 2016 by the graduate students. We used a graduate-undergraduate research mentorship model for the course, where five PhD students worked closely with the undergraduate students to analyze and interpret the data. Designed and coordinated by the Nepal Study Center of UNM, a similar teaching approach was adopted in our two other Problem-Based Learning Using Data Analytics courses: Econ 395 (Fall 2017) and Econ 369*[3] (Fall 2018). An important aspect in these two courses was the development of ten to twelve learning modules that were used to teach the theory of basic statistics and econometric models and then practically execute them in the software STATA, using variables from our Danda River survey data. The final research outcomes of these courses were group posters that students presented in class and at the UNM UROC conference. For example, a group of students from Econ 395 developed a research poster on linkages between water quality risk perception and water treatment actions. Another example is a research poster, developed in Econ 369, that examined the relationship between the presence of E. coli in drinking water, handwashing behavior, and the occurrence of diarrhea. The health impact of water quality is also discussed in an ECB305: Economic Development class at Gordon College. This class has a multidisciplinary design, incorporating students focusing on economics, biology, environmental science, and international affairs. The students are assigned a research paper to read (for example, “The Interconnection Between Water Quality Level and Health Status: An Analysis of Escherichia Coli Contamination and Drinking Water from Nepal” (Kunwar and Bohara 2020; Rahman, Kunwar, and Bohara 2021). After that, students participate in an online discussion forum to share what they have learned from the reading. Embedding a discussion portion in this type of interdisciplinary development economics course can be effective in teaching water-related issues.

These courses are designed not only to teach real-world problems with data analysis, but to expose the students to the implementation and dissemination of their classroom findings. An important extension to these courses took the form of two Himalayan Study Abroad Programs offered at UNM through its Nepal Study Center in Winters 2017 and 2018. Around eighteen students from Econ 395 and Econ 369 traveled to Nepal to implement the solutions developed in the classes, which included installing a water quality monitoring device in the Danda River and designing a sanitation awareness bulletin board for public viewing. Students from the Econ 395 class had the opportunity to further enhance their learning by presenting their research to the wider research audience at the Undergraduate Research Opportunity Conference, UNM (2018), and the Annual Meeting of the Southwestern Society of Economists (2018). Students had hands-on experience on projects in solving community-based problems by applying what they had learned in the classroom. This classroom-to-field approach, which teaches a combination of theoretical and practical knowledge, has far-reaching impacts on students, institutions, and communities.

The teaching approach that we have adopted to enhance students’ understanding of water-related challenges and potential solutions using real-world data has been enriching on several fronts. Undergraduate students who have completed these courses have a deeper understanding of the importance of water resources through their research and learning experiences, and have a deeper understanding of statistics and data analytical tools. The graduate-undergraduate mentorship model that we used in our courses was helpful for the undergraduate students and provided the undergraduate mentoring experience to the graduate students. Students who took part in the study abroad programs had

[3] *Indicates that the course is also available for graduate credit.

the opportunity to witness water-related problems and implement solution projects in the field. Moreover, the study abroad programs helped students better understand the social, economic, and cultural significance of water resources like rivers in local communities in developing countries. The field component of this innovative program was facilitated and inspired by a team of interdisciplinary UNM faculty, an economist, a hydrologist, and a climate scientist. Their trip to Nepal in 2015 was supported by a small National Science Foundation travel grant.

4.2 Examples of Graduate Teaching

At the graduate level, the approach tends to be research-oriented. In an interdisciplinary graduate course ECON545 (AOA WR 572) Water Resources II at UNM, which is co-taught by an economist, a hydrologist, and a journalist, students spend six weeks on a team modeling project that focuses on developing an integrated hydro-economic dynamic model for the local Middle Rio Grande Basin. Students look into different water-using sectors in the basin (agriculture, cities, environment, etc.), talk to stakeholders, identify their research questions, search data sources, explore future scenarios (climate change, population growth, etc.), build models (using system dynamics modeling software such as Powersim or GoldSim), obtain results, write reports, and present to a policy audience at the end of the course. The research questions are typically identified via discussion with local stakeholders such as the Bureau of Reclamation, irrigation districts, farmer associations, and environmental organizations. Student teams have different yet closely related research questions, which aids in student interaction and group problem-solving. This type of cooperative and active learning has proved to be very effective as evidenced by skills acquired by the students and their successful placement at various sectors, including top national research labs and consulting firms.

A similar approach is taken for the Applied Environmental Economics (ECO 526) course at Northern Arizona University. The negative externality of water pollution and how to incorporate that into market outcomes are taught as a subtopic in this course. A simulation scenario is created involving water pollution where students learn to identify optimal pollution reduction activities. Students learned why the individual level of effort to reduce pollution varies from the social outcome. Students also completed a class paper as a requirement of the course, and several students selected water pollution as their class project. The class paper is designed to review the current policies related to water pollution, and the students need to propose better policies than the status quo to account for the marginal social cost. For this paper, students identify water pollution point sources such as agriculture, dairy production, industrial run-off, etc. Then, they must propose policy tools to reduce water pollution, such as cap and trade, pollution tax, etc., for both point and nonpoint sources of water pollution. At the end of the semester, students present their research, generating discussion in the classroom. Along with the skill development, students receive significant exposure to the public policy aspect of water economics from this inquiry-based learning approach.

The teaching approach we have adopted at the graduate level has higher research exposure in terms of technical knowledge and research implementation compared to undergraduate teaching. From the identification of research questions to methodology to the policy implication of results, students experience different components of research and actively engage in class projects. Along with quantitative research skills in water economics, students also gain practical knowledge from a comprehensive research experience.

5 Discussions and Further Thoughts

Water resource management is an ideal topic for use in exploring scarcity, crisis, pollution, health impacts, and international disputes, especially in its usability in the innovative teaching approaches described previously. The need for such an intervention arises from the fact that, in most economics courses, analysis is limited to pricing mechanisms and marginal analysis, and without an opportunity for real-world exploration and application of these analyses, the scope of learning outcomes may be diminished or incomplete. This paper proposes innovative teaching interventions and frameworks at the graduate and undergraduate levels that we believe are lacking in the broader economics curriculum. In this article, we first provide an overview of water economics teaching in different U.S. institutions. Then we introduce different types of teaching methods in which water economics can be embedded, delineated by undergraduate and graduate applications.

Most standard water resource economics courses use basic applied microeconomic theory and principles, supply and demand, pricing, welfare optimization, and cost-benefit analysis. Students also get exposure to water markets and water rights, and some game theory as a tool for conflict resolution. Econometric tools are also used to perform forecasting of the supply and demand models of water usage. This standard curriculum practiced in economics departments seems to fall behind when it comes to underscoring the importance of regulatory mechanisms, which influence a wide range of water-related issues. For example, the public-private partnership in water and sanitation infrastructure projects can have far-reaching implications for public health and safety. There are laws regarding the recharging of groundwater with treated water, and it is not uncommon to have “fights and rights” debates and litigations over it. Regulations governing surface water quality can also affect water usage activities in the residential and commercial sectors, especially in the use of products with certain chemical compositions. It is worth noting that the Clean Water Act of 1972, which was designed to ensure the safety of drinking water, was extended by the Obama Administration’s Clean Water Rule to protect the U.S. rivers and streams. The recent repeal of this regulation by the Trump administration further highlights how regulations surrounding water resources can have far-reaching consequences when it comes to usage, public health, and the environment. Likewise, climate change and its impact on freshwater bodies have forced many countries around the world to devise various institutional mechanisms to deal with their respective water crises. Thus, it would be important to incorporate these legal aspects into the modern curriculum of water economics.

Economics departments could take an inclusive approach to help address water challenges by collaborating with other departments within and beyond their institution. Water cannot be taught by simply looking at allocation and pricing issues as is traditionally done in economics courses. Economics students, especially those who are interested in environmental and resource economics, need and ought to be exposed to holistic dimensions of water resources. In addition to faculty and departments’ initiatives, institutional support and assistance from external sources such as institutional benchmarking can be effective in moving toward a modern economics curriculum pertinent to water. An example is the Sustainable Water Resources Grand Challenge launched at UNM in Spring 2019, which is one of the university’s three Grand Challenges. This challenge requires high levels of interdisciplinary research, scholarly innovation, and community connection. By using the size and strength of its interdisciplinary programs in natural sciences, social sciences, engineering, law, and policy, the UNM Sustainable Water Resources Grand Challenge is seeing great success in its first three years of establishment. A reason for this is the cultivation of collaborative partnerships across campus, which increases the visibility of research (Whitt 2021). These collaborative partnerships among colleges, centers, and departments (including the Department of Economics, and with an economics faculty member on the Grand Challenge leadership team) also significantly improve the training of the next generation of water managers and leaders needed to solve local and global water problems. For example, more courses have been cross-listed across programs, and several departments, including economics, are considering co-taught interdisciplinary water-focused courses. An Academic Affairs General Education Teaching Fellowship that targets Grand Challenge course enrichment was also established via the UNM Office of the Provost to recruit faculty interested in transforming how undergraduates are educated in the general education program. Specifically, teaching fellows collaborate to leverage the UNM Grand Challenges to further enrich an existing general education course or to develop a new general education course. The corresponding author of the article was awarded the fellowship with funding support to develop a water-focused module for an introductory microeconomics course and has successfully implemented it in both face-to-face and online classes with excellent feedback from the students. The course was further enhanced in subsequent semesters to use a set of research-based interventions to build equitable learning environments via the UNM Student Experience Project program, which is part of a national program with six university partners, and to offer students entry-level water economics research engagement via the UNM ECURE program. Institutional support like the Grand Challenge initiatives and teaching fellowship programs provides great opportunities for instructors to share ideas across disciplines and connect teaching and learning with global challenges like water issues.

External funding and resources can be sought from various funding agencies and foundations to support such efforts within and across institutions. For example, the UNM Sustainable Water Resources Grand Challenge led a $3 million, five-year proposal to the National Science Foundation Research Traineeship Program focusing on big data for multi-scale hydrologic systems. The proposal had an economist as a co-PI and, although not funded, has laid a foundation for future collaboration of similar training proposals. A successful training grant example is the PATHWAYS (Partnerships Along the Headwaters of the Americas for Young Scientists) program, co-hosted by UNM and Washington State University as part of the National Science Foundation’s International Research Experience for Students, where students conduct research and receive training on headwater dependent systems along the Transect of the Americas in Central and South America (Washington State University 2022). Improved availability and securement of these external resources will assist in moving toward a modern water economics curriculum where students are introduced to the practical implementation and analysis of local and global water issues. In summary, we call for a dynamic economics curriculum to help address challenges and workforce demands related to water resources. We also call for better education and training of the next generation of water economists and, more generally, water citizens.

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Appendix

A1. Details of Text Analysis

The generation of word clouds for text analysis is detailed in this section. We started by searching the phrase "water economics course" on Google (https://www.google.com/). From the resulting pages, we collected the names of the courses and institutions. We browsed all the pages until the course listings ended. After identifying the course names, we collected the syllabus of those courses. However, some course syllabi were not available on the institution's website. In those cases, we collected the course description and other related content information from the website of that department.

Next, we moved to the text-gathering part. First, we gathered all the course descriptions and course content from the syllabi and websites by each water stress area and by economics vs. non-economics disciplines. Second, we cleaned the text to carry out the text analysis. We removed any punctuation, numbers, and stop words (i.e., common terms like "a," "an," "the," "was," "from," "for," etc.). Additionally, any words in the syllabi that captured classroom decorum, but were not relevant to understanding water-related topics were also removed. These are "assignment," "students," "university," "attendance," "description," "class," "topics," "related," "particular," "course," "work," "techniques," "change," "options," "united," "role," "based," "explain," "include," "with," "introduction," "such," "part," "their," "how," "each," "assigned," "learning," "these," "syllabus," "help," "also," "particular," "covering," "instructor," "apply," "focusing," "based," "take," "meet," "draft," "objectives," "due," "audience," "used," "week," "discussion," "review," "brief," and "tools." We have also combined a few similar words: "resource" and "resources" to "resources"; "policy" and "policies" to "policy"; "economic," "econ," "economists," "economist," and "economics" to "economics"; and "environment" and "environmental" to "environmental." After cleaning the text, we created the word clouds and frequency tables of words.

A2. Suggested Course Syllabi in Different Water Stress Regions

1. High Water Stress Region
https://are.berkeley.edu/sites/are.berkeley.edu/files/job-candidates/pdfs/EEP162_Syllabus_2019.pdf
2. Medium-High Water Stress Region
http://www.uwyo.edu/agecon/about-us/facultystaff/faculty-pages/McLeod/AGEC%204720%20Syllabus%20Water%20Resource%20Economics.pdf
3. Low-Medium Water Stress Region
https://cpb-us-e1.wpmucdn.com/blogs.uoregon.edu/dist/3/5358/files/2014/01/467_intnl-water-policy-192a76h.pdf
4. Low Water Stress Region
https://seas.umich.edu/sites/default/files/2022-04/EAS_501.086_Fall_2021.pdf

A3. Expanding Course-Based Undergraduate Research Experiences (ECURE)

Activities in an Introductory Microeconomics Course

ECURE Activity 1: Your Water Price

1. Do you know the current price you (or your landlord) pay for a gallon of water from your tap? If so, what's your current water price? If not, can you try to find it out? (If you receive water bills, you may calculate it from your last bill; if you don't receive water bills, ask a family member or a friend who does receive bills.)
2. Do you think your current water price reflects water abundance/scarcity in your region?

ECURE Activity 2: U.S. Urban Water Prices: Cheaper When Drier?

Read the following two papers (published in a top water journal but easy to read):

1. Luby, I.H., Polasky, S., and Swackhamer, D.L. 2018. "U.S. Urban Water Prices: Cheaper When Drier." *Water Resources Research* 54(9):6126–6132.
2. Switzer, D., and Teodoro, M.P. 2019. "Comment on 'US Urban Water Prices: Cheaper When Drier' by Ian H. Luby, Stephen Polasky, and Deborah L. Swackhamer." *Water Resources Research* 55(7):6316–6321.

After you read Paper 1:

1. What is the purpose of the research (aka, what is the research question)?
2. What data is collected in order to investigate the research question?
3. What is the finding of the research?

After you read Paper 2:

1. According to Paper 2, what are potential flaws in the research in Paper 1? Do you agree?

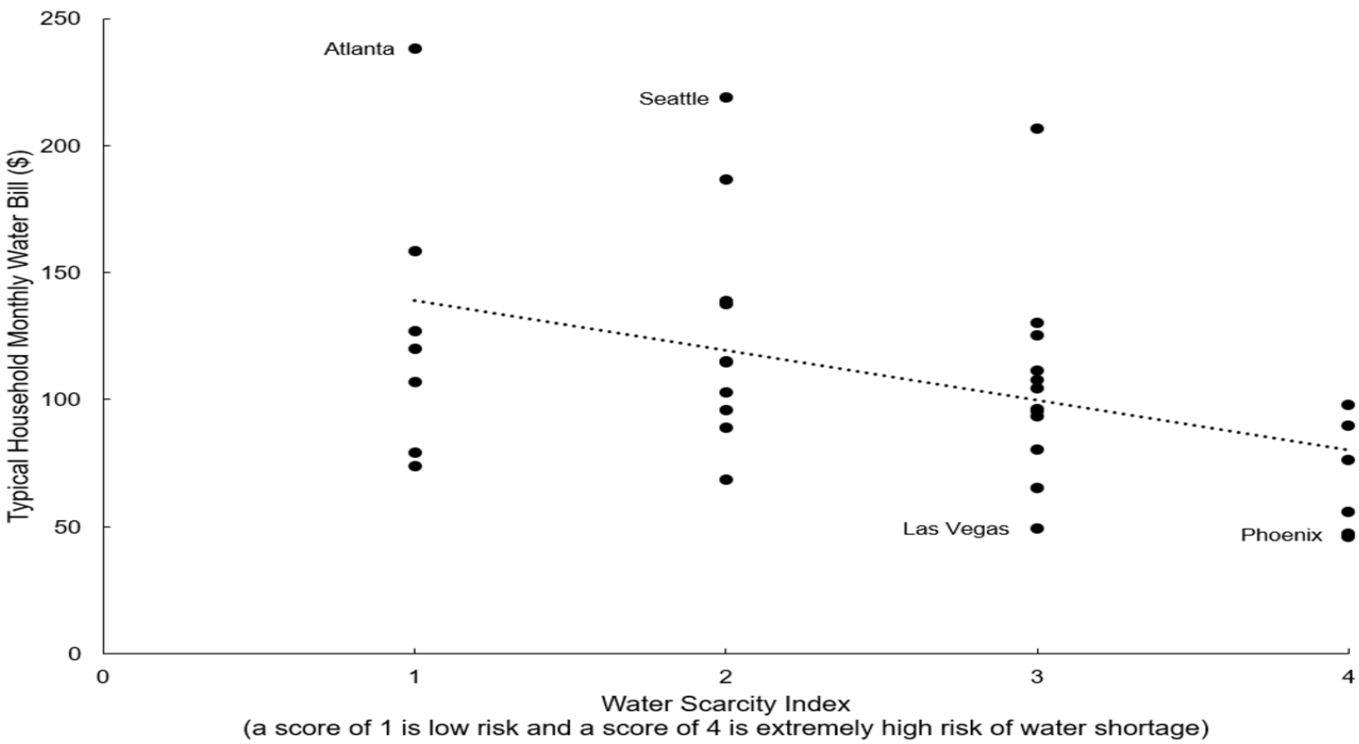
An ECURE Performance-Based Assessment
Here we provide an example of a performance-based assessment designed for an introductory microeconomics course that offers students entry-level water economics research engagement. The research project described in the assessment is adapted from Luby et al. (2018).
Your partner on a research project drafts results for a poster you will both present at a regional conference. They share a draft with a research question, figure, and bullet points below, which relate to data you collected and analyzed.

The purpose of your research project is to examine how municipal water rate structures align with the issue of water scarcity in the United States (US). Specifically, the project investigates whether water prices are higher in water-stressed regions like the Desert Southwest than in water-rich areas like the Northeast. You collected data on water pricing in the largest city within the 35 most populous metropolitan areas in the US and analyzed the pattern in the data. You found that cities facing greater water scarcity tend to have lower water prices. In fact, the least expensive water in the country was found in the cities with high water scarcity (Sacramento, Las Vegas, and Phoenix). Below is the poster:

a. *Write a three- or four-sentence summary of the research project that communicates the main findings to an interested friend or family member who isn't familiar with the project.*
b. *In addition, write constructive criticism of the draft for your partner. Be specific about what changes or additions you would make to overcome any problems you notice, and why you would make those changes/additions. Make sure to provide feedback about the (1) research question, (2) figure, and (3) bullet points.*

Research question: Are municipal water prices high in the U.S.?

Results



- Cities facing greater water scarcity tend to have higher water prices
- The least expensive water in the U.S. are in the cities with high water scarcity

Figure A1: An Example Poster from a Performance-Based Assessment Designed for an Introductory Microeconomics Course

Data source: Luby, Polasky, and Swackhamer (2018).

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Teaching and Educational Methods

Reimagining Teaching Water Issues through Integrative Experiential Learning

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Abstract
This paper highlights an undergraduate experiential learning course on water resources, which was designed and coordinated by the Nepal Study Center (NSC) and offered by the economics department at the University of New Mexico (UNM). The experiential learning course, "Problem-Based Learning," combined learning experience in the classroom with community outreach and international research experience via a study abroad program. The course development closely followed the principles of the "experiential learning theory" (ELT), and the course structure comprised four components: (1) field-based data collection, problem identification, and conceptual framework development, (2) data analysis and development of potential intervention and solutions, (3) study abroad and implementation in the field, and (4) dissemination of findings and community outreach. A noteworthy feature of this learning model included graduate and undergraduate student collaboration. Graduate students aided instructors by serving as mentors for undergraduate students, helping them with empirical analysis and leading discussions in the development of policy tools and solutions implemented in the study abroad program. The broader impacts of these experiential learning courses can be summarized as: (1) student learning experience, (2) community impacts, (3) research experience, and (4) potential for the program to serve as a model for other institutions.

1 Introduction

Water is an essential resource that sustains all forms of life, yet ensuring its quality and availability continues is an increasingly urgent contemporary issue. Water scarcity is an acute issue in many parts of the United States, including Arizona, California, Colorado, Nebraska, and New Mexico, which are all facing considerable strain on their water supplies (Hofste et al. 2019). The problem is even more widespread globally, with more than 40 percent of the world population residing in regions of moderate water stress. Additionally, countries in the Northern African, and Central and Southern Asian regions are facing the issue of groundwater consumption far exceeding the replenishment rate (Food and Agriculture Organization and UN Water 2021). The inevitable consequence of increasing water scarcity is the prevalence of unsafe water practices, which pose significant public health implications (Jury and Vaux 2007). In several regions of Asia and Africa, waterborne diseases like diarrhea and dysentery have inflicted tremendous damage on their respective development (Weli and Ogbonna 2015; Zahid 2018).

To address the multifaceted nature of water, it is crucial that water-related topics be integrated across academic disciplines including social sciences, natural sciences, and humanities (Yarime et al. 2012; Amahmid et al. 2019). However, merely integrating these topics into the classroom is not enough. It is essential for departments to collaborate, co-design, and co-teach water-related topics that provide students with practical, hands-on learning experiences that go beyond traditional classroom lectures. To this end, undergraduate institutions have started to emphasize the importance of richer learning experiences such as capstone projects, internships, study abroad programs, and undergraduate research

(Fink 2013; Barber 2014). These integrative learning programs have the potential to improve students' appreciation and comprehension of topics such as water resources from multiple disciplinary perspectives, which is crucial in tackling water-related challenges in the future.

This article highlights the development of a problem-based experiential learning course to investigate issues that lie at the intersection of environment and health. The course, Econ 369*[1]: "Problem-Based Learning Using Data Analysis," has been recurrently offered by the economics department at the University of New Mexico (UNM) in collaboration with the Nepal Study Center (NSC[2]) at UNM since Fall 2018. This course came into existence following two years of trial runs with two separate courses: Econ 395: "Problem-Based Learning Using Data Analytics: Health and Environment in Urban Nepal," and Econ 451: "Sustainable Development Action Lab" during Fall 2016 and Fall 2017. In Fall 2018, the three courses, Econ 395, Econ 451, and the Econ 369*, all focused on water-related issues in Nepal, but since Fall 2018, the Econ 369*[3] course has investigated other environmental topics such as air pollution and solid waste management. The primary focus of the problem-based learning courses was to provide undergraduate students with an international research experience by taking the classroom to the field. These courses followed a pedagogical approach that encouraged students to engage in problem-driven, policy-relevant work. In these courses, students were exposed to real-world problems through data and research, and had the opportunity to visit the area where their research focused and implement their findings. These courses relied on a primary teaching instructor, with the assistance of a volunteer team of doctoral student mentors.

We discuss in the following the comprehensive overview of the design and implementation of the Econ 369* course along with the Econ 395 and Econ 451 trial courses, highlighting the positive outcomes achieved through this experiential learning approach. Section 2 introduces the theoretical underpinning of the Econ 369* course design, emphasizing the importance of learning by doing through Kolb's (1984) "experiential learning theory" (ELT). Section 3 delves into the pedagogical structure of the course, encompassing both classroom and fieldwork components. Section 4 discusses the broader impacts of the course, alongside the metrics used to evaluate its effectiveness, and finally, section 5 outlines the challenges of implementing similar courses and provides suggestions for the future programs.

2 Theoretical Framework

The problem-based learning[4] course was based on the theoretical foundation of the experiential learning model, which emphasizes the role of experience in the learning process. The experiential learning model has its intellectual origins in the works of prominent twentieth-century scholars such as John Dewey, Kurt Lewin, and Jean Piaget (Kolb 1984). The ELT was proposed in Kolb (1984) as an alternative pedagogical approach to traditional educational methods that focus on theories taught in classroom settings and reflection on these theories through written exams. ELT, on the other hand, views learning as a holistic process that aids in the creation of knowledge through the transformation of experiences (Kolb and Kolb 2009).

[1] More information on the Econ 369*, Econ 395, and Econ 451 courses is available at https://nepalstudycenter.unm.edu/SustainableResearchLab/UndergraduaterResearchInitiatives.html

[2] NSC is a research center housed in the economics department at UNM. It was established in 2005 with the aim of creating a platform for knowledge transfer where graduate students and scholars could develop, restore, and promote policy-oriented research on issues pertinent to the Himalayan region. Over time, NSC has developed innovative strategies and tools to facilitate knowledge sharing between North America, South Asia, and other regions. One notable example is the "problem-based learning" courses discussed in this paper, which the Economics Department at UNM offers regularly.

[3] This course can be taken for graduate credit too, which is why there is an asterisk (*) in the course number.

[4] We use the terms "problem-based learning" and "experiential learning" interchangeably throughout the paper. Both terms capture the approach to teaching the Econ 369*, Econ 395, and Econ 451 courses.

The ELT model posits that effective learning occurs in four phases, namely "concrete experience" (CE), "reflective observation" (RO), "abstract conceptualization" (AC), and "active experimentation" (AE). These phases are illustrated in Figure 1, where the vertical axis depict the knowledge grasping dimension, showing that knowledge can be acquired through apprehension (CE), comprehension (AC), or a combination of both. The horizontal axis represents the knowledge construction or transformation process, which can be achieved through intention (RO) or extension (AE). Kolb emphasized that all four modes of experiencing, reflecting, thinking, and acting are equally important in facilitating the learning process. The course structure of Econ 369* was modeled under the ELT framework and comprised four main components: (1) field-based data collection and problem identification, (2) data analysis and development of potential intervention problems, (3) study abroad and implementation in the field, and (4) dissemination of findings and community outreach. Figure 1 also displays the structure of the Econ 369* course by mapping it to the ELT framework.

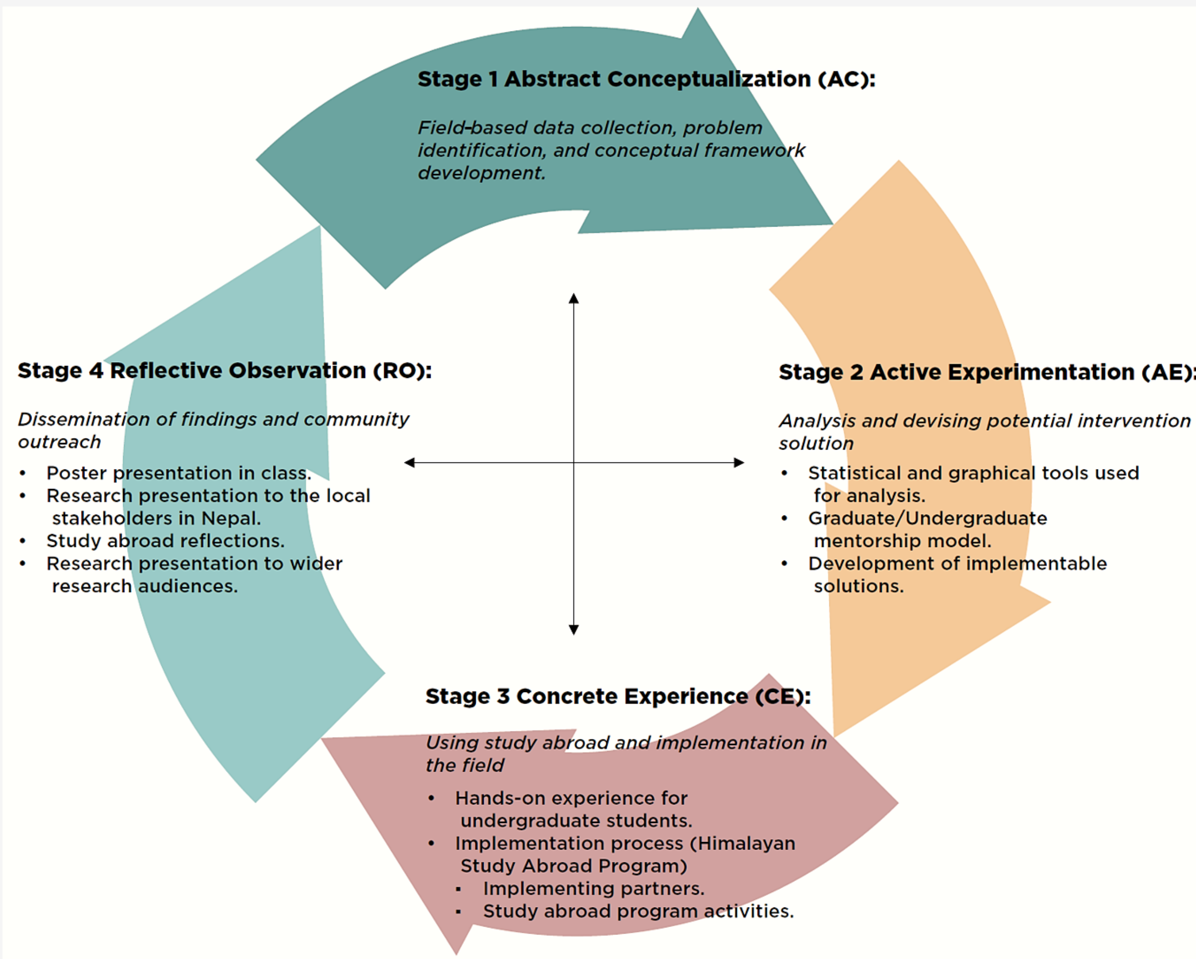

Figure 1: The Four Stages of Learning Construction (CE, RO, AC, AE) in Kolb's Experiential Learning Model Knowledge grasping occurs during the CE and AC phase, while RO and AE represent the knowledge transformation dimension. This figure also illustrates how these four elements of ELT align with the course structure of Econ 369*.

The learning process, according to the ELT model, requires that students first grasp knowledge, either through AC and/or CE, after which a phase of construction, via AE and/or RO, is necessary to complete the learning process (Kolb 2014). The construction allows the grasped knowledge to be transformed into a mental model through the experience of this knowledge. The principles of ELT have been adopted in many courses across various institutions around the world, and the results on the outcome of student learning are largely positive (Healey and Jenkins 2000; Ahn 2008; Abdulwahed and Nagy 2009; Rajasulochana and Ganesh 2019). Supporters of experiential learning believe that it promotes greater interest in the subject material, enhances intrinsic learning satisfaction, increases understanding and retention of course material, develops the desire and ability to be continuous learners, and improves communication, interpersonal, problem solving, analytical thinking, and critical thinking skills in the students (Brickner and Etter 2008).

3 Detailed Course Description

The experiential learning courses were designed to provide undergraduate students with an opportunity to develop, analyze, and execute original research projects on environmental and health issues, and to implement their solutions in the field. These courses, which included Econ 369* and the earlier trial courses (Econ 395 and Econ 451), enrolled 15–18 undergraduate students on a first-come, first-served basis. To encourage students from diverse academic backgrounds to collaborate and develop research ideas, the course did not require an economics prerequisite for enrollment. This allowed for multidisciplinary teams to be created that could leverage each student's skills and expertise to develop executable plans. Students were, however, required to have completed an introductory statistics course for enrollment in the course.

The experiential learning course was first offered as a pilot course in the Fall of 2016. This course, Econ 451, was offered to undergraduate students with a theme of "*moving from classroom to action research.*" This pilot course aimed to create a classroom-based research learning environment where students, graduate mentors, and faculty could collaborate on research projects that could be implemented, monitored, and evaluated. In Fall 2017, Econ 395 was offered as another trial course following the same structure as Econ 451, but with a few extensions. One extension was the inclusion of the Himalayan study abroad program during Winter 2017–2018, which offered interested students an opportunity to take their classroom ideas to the field by engaging in interdisciplinary research in Nepal. Econ 451 and 395 were eventually combined to form a permanent course known as "Problem-Based Learning Using Data Analytics" (Econ 369*), which has been offered since 2018.

Nepal was selected as the location of the study abroad program in these courses. This is partly due to NSC's field connections with the country, which provided a natural platform to teach a field-based course on water issues in a developing country context. Nepal is also an ideal case study for water-based courses due to its unique geography and topography. This small country boasts around 6,000 rivers, including rivulets and tributaries, as part of the Indo-Gangetic plain. The Ganges Basin, one of the world's most populated river basins, is heavily reliant on Nepal's rivers, which contribute around 70 percent of the dry season flow and 45 percent of the annual flow in the Ganga River (Upreti and Acharya 2017), making Nepal a unique and effective location for research and education on water-related issues.

During the first three occurrence of these courses (Fall 2016, Fall 2017, and Fall 2018), students learned about environmental and health issues stemming from the Danda River, which falls in the Western region of Nepal. The river flows from the Northern Mountains near Tibet, passes through urban and agricultural districts, and finally crosses the Indian border to join the Ganges River. One of the major concerns with the Danda River stems from unplanned urbanization around the town of Siddharthanagar, which has transformed the once-pristine river into a sewage drainage. The unfortunate result of such urbanization has been the degradation of the river ecosystem, making it unsuitable for irrigation, spiritual rituals, and recreational activities, which were once the primary benefits derived by the community (Kunwar, Bohara, and Thacher 2020).

The experiential learning courses employed several innovative pedagogical approaches for imparting students with adequate knowledge of critical water-related issues. First, there was an effort to incorporate an interdisciplinary approach to learning, which started from the student background itself. The students enrolled in these courses came from diverse backgrounds in social sciences, natural sciences, and humanities, and brought different perspectives to water-related issues in the classroom. The class also provided opportunities for students to hear and learn from guest lectures affiliated with the Bosque Ecosystem Monitoring Program (BEMP), the Water Resources Program at UNM, the UNM Global Educational Office (GEO), and the doctoral students in the economics program.

Second, the course incorporated a graduate–undergraduate mentorship model, where graduate students served as research mentors to undergraduate students. Under the guidance of graduate students, the undergraduate students developed water-related research projects and identified several interventions, policy tools, and solutions. Third, the Fall semester course offered in the classroom was followed by a three-week winter session study abroad program in Nepal where students implemented some of the solutions they identified, such as collecting water quality data and setting up awareness kiosks. During the study abroad program, students also got the opportunity to interact with local stakeholders in Nepal, including government officials, local students, and the larger community.

The general structure of the experiential learning courses comprised four major components: (1) field-based data collection, problem identification, and conceptual framework development, (2) data analysis and development of potential intervention and solutions, (3) study abroad program and implementation in the field, and (4) dissemination of findings and community outreach, which we discuss as they related to our course development in the following.

3.1 Field Based Data Collection, Problem Identification, and Conceptual Framework Development

The courses were designed using a holistic approach that drew inspiration from real-world problems. The course curriculums had a central focus on the topic of water and aimed to examine the feedback and linkages between water resources and the built environment. This included exploring the impact of households' knowledge, attitude, perceptions, and behaviors on water bodies; understanding the relationships between water-handling behaviors and human health; and assessing the effects of built environment and water resources on various household outcomes. The flowchart presented in Appendix A1 provides a comprehensive view of the key factors involved in the conceptual design of the course. Once students gained an understanding of the potential connections between water bodies, environment, human behaviors, and health, they were expected to formulate research questions and hypotheses, which they would then test empirically using primary data.

To aid students in their understanding of real-world problems and to develop potential solutions, the problem-based learning courses focused on providing exposure to actual data from the beginning. The data sets utilized by students in the course were based on actual data collected by UNM economics doctoral students for their dissertation research. NSC has collaborated with PhD students at UNM and local institutional partners in Nepal to design and conduct several primary surveys, including three surveys on water-related issues.[5] These surveys included studies on the management of Bagmati and

[5] In addition to supporting studies on water-related issues, the NSC has also facilitated primary surveys for PhD students at UNM in a range of other areas, including cancer and HPV vaccine-related issues, climate change and natural disasters, solid waste management, and air pollution. The experiential learning classes offered at UNM were made possible in part by NSC's field connection of NSC to the Himalayan region and its capacity for doctoral research. Under the guidance of Professor Alok Bohara (Director of NSC), several economics PhD students at UNM have worked as a NSC research team to design and carry out primary surveys on water-related issues. These data sets were utilized in the problem-based learning courses. For example,

Danda Rivers in Nepal and the health impacts of groundwater arsenic in the Rupandehi and Nawalparasi districts of Nepal (Katuwal 2012 Kunwar, Bohara, and Thacher 2020). These data collected from the graduate research survey have been extensively used in the problem-based learning courses to enhance real-world data-based learning.

Some examples of research questions that students identified by analyzing the survey data in the course included: How do public awareness initiatives affect the adoption of water filtration measures? What is the impact of environmental knowledge and attitudes on households' behaviors and beliefs regarding the Danda River? How does arsenic contamination in groundwater impact health outcomes among the females? What roles do education and income play in determining preferences (and valuation) for the Danda River ecosystem? And, whether households consider contribution of their time and money as substitutes in their preference for conservation of the river ecosystem. This phase of the course is akin to the AC stage of the ELT.

3.2 Data Analysis and Development of Potential Intervention and Solutions

One area of emphasis in the problem-based learning courses was to develop students' statistical knowledge, and train them on analysis and interpretation of survey data using the Stata software. The learning objectives of the course were organized into several data analytical modules. Some examples of the topics covered in the class include water quality index calculations; public health consequences of poor water quality; and households' knowledge, attitude, and behavior toward drinking water and the Danda River. The data analytical modules started with coverage of basic statistical concepts such as mean, median, *T*-test, and Chi-squared test using variables from the survey data set. For instance, to understand the test of association, students examined the connection between households' distance to the Danda River, water treatment and sanitary behaviors, and the prevalence of waterborne diseases like diarrhea.

As the course progressed, students were introduced to several regression models including ordinary least squares (OLS), logit, probit, negative binomial, and two-stage least squares, which were then utilized using information from the data. As an example, a linear regression and a logit model were employed to investigate the impact of education level on the willingness to pay for Danda River restoration while controlling for confounders such as household wealth and other socioeconomic characteristics. Another area of emphasis in these courses was on the development of a graduate–undergraduate mentorship model. To implement this model, students were divided into small groups of 3–4 undergraduate students, with a graduate student assigned as a mentor to each group. As mentors, the graduate students worked closely with their groups, assisting them in selecting research topics, finding relevant peer-reviewed studies, identifying key variables from the data set related to their topics, and analyzing the data. This mentorship model played a key role in the undergraduates being able to develop interventions, policy tools, and solutions, which would be implemented in the field.

The graduate–undergraduate mentorship model proved to be a mutually beneficial learning opportunity. Graduate students acquired valuable skills in mentoring and working with undergraduate students. Additionally, they learned how to work closely with students from diverse backgrounds and majors, which provided a uniquely enriching experience, since economics graduate students typically only work with undergraduates who are economics majors or minors. Meanwhile, the undergraduate students gained experience in collaborating with peers from different disciplines. Further, they got the opportunity to work closely with graduate students and received insights into how research is

Hari Katuwal (2012) conducted a primary survey in Kathmandu, Nepal, to understand the attitude and beliefs toward the Bagmati River; Samrat Kunwar (2019) looked at public preferences for river ecosystem in the Danda River Basin, Bhairahawa; and Mashiur Rahman worked on water and waste management issues in Siddharthanagar, Nepal (Rahman, Bohara, and Vazquez 2021). The undergraduate students enrolled in Econ 369*, Econ 395, and Econ 451 were able to work with actual data collected by graduate students for their dissertations.

conducted and presented at the graduate level. These experiences are likely to be helpful in their future careers, particularly when working alongside peers with diverse backgrounds and skills.

An important element of these courses was also the focus of the development of implementable solutions that students were required to come up with based on their research findings. One such solution was regular monitoring of water quality in the Danda River to track the spatiotemporal changes in water quality. An innovative aspect of this solution was the development of a citizen science protocol to monitor water quality, where our students developed the curriculums and protocols for water quality monitoring in the classroom, and trained students from local schools in Nepal during the study abroad program. The citizen science approach-based water quality monitoring project was later implemented in the field during the Himalayan study abroad program in 2017. Another solution presented was increasing community awareness about water treatment and sanitation through seminars and setting up awareness kiosks, which was proposed based on the students' finding that educational attainment positively correlated with improved sanitation practices and higher willingness to pay for river restoration in the Danda River Basin. These aspects of the course, which included data analysis, discussion and presentations of policy-relevant papers, group collaboration, graduate–undergraduate mentorship, and development of intervention programs, collectively represent the AE stage of learning within the ELT framework.

3.3 Study Abroad Program and Implementation in the Field: Translation of Research into Action

The opportunities afforded to students by these programs to analyze field data, to collaborate on devising interventions and solutions, and to have graduate students as mentors are all effective ways to learn and be introduced to the real-world problems. Nevertheless, this approach can be further enhanced by providing students with a hands-on experience to implement their classroom learnings by visiting the field and interacting with the local community. This concept aligns with the philosophy of experiential learning, which recognizes the importance of experience in the learning process (Kolb 2014). We present in the following the implementation process of the Himalayan study abroad program, which provided a platform for students to translate their research ideas into action. This phase of the course exemplifies the CE phase of the ELT framework.

3.3.1. Study Abroad Program Preparation

The study abroad sessions took place immediately following the end of the fall semesters. During the winter break, students who participated in the Himalayan study abroad program had the opportunity to put their classroom learnings into practice by engaging in a series of hands-on activities in the field. Students embarked on a three-week international research-focused trip[6] to Nepal, which was led by the main instructor and the program's graduate student coordinators. Prior to departing,[7] students worked with the Global Education Office (GEO) at UNM to ensure they completed the necessary requirements. Among other items, this included a detailed preparation guide to inform students of the predeparture expectations and provide them with helpful information on Nepal. Once in Nepal, students participated in various orientation sessions, including a session on understanding Nepalese culture. The study abroad program was carried out with the assistance of a host institution in Nepal, the Lumbini Center for Sustainability (LCS), situated at the Pratiman-Neema Memorial Foundation (PNMF) in Siddharthanagar, Nepal.

[6] The study abroad program flier and the syllabus is presented in Appendix A4.

[7] The budget allotted per student was approximately $2,000. Financial assistance of around $10,000 was provided by the UNM administration, which was distributed among the students at a rate of approximately $500 per student. The cost of the travel was borne by the students themselves.

3.3.2 Study Abroad Program Activities

The first phase of the three-week study abroad program was spent in the urban town of Siddharthanagar, Nepal, where UNM students collaborated with local researchers and Nepalese students at the host institution to implement the solutions developed during the semester. Some examples of this included collecting data in the field, installing environmental monitoring equipment, and engaging with community members and local policy makers. Since the first Himalayan study abroad program that took place in 2017, UNM students have worked together with institutional collaborators and eco-club members of local colleges and schools in Nepal to establish ongoing monitoring programs across five primary areas: water quality, air quality, climate, waste management, and biodiversity. During the first study abroad program, UNM students created a citizen science[8] initiative called the "Danda Ecological Monitoring Program" (DEMP), which monitors river water quality and various climate parameters. The DEMP citizen science initiative was modeled after a successful program run by the Bosque School of Albuquerque known as BEMP. Prior to departure for Nepal, students visited BEMP sites to receive guidance and to refine their DEMP protocol.

As part of the DEMP initiative, UNM students trained Nepalese students from local high schools to monitor water quality levels. Together, they collected water samples and placed a pressure transducer along the Danda River to analyze water quality and river flow dynamics. Additionally, they installed a device (The Geotech) to measure groundwater depth to track changes in groundwater level over time. A log of the groundwater level data is provided as an example in Appendix A2. Figure A1, in Appendix A3, shows example images of some monitoring devices used by students to carry out various tests.

Following a week in Siddharthanagar, students embarked on an ecological and cultural tour of rural villages in the Himalayas. This provided them with a firsthand knowledge of the challenges of sustainable development in a developing country, as well as exposure to grassroots community activities. During the tour, students gained insight into a range of issues faced by these communities, including watershed management, biodiversity, and health and sanitation concerns. Figure 2 shows a map of the route for the study abroad research experience tour.

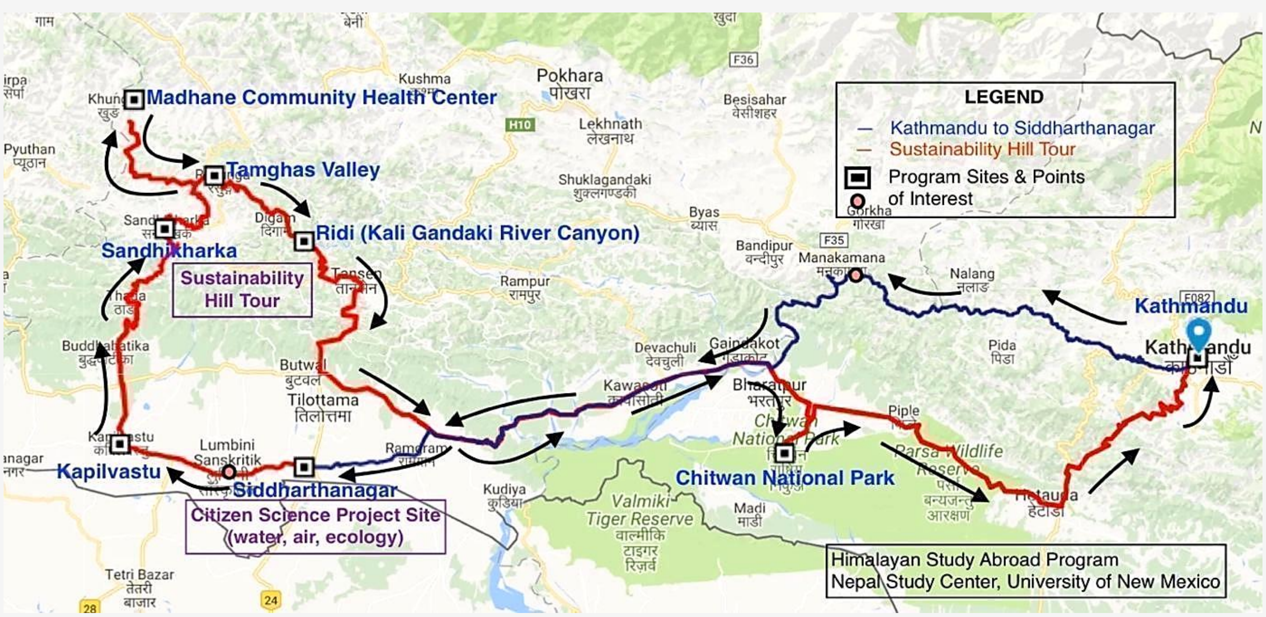

Figure 2: Map of the Study Abroad Route (Source: Himalayan Study Abroad Program, NSC, UNM, Winter 2017–2018)

[8] Citizen science involves the public in the collection of large quantities of data across various habitats and locations over an extended period of time.

3.4 Dissemination of Findings and Community Outreach

The fourth segment of the course comprised community outreach programs, research dissemination, and a personal reflection piece for each student, all of which are integral components of the RO phase of the ELT. To date, students have disseminated their research through three major platforms: research presentations to their classmates and to wider research audiences, research presentations to local stakeholders in Nepal, and study abroad reflections.

Before embarking on the study abroad component of the course in Nepal, students were required to complete a group-based research project, to develop implementable solutions based on their research findings, and to prepare a poster presentation as part of their final project for the in-class portion of the course. An example of this was a poster presentation by a student group that examines the linkages between the presence of E. coli in water, sanitation behavior, and the risk of contracting diarrhea. These poster presentations were meant to give students the opportunity to showcase their research and receive feedback from their peers, graduate mentors, and the instructor.

Additionally, students from these courses were able to participate in various conferences and exhibitions to share their work with a wider research audience[9] once they returned from their study abroad trip. This included research presentations by the students in meetings such as the Undergraduate Research Opportunities Conference at UNM, the STEM bridge undergraduate session at the Southwestern Society of Economists, and an undergraduate panel at the Annual Himalayan Policy Research Conference. Overall, these group-based research projects and presentations provided students with valuable opportunities to develop teamwork skills, receive feedback on their work, and present their research to a broader audience.

The research posters that students developed in the classroom were also presented to Nepalese policy makers and distinguished guests, including the mayor of Siddharthanagar municipality and the U.S. ambassador to Nepal, and were displayed in the LCS lab in Nepal. During the study abroad program, students used the findings from their research to engage with the community and raise awareness on water-related issues. Examples of these included informing community members about the presence and implications of E. coli contamination in drinking water and highlighting the importance of sanitation and hygiene practices. Students also engaged in a citizen science initiative that was aimed at tracking the quality of the Danda River.

As part of the citizen science initiative, local students were taught to collect water samples and carry out tests on ten different indicators of water quality, including nitrates, ammonia, turbidity, and phosphates. The resulting scientific data on the river water quality indicators were then sent to NSC, which have been used for various purposes, including student research projects, development of new experiential learning courses, and assisting in policy interventions and awareness-raising efforts in Nepal. Figure A2, in Appendix A3, shows a picture of UNM students collecting water samples from the Danda River during the citizen science initiative. Figure A3, in Appendix A3, presents one example of a Danda River conservation plan that was proposed by the students to the Mayor of Siddharthanagar and his environmental assessment team.

The 2017 cohort of the Himalayan study abroad program shared their experiences through an online blog that is publicly available (see Appendix A2). The blog provides a detailed account on the day-to-day activities performed by students in the field, along with pictures and short reflections. In addition to the daily updates, students who embarked on the study abroad trip were required to write a 3- to 5-page reflection paper on a water-related issue they witnessed and experienced in Nepal. Specifically, the students were asked to

[9] Two master's students from UNM's College of Fine Arts also presented their environmental art project, which included a floating wetlands model that used natural vegetation to purify river water, to the communities in Albuquerque during a one-month exhibition at the Maxwell Museum of Anthropology.

identify and critically assess a problem that they encountered and offer solutions based on their research or best practices discussed in other studies. The reflection essay was an integral part of the final grade of the program.

4 Broader Impacts

The broader impacts of the Econ 369* and earlier trial courses can be categorized into four major fronts: (1) the learning experience for the students, (2) the impact on the community, (3) the research experience gained by the students, and (4) the potential for this program to serve as a model for other institutions.

4.1. Student Learning Experience

The biggest outcome of the experiential learning courses was the learning experience it provided to the students. These courses were developed with the aim of delivering a comprehensive learning environment to aid in developing students' essential research skills while allowing them to put their ideas into practice in a real-world setting. The courses used a combination of classroom-based learning, field experience, and international research to give students a unique hands-on learning experience.

The learning process followed Kolb's ELT, which involved moving from AC to AE, to CE, culminating in RO. During the semester, students worked on completing different modules developed from real-world data previously collected in Siddharthanagar, Nepal. Students were introduced to various econometric methods and were equipped with the skills to analyze and evaluate data and empirical relationships using Stata software. Students also worked in groups to read, discuss, and present relevant literature on different environmental issues found in the data set. The exposure to real-world data, application of different econometric approaches, and discussion and presentations of policy-relevant papers helped empower students to make informed decisions about their research questions and develop solutions that were implemented in the field.

The learning process continued to the field where students had the opportunity to put their ideas into action during the three-week research-focused study abroad trip to Nepal. Students played an active role in increasing awareness and promoting actions on critical water-related issues by engaging with the community and sharing their knowledge with local students in Nepal. Throughout this entire process of the experiential learning course, students also gained valuable life skills in areas such as problem solving, critical thinking, communication, and collaboration, which likely enhanced their academic experience and prepared them for their future careers. Overall, these courses provided a holistic learning experience that began in a classroom setting and concluded in the field.

4.2 Community Impacts

There was a tangible impact on the local community in Nepal, one which made the results of policy work, research, and community outreach visible to students, and validated their research and the class methodology. Students who took the course between 2016 and 2018 were able to create and share their findings with the local community in Nepal. For instance, one group of students created and installed a three-dimensional floating wetland model in the LCS lab to demonstrate the functioning of wetlands in the Danda River ecosystem. Another group created an interactive citizen science curriculum and toolkit to monitor river water quality, and subsequently, trained local high school students to monitor river water quality and to share the data with NSC. Students also collaborated with local eco-clubs in Nepal to create instructional manuals and educational programs aimed at educating the community on hygiene and sanitation behaviors. The actions students took in terms of community-based education, showcasing environmental artworks and the citizen science initiative, raised awareness among locals about their health and encouraged them to appreciate their local water bodies. Moreover, the scientific data that were generated from the citizen science project were used for ongoing research projects, as well as guiding local policy interventions and awareness.

4.3 Research Experience

The experiential learning courses created an environment that was conducive for undergraduate students to learn about the process of conducting research from start to finish. Students who were enrolled in the course were required to complete an original group-based research project and present their findings to their peers and the local UNM community. Some students from the course also presented their papers to wider audiences, ranging from showcasing their projects to the Albuquerque community to presenting their findings in academic conferences at UNM and beyond. In addition, students who participated in the winter session study abroad programs were encouraged to share their work with the local stakeholders. These students shared their findings to the local community, government representatives, and international delegates in Nepal. Many students who completed these courses also gained personal benefits in terms of graduation, publications, and acceptance to prestigious graduate schools around the country.

4.4 Model Program That Can Be Emulated by Other Institutions

These experiential learning courses emphasize holistic learning, and the program developed at UNM is highly adaptable in terms of investigating water issues within the United States or in different regions of the world. These courses have become increasingly popular in both economics and noneconomics disciplines at UNM. Table 1 displays the number of students that have taken these courses by their major. Table 2 provides metrics on the overall outcome of the experiential learning courses between 2016 and 2018.

Table 1: Number of Students in Problem-Based Learning Courses by Major

Major	Frequency
Anthropology	1
Biochemistry	3
Biology	3
Business Administration	1
Economics	46
Health, Medicine, and Human Values	1
International Studies	4
Mathematics	4
Nondegree	3
Political Science	2
Pre-Business Administration	3
Pre-Civil Engineering	1
Pre-Computer Science	1
Pre-Economics	4
Pre-Population Health	1
Psychology	1
Sociology	3
Statistics	1
Water Resources	4
Total	88

Table 2: Metrics Used to Quantitatively Examine the Overall Impact of the Problem-Based Learning Courses

Metrics	Number/Facts
Number of honors and master's theses	5 (3 undergraduate and 2 master's)
Number of peer-reviewed research papers	3 (1 published and 2 working papers)
Number of students that attended and presented in research conferences	14 students
Total students enrolled in these courses	88 (Econ 369–37, Econ 395/595–34, Econ 451–17)
Total students that went to the Himalayan study abroad program in Nepal	18 students

As shown in Table 1, students enrolled in these courses tended to major in various fields, including international studies, biochemistry, mathematics, political science, biology, engineering, statistics, business administration, and water resources, to name a few. There was a total of 19 majors represented among the students who took these courses, with economics major representing only half of the total enrolled students. Table 2 provides additional metrics that quantitatively examine the overall impact of the problem-based learning courses. Five students from the course continued to work on their research projects and were able to convert their projects to their undergraduate and master's theses. In addition to the theses, one student from the course was able to publish their paper in a peer-reviewed journal, while other students were able to complete two working papers. Similarly, several students attended national-level research conferences to present their research findings. The total number of students enrolled in the course between 2016 and 2018 was 88, of which 18 students participated in the Himalayan study abroad[10] program in Nepal. The success of these courses is more evident when we consider the metrics from Table 2 with other conventional economics courses offered at UNM. For example, in upper-level courses[11] such as Eco 343 (Environmental Economics) or Eco 409 (Econometrics) at UNM, it is rare for students to convert their class papers to honors theses, present their papers at conferences, or to publish peer-reviewed articles.

An interesting feature of the experiential learning course is that it was designed with flexibility in mind and can be extended to cover other water-related issues, such as drought, flooding, extreme climate events, urban water crisis, waterborne diseases, and their mitigation strategies. Moreover, the study abroad sequence of the course can be expanded to include investigations in the United States or other parts of the world. Although Nepal was selected as the study abroad site for the courses discussed in this article, a similar outcome could have been achieved locally, thereby avoiding the high cost associated with study abroad programs. The main objective of the course was to provide students with hands-on learning experience to supplement the theoretical knowledge gained in a classroom environment. The study abroad component was not the primary focus but rather a means of enabling students to immerse themselves in a different cultural and environmental context to learn about water-related challenges and solutions.

[10] The study abroad component of the course has not been offered since 2019 due to COVID-19 concerns.
[11] We chose Eco 343 and Eco 409 as example courses since both courses are taught by the co-authors of this paper.

The UNM economics department now regularly offers the Econ 369* course, which is a result of two years of trial runs with the Econ 395 and Econ 451 courses, providing a valuable collection of data and relevant pedagogical materials. Appendix A2 includes some of the curricula, syllabus, and modules used in the course. More information is available on the NSC website, and other materials are available upon request to any interested institutions.

5 Challenges, Opportunities, and Way Forward

Study abroad programs, while highly beneficial and popular, will require careful effort to design and execute. It is even more difficult to design study abroad programs that incorporate experiential learning aspects like the courses discussed in this paper. Their successful completion requires lengthy planning and competent support teams both in the United State and in the host country. One major hurdle we faced was maintaining regular communication with local institutional collaborators in Nepal to coordinate program details. This required scheduling virtual meetings and phone calls outside of normal working hours. The study abroad coordinating team conducted multiple orientation sessions to brief the participating students on program objectives, logistics, and expectations. In addition, the team had to ensure that the environmental monitoring equipment functioned properly in the field before leaving for Nepal, which required significant research and trial testing.

Another set of challenges that we faced was coordinating with the UNM GEO to ensure that the program requirements and expectations for the study abroad programs were met, such as vaccination, travel orientation, and course learning objectives. Many students had limited knowledge about preparing for international travel, particularly to South Asia, and encountered cultural and language barriers in Nepal. It is important to ensure that study abroad programs like the ones discussed in this article are sustainable and allow for maximum participation. However, sustaining such a program is challenging due to various factors including innovation, scalability, finances, and support from the university. These challenges were further exacerbated by the COVID-19 pandemic, which made travel more difficult, expensive, and unpredictable.

Going forward, several steps can be taken to sustain the program and enhance its features. First, to provide an interdisciplinary perspective, instructors from multiple disciplines could co-teach the class. Additionally, to create a more immersive learning experience on community- focused projects, a "semester abroad program" could be developed, where students could go to Nepal (or a different location) to work on their projects in collaboration with local partners. The first half of the semester would be taught in the United States, and the second half would be taught by local faculties in Nepal. Another option could be to organize a summer camp to train students and faculties on water-related topics. The courses discussed in this article were developed and executed with the help of graduate students who served as volunteers. However, moving forward, arrangements to provide graduate students with credit as co-instructors or co-organizer can help make similar programs more successful and sustainable.

To ensure the longevity of the program, it is also crucial to secure grants that can cover the high costs. These funds can be utilized for various purposes, such as providing stipends to graduate students and coordinators, purchasing scientific equipment, and subsidizing travel expenses. To make such programs more inclusive, targeting minority students who may have limited opportunities to participate in study abroad programs due to financial constraints should also be considered.

The NSC facilitated UNM in signing a Memorandum of Understanding (MOU) with the Himalayan University Consortium (HUC) of the International Center for Integrated Mountain Development (ICIMOD). ICIMOD is an international nongovernmental organization based in Nepal that coordinates and conducts research in the Hindukush region spanning eight countries. Through HUC's consortium of over sixty universities, NSC has been able to connect with the Himalayan community, enabling U.S.-based students to gain a broader understanding of the region. Participating students are made aware of specific water-related issues in the climate change-prone Himalayan belt, such as water resiliency along the Tibet/China/Nepal border. There is also the possibility of organizing multiuniversity study abroad programs to enhance the students' learning experiences.

Finally, it should be noted that while the experiential learning courses in this paper were focused on Nepal for the study abroad component, similar environmental issues are a concern for many communities within the United States. There are many water-related issues in different U.S. states that students could investigate and visit as part of their field trip, which would provide similar learning opportunities. For instance, communities in Flint, Michigan, have been struggling with lead contamination in their water supply for years (Hanna-Attisha et al. 2016). The Navajo Nation in Arizona and New Mexico has been dealing with the aftermath of abandoned uranium mines, which has led to contaminated drinking water (Rock and Ingram 2020). Likewise, sea-level rise could severely impact freshwater resources in Florida (Williams et al. 1999).

There are opportunities to further explore aspects of environmental justice issues as well. For instance, there is potential to investigate the impact of drought on water availability and quality from an environmental justice perspective in areas like California and Colorado (Abboud et al. 2022; Simpson et al. 2023). Agricultural production in California's Central Valley is heavily reliant on the water from aquifers, which has caused the land to sink and contaminated the drinking water sources (Pannu 2012; Nelson and Burchfield 2017). The burden could disproportionately affect low-income communities of color, who are more likely to live near contaminated sites and have limited access to clean drinking water (Lee 2002). To summarize, while the study abroad program in Nepal provides a valuable opportunity for students to learn about water-related issues in a developing country context, similar environmental challenges can also be found closer to home. By conducting field trips locally, students will gain a deeper understanding of the environmental issues faced by communities in the United States and learn about the actions being taken to address them.

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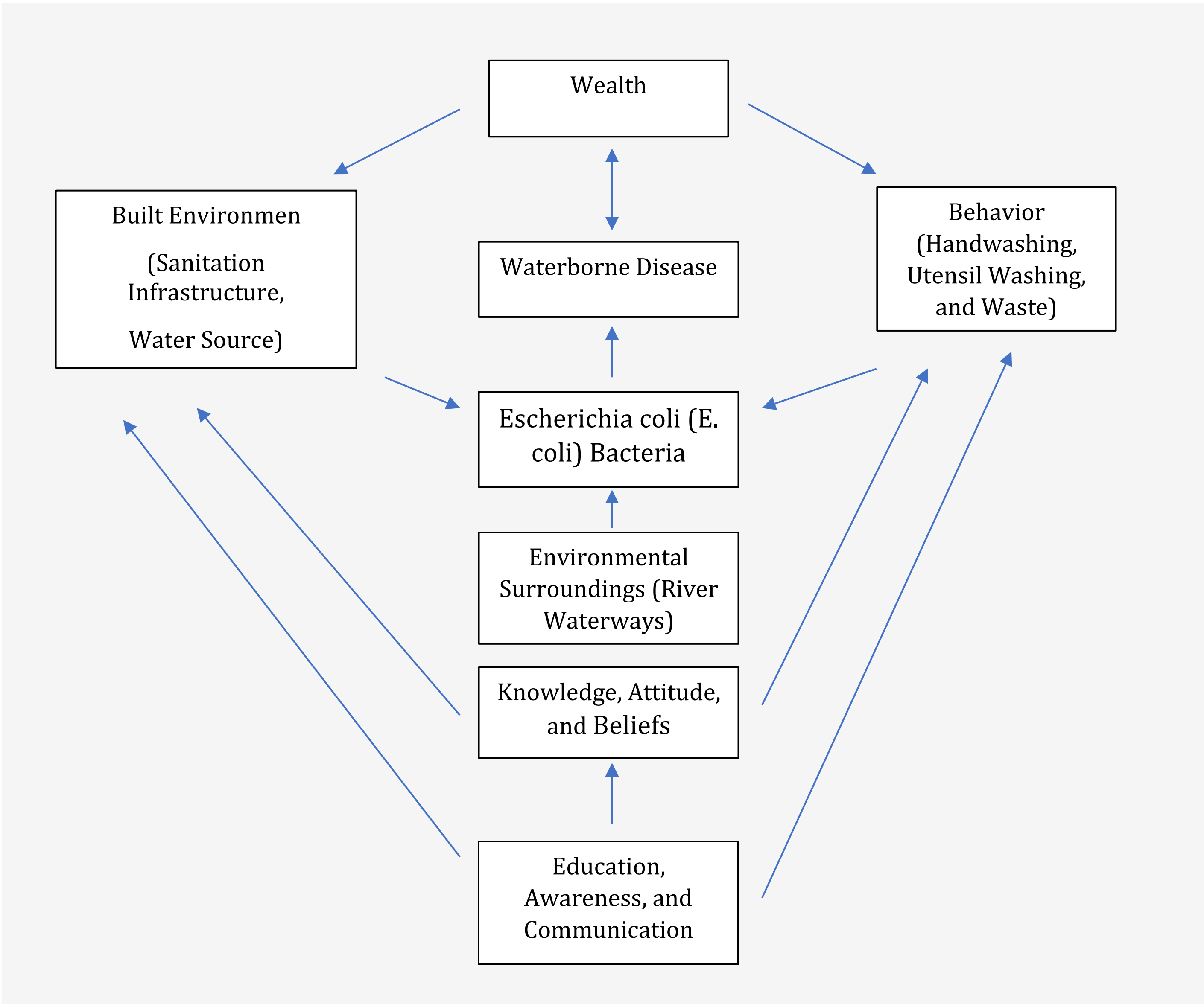
Appendix A1: Conceptual Framework

The following flow chart illustrates the connection between human behaviors, environment, health, and wealth. Additionally, the chart also shows how built environment, attitude, and education components could relate to the topics. This is an example of the conceptual framework development for the problem-based learning courses



Appendix A2: Course Materials and Outputs

1. Nepal Study Center and other local collaborating partners
   - http://nepalstudycenter.unm.edu/index.htm
   - https://pnfoundation.org.np

2. Thesis and undergraduate/graduate research
   - http://nepalstudycenter.unm.edu/SustainableResearchLab/WRP_Corinne%20Fox_July2018.pdf
   - https://www.tandfonline.com/doi/abs/10.1080/21606544.2021.1903560
   - https://digitalrepository.unm.edu/econ_etds/103/

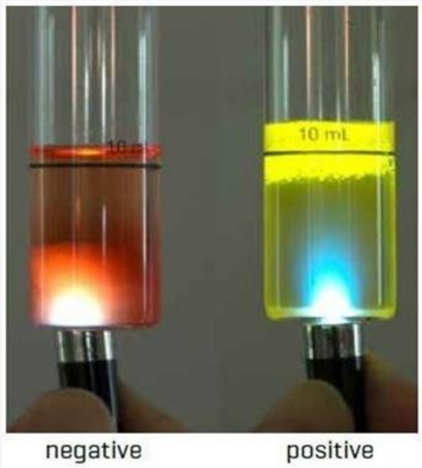
3. Econ 369 course materials
   - Course flyer
     http://nepalstudycenter.unm.edu/SustainableResearchLab/Econ%20395_595%20Fall%202019Flyer.pdf
   - Course syllabus
     http://nepalstudycenter.unm.edu/SustainableResearchLab/Econ%20369%20Syllabus_Fall2018Ver10PDF.pdf
   - Sustainable Development Action Lab, NSC overall page
     http://nepalstudycenter.unm.edu/SustainableResearchLab/UndergraduaterResearchInitiatives.html

4. Himalayan study abroad program materials
   - Program flyer
     http://nepalstudycenter.unm.edu/SustainableResearchLab/Himalayan%20Study%20Abroad%20FlyerVer6bPDF.pdf
   - Program syllabus
     http://nepalstudycenter.unm.edu/SustainableResearchLab/HimalayanStudyAbroadSyllabusOutline2018V4PDF.pdf
   - Himalayan Study Abroad Program Online Blog (created by student Corrine Fox)
     https://foxc01.wixsite.com/yogdan/projects?pgid=jbn3ux4b-cd4f5313-5c55-4428-b92e-9005d7ba6890

5. DEMP website and data collection
   https://pnfoundation.org.np/home

6. Groundwater log
   http://nepalstudycenter.unm.edu/SustainableResearchLab/Groundwater%20Level%20Log.pdf

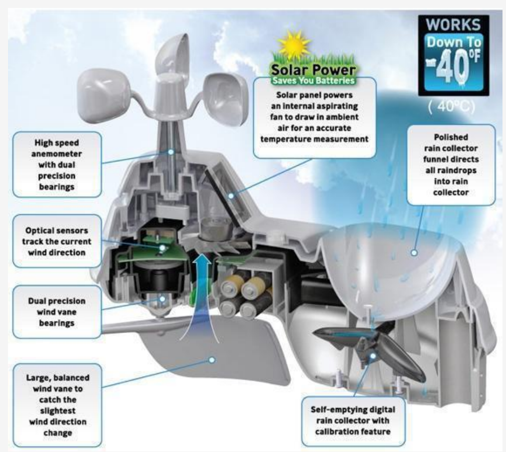
Appendix A3: Monitoring Equipment, Citizen Science Initiative, and River Conservation Plan



E. coli bacteria testing procedure

LaMotte water testing kits

Solinist Levelogger



AcuRite 5-in-1 Weather Sensor

Figure A1: Water Testing Kits and Monitoring Devices

Figure A2: UNM Students Collecting Water Samples from Danda River, Nepal

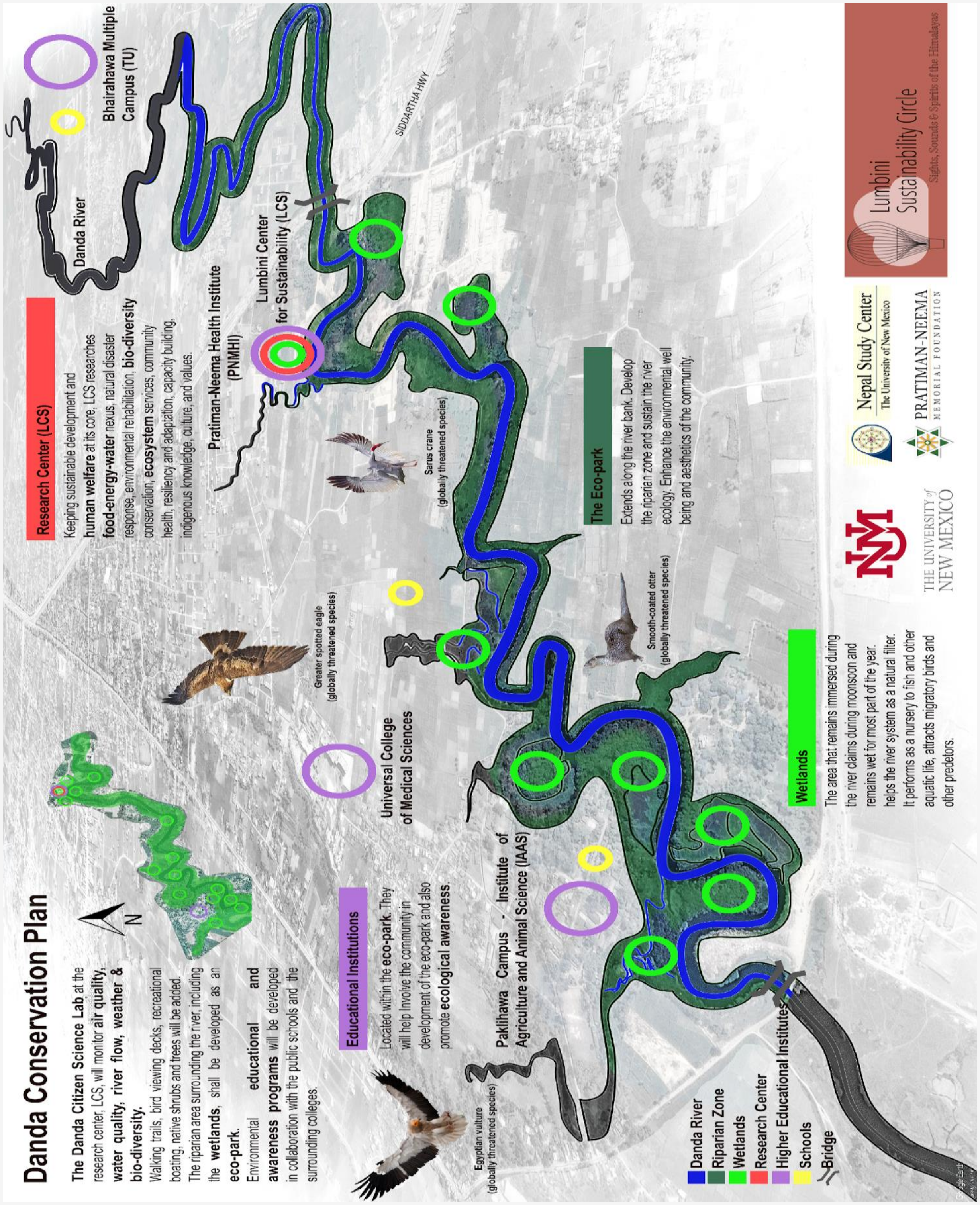


Figure A3: Danda River Conservation Plan (Source: Himalayan Study Abroad Program, NSC, UNM, Winter 2018–2019)

Appendix A4: Syllabus

A4.1: Course Syllabus – Econ 369*
(http://nepalstudycenter.unm.edu/SustainableResearchLab/Econ%20369%20Syllabus_Fall2018Ver10PDF.pdf)

A4.2: Study Abroad Program Syllabus
http://nepalstudycenter.unm.edu/SustainableResearchLab/HimalayanStudyAbroadSyllabusOutline2018V4PDF.pdf)

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Applied Economics Teaching Resources

Teaching and Educational Methods

Teaching Price Elasticity of Demand and Marginal Analysis using Household Water Pricing

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JEL Codes: A20, Q25
Keywords: conservation pricing, graduate teaching, undergraduate teaching, urban water

Abstract
Understanding the economics of urban water pricing is fundamentally about the concepts of price elasticity of demand and marginal analysis. Recent advances in our understanding of consumer response to water pricing, emerging discussions of equity issues, and water utility interest in innovative pricing approaches make this topic important to integrate into any class on natural resources or water economics. To aid instructors, we highlight current issues in the field and emerging research, and present materials used to teach urban water pricing to both undergraduate and graduate audiences. We present a variety of activities and resources to integrate concepts of price elasticity of demand, conservation pricing, utility considerations, and equity issues. After using these materials, students are expected to know how to calculate prices and elasticities and explain these values in the broader context of conservation and equity.

1 Introduction

Water shortages in major urban centers across the globe and recent droughts across the western United States have pushed water issues into the forefront of natural resources policy issues (Kummu et al. 2016; Brown, Mahat, and Ramirez 2019). Climate change, growing populations, and drought have intensified coverage of water scarcity to the point most students are aware of challenges to urban water delivery, either in their local areas or through national and international media coverage. How urban water utilities price water and how consumers respond has emerged as an increasingly important issue in natural resources economics.

While water remains a topic in most natural resources classes, teaching students water economics today requires a broader understanding that extends beyond traditional concepts of balancing supply and demand across multiple time periods (Grafton 2017). To address these challenges, students must bring together foundational economic concepts while understanding the accounting structure of water delivery systems and how users respond to price signals. Finally, to satisfy students' desire for real-world examples and topical application of concepts, instructors must address current pricing strategies, behavioral economics, and equity issues.

The topic of water pricing links key fundamental concepts from economics such as marginal price and elasticity of demand to emerging issues like equity and behavioral economics. We present a multi-modal approach to teaching a module on the economics of water pricing with a focus on residential consumers. We draw on our experience teaching a wide array of topics in water economics to students from both economics and interdisciplinary backgrounds at a variety of academic levels to provide a set of key concepts that emphasize: price elasticity, conservation pricing, utility accounting, and equity. These concepts highlight the relevant economic theory and provide a targeted treatment of current literature to provide students a basis for understanding the challenges of meeting water demand in the 21st century.

In the discussion below, we present an overview of the emerging issues in consumer water pricing as context for preparing instruction or leading a discussion. Then, we provide classroom-ready material organized around teaching the four key concepts. This material is intended to help students understand the complexity of water demand by different user groups. After utilizing the materials given below, students should be able to:

1. Understand and calculate the marginal price, average variable price, and total average price of water.
2. Define different water pricing strategies and explain how water pricing can motivate conservation.
3. Apply the concept of price elasticity of demand qualitatively and through numerical calculation.
4. Explain some of the complex issues in water pricing, equitable access, and tradeoffs facing water managers in the 21st century.

The paper first discusses the key economic concepts in residential water pricing and understanding demand response. We then introduce our module's materials and approach, referencing assignments, lectures, and case studies, which we make available as supplementary material. We then document our expected learning outcomes from the module and discuss some of the frequently asked questions in the classroom before concluding.

2 Economic Concepts and Framework

Addressing water scarcity from the lens of an economist requires an understanding of incentives faced by water providers and users, and the economic framework under which they operate. In this section, we provide a background on the basics of water pricing, key economic concepts, and emerging areas of research.

Water utilities construct and operate water distribution systems and charge consumers some price via a combination of fixed fees and per-unit pricing. While utilities deliver water to a variety of industrial, single-family, multi-family, and agricultural water users, our class material follows the bulk of the literature on consumer response to water pricing by focusing on residential single-family consumers. Throughout this paper, we use "price" to refer to the charges consumers face and "cost" to refer to those incurred by utilities. Water utilities are characterized by high fixed and low marginal costs. Consumer water price is often low because the average private cost (APC) of water delivery is typically low and, for utilities, setting residential prices at levels near APC allows consumers to meet their essential uses at a low cost (Grafton, Chu, and Wyrwoll 2020).

The goal of a profit-neutral utility would be to set average consumer price to APC.[1] From an economic perspective, however, this is not ideal when new water sources have a higher marginal cost than existing sources. For instance, a key challenge associated with urban growth is finding water. If a utility sets the price at APC, then the consumer sees a marginal price below marginal cost. Economically,

[1] Theoretically, there are several interesting considerations for how a regulated utility should set a tariff to pay back fixed costs. Ramsey pricing, the result of the work of Ramsey (1927), sets a tariff for a single good with a markup necessary to recover the full cost, but when multiple goods are present, like water for indoor and outdoor use, price is set following the inverses-elasticity rule. This rule maximizes total utility (consumer plus producer surplus) but is unlikely to be palatable for utilities and regulators when low elasticity and low incomes coincide, as in water pricing. Feldstein (1972) addresses this concern with a fixed fee weighted by the marginal utility of income, and other authors have considered efficiency, equity, and financial payback considerations in setting tariffs (e.g., García-Valiñas 2005). This material is beyond the scope of the module we typically teach on water pricing.

the volumetric charge for water should equal its long-run marginal cost, but this can be difficult for utilities to achieve because it creates a situation where total revenues exceed costs.[2]

Where water is scarce, the value of water exceeds the cost of delivering it. This is typical in arid regions, but acute drought or misalignment between infrastructure and short-run demand can make water scarce in wet regions as well. To ensure water demand and supply are equal (i.e., no shortages), water utilities may employ demand management strategies or invest in new supply. Supply-side management can involve building new dams or canals, or purchasing water from other municipalities or farmers. In many arid areas, opportunities for increasing supply are extremely limited. Demand management strategies may involve price or non-price approaches to encourage water conservation. Non-price strategies can include subsidies for conserving technologies, reminders or other behavioral nudges, or rationing. Rationing can involve absolute quantity restrictions but more often limits certain behaviors (e.g., car washing or lawn watering) entirely or to certain days/times. These noneconomic instruments can misallocate scarce water where high surplus activities are curtailed, but may be undertaken for political or logistical reasons. For instance, utilities may find it is easier legally and in terms of public opinion to impose a watering ban due to a severe drought instead of doubling water rates.

Volumetric pricing offers several advantages over rationing. First, because elasticity of demand is less than one, increasing price conserves water *and* increases revenue. Second, volumetric pricing provides the utility the opportunity to increase allocative efficiency, although this comes at the expense of higher transaction costs for utilities creating and consumers interpreting prices, and makes utility revenue more uncertain (Grafton et al. 2020). Utilizing price strategies requires knowledge of the relationship between the price of water and quantity demanded. Students should be aware upon entering the class that the degree of responsiveness of consumers to changes in price is the price elasticity of demand—for instance from a course in the principles of microeconomics—and lessons on water pricing can reinforce this crucial concept. Understanding elasticity is a prerequisite for understanding the use of price as a tool to influence water consumption.

Elasticity of demand is influenced by many factors. Demand tends to be relatively inelastic when there are few substitute goods and for goods that occupy a small portion of the overall consumer budget—where price increases are less impactful on the consumer's overall spending power—which are both generally true of water. Demand also tends to be less elastic when the good is a necessity. Consumers need water to do very basic things such as drink, cook, and bathe, and there are few, if any, substitutes to using water for these activities. In 2010, the United Nations passed a resolution recognizing access to clean drinking water and water for sanitation as an essential human right.

In contrast, most outdoor water use including landscaping and swimming pools is not essential, and therefore would not be considered a necessity. Additionally, if water becomes very expensive, in the long run, consumers can install alternative forms of ground cover such as drought resistant vegetation, rocks, or mulch in place of traditional turf and reduce water use (Brent 2016). For these reasons, both outdoor water use and water use in the long run are more elastic than indoor and short-run water use, respectively. Most literature estimates urban water price elasticity of demand to be between -0.1 and -0.76, suggesting overall demand for urban water is relatively inelastic (Bruno and Jessoe 2021). Outdoor demand elasticity estimates range from -0.67 to -1.2, with elasticities depending on the seasons because most outdoor water use in many locations occurs during the summer (Mansur and Olmstead 2012).

[2] In California, for instance, utilities may be found to be in violation of proposition if rate increases exceed to cost of providing the water service.

There are three primary rate structures used by utilities—flat rate, uniform rate, and block rate—along with more complex budget-based rates. Each structure provides consumers with a different price signal, and this offers instructors an opportunity to build student understanding of behavioral responses to price. Flat rates charge consumers the same amount regardless of usage.

Uniform rates charge the same per unit rate for all units of consumption. Increasing block rates (IBRs) charge an increasing marginal price of water at discrete intervals as consumption increases. IBR pricing is quite unusual except in the case of water and energy pricing, and many economic papers have been written about behavioral response. The complex information conveyed by IBR pricing, however, has led some researchers to question whether consumers are responding to changes in the marginal or average price of water (Ito 2014; Wichman 2014). There is evidence that high-use consumers respond to large increases in the marginal price of water (Nataraj and Hanemann 2011), but recent work suggests demand is more responsive to changes in average price than marginal price (Browne, Gazze, and Greenstone 2021).

Budget-based pricing is an alternative water pricing scheme used to cater water prices more specifically to individual household characteristics. When used in the context of increasing block rates, block sizes may differ based upon environmental conditions, household characteristics, or other metrics determined by the regulator (Baerenklau, Schwabe, and Dinar 2014). To provide affordable water for essential uses, the lowest tier or block of water has the lowest marginal price. Low-income households are more likely to have a high number of occupants per house or live in inefficient homes, and consequently, have a higher rate of essential water use. Varying the size of the lowest-priced, first block can help ensure that the pricing structure does not put an excess burden on low-income households (Borenstein 2012; Smith 2022).

Understanding what price consumers are responding to links this topic to key concepts from behavioral economics like rational inattention and decision biases. Assuming consumers respond to marginal price requires fairly strong assumptions on the ability and interest of households. Generally, consumers know much less about their water use and the price they pay than these assumptions would require (Brent and Ward 2019). Utilities vary in what information is displayed on consumer utility bills. The bill may contain information on marginal or average price, or not.

Another emerging area of economics where urban water pricing has formed a key part of the literature is around equity. Equity is a normative concept used to describe the allocation of resources in society. In the context of discussing equity and water pricing in the classroom, we broadly describe a water pricing scheme as equitable if the pricing system does not disproportionately harm low-income households or benefit high-income households and provides all individuals with access to water for essential use. Water used for drinking or sanitation is considered essential while outdoor water use, which is typically landscape irrigation, is considered discretionary.

Water affordability is particularly important for low-income households where water expenditures make up a relatively large percentage of total income (Cardoso and Wichman 2020; Teodoro and Saywitz 2020). In the United States, the price of water and wastewater services is increasing faster than inflation, and 10 percent of households face water affordability issues (Cardoso and Wichman 2020). Households within the lowest income bracket earning less than $15,000 per year are spending nearly 6.8 percent of income on water and sewer services. The use of fixed or user fees can have implications for affordability because their burden is decreasing with income; price setters concerned about equity may opt for lower fixed fees and higher marginal prices (Beecher 2020; Levinson and Silva 2022). IBRs and budget-based rates are considered more progressive because lower end essential units of water are more affordable and higher use discretionary units are more expensive (Smith 2022).

To ensure the lowest block is large enough, block size can be adjusted to account for household size or other characteristics (Mayer et al. 2008; Barberán and Arbués 2009). Smith (2022) examines the use of average winter consumption (AWC) as the basis for the size of the lowest or essential water tier. The justification for using AWC to determine the size of the lowest tier is that winter usage likely incorporates only essential use because outdoor watering does not take place. This type of budget-based pricing may violate concepts of horizontal equity because households consuming the same amount of water face different prices.

Price-based approaches to reducing water demand can be made more progressive by returning utility profits to lower income households in the form of rebates (Olmstead and Stavins 2009). Research on electric utilities finds evidence that utilities located in areas with more unequal income distribution use more redistributive tariffs (Levinson and Silva 2022). Some municipalities have used other tools to address equity, including income-based rates and low-income water rate assistance programs (Cardoso and Wichman 2020).

For equity or other reasons, some utilities have chosen to forego price interventions in favor of mandates and information campaigns. Complicated rate structures have higher administrative costs, which are often reflected in increased fixed fees. The increased fixed fees tend to be regressive, disproportionately paid by minority, lower income, and rental households (Smith 2022). Restrictions on outdoor water use tend to induce a more uniform response in water usage than do price controls (Wichman 2014). Other nonprice interventions include social comparisons in which a user is provided information on peer usage and technology standards (e.g., low-flow or efficient appliances). Although more equitable, nonprice mechanisms are generally less efficient (more costly) and more difficult to monitor and enforce (Olmstead and Stavins 2009).

The adoption of some form of real-time pricing has also begun to emerge as an option for some urban water pricing agencies. Energy can account for up to 40 percent of operating costs for drinking water systems, and pumping in high demand periods requires the use of additional pumping resources. As utilities adopt advanced metering infrastructure, new options to price water at high temporal resolution and accuracy are possible. If effective, pricing to flatten peak hour water demand can reduce the magnitude of peak energy consumption and the cost of distributing water. In electricity consumption, consumers that are more accurately able to receive energy price through real-time availability of price data are more responsive to short-term price increases (Jessoe and Rapson 2014).

3 Materials and Details

To elucidate our approach to teaching elasticity of demand and marginal analysis in the context of an urban water utility, we break the subject into four topics: elasticity of demand, conservation pricing, utility considerations, and equity issues. These topics can be taught as an integrated whole or broken down into the four topic areas. Table 1 provides a description of the four topic areas and the modalities we use to engage students and convey information. The table also provides descriptions of the materials used to teach these topics. Additional information on teaching approaches, suggestions for delivery, and the materials can be found in the Teaching Notes.

Elasticity of demand (EOD) can be a challenging concept for students to apply. A lecture on the basics of elasticity in the context of water pricing is a good kickoff to water pricing and should focus on reviewing key concepts from earlier classes as well as the literature on elasticity of demand in urban water. Papers have estimated the elasticity of demand in numerous countries and settings using various approaches. We use two meta-analyses to provide students an idea of the range of elasticities that have been estimated. Espey, Espey, and Shaw (1997) perform a meta-analysis of the water pricing literature and provide a nice summary of the studies they use and the potential factors that change elasticity of demand. However, their econometric approach may not be easily interpretable to students. We typically show results from the meta-analysis by Dalhuisen et al. (2003), which reviews 314 price elasticity estimates. Figure 1 in the paper is compelling for students because it shows the wide range of price elasticity of demand estimates. In our classes, we encourage discussion of why elasticity of demand estimates vary so widely.

Table 1: Topics and Associated Materials

Topic	Modalities	Description	Materials
Elasticity of Demand	Lecture Coding	Elasticity of demand for water lecture slides Regression coding exercise using data from a Utah water facility	EOD slides.pdf Water rate regressions.pdf Utah Water Datat.csv IBR Slides.pdf
Conservation lecture Pricing	Spreadsheet	Urban water conservation pricing lecture slides Spreadsheet for group activity calculating rate changes and elasticity of demand from IBR schedule	IBR_Group.xlsx IBR_Group_Instruct.pdf IBR_Group_instruct.pdf
Utility Considerations	Reading	Extension reading of conservation pricing geared for water utilities	Municipal_conservation.pdf
Equity Issues	Discussion Lecture Supplement Discussion	Comparison of water bills from different utilities in different locations Supplemental slides for including equity in discussion of IBR/EOD Supplemental materials to engage students in discussion of human right to water and water availability/price for low-income users	Bill_Handout.pdf Equity_slides.pdf Colonias_handout.pdf
Learning Evaluation	Assignment	EOD/IBR assignment where students fill in marginal and average prices	IBR_pricing.xlsx IBR_assignmnet.pdf

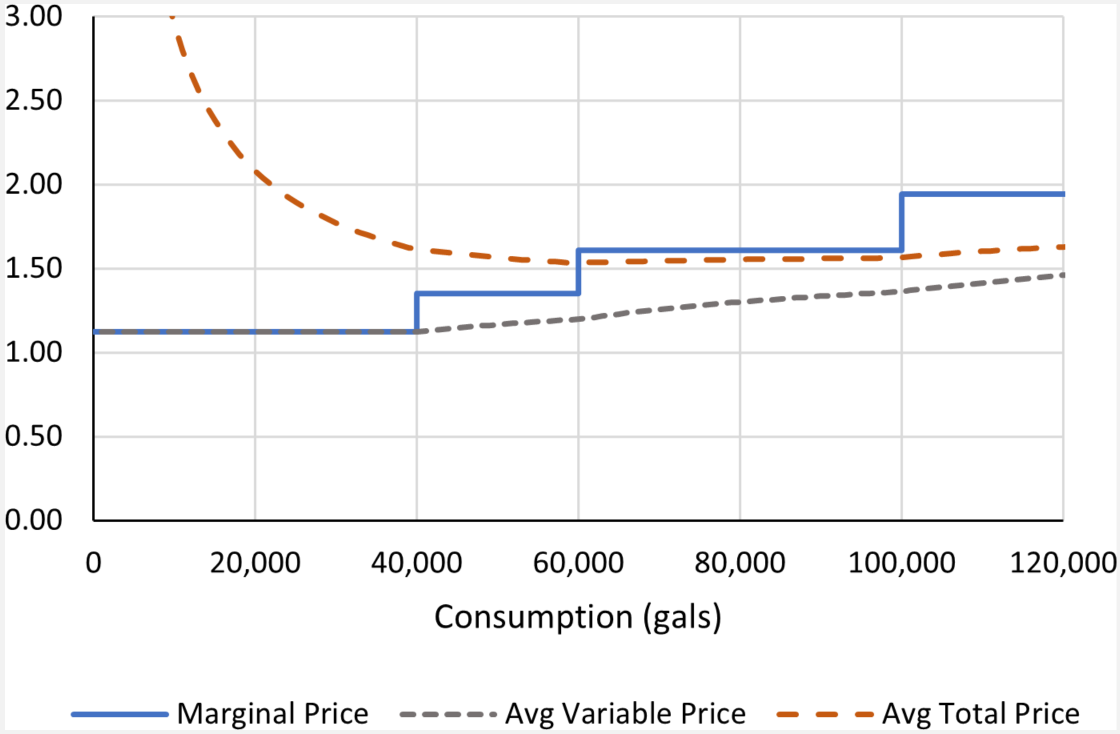


Figure 1: Consumer Prices from Example Utility in Teaching Notes

For advanced students who have taken econometrics, using real price and rate data to estimate elasticity of demand is an exciting exercise with a myriad of possible extensions to complement other course content and build on students' existing econometric background (see Teaching Notes). For all students, having a solid grounding in what the elasticity of demand for water is and what it means is crucial. We typically use a point estimate of price elasticity of demand for urban water of -0.41 (Dalhuisen et al. 2003).

As the material transitions from EOD to IBR pricing, students often encounter a key barrier in understanding the difference between marginal and average price. In a standard principles class, students would have worked with graphs of marginal and average cost curves. Water pricing offers a unique application of these ideas because IBR pricing is such an unusual pricing structure. Although IBR pricing has become popular among utilities, recent work has emphasized that consumers may know little about the marginal price they pay for water, and little about their water use in general, and so may not respond in their behavior to marginal price (Wichman 2014; Brent and Ward 2019). We spend substantial in-class time training students to take a marginal IBR pricing schedule and compute the average variable cost and average total cost, as shown in Figure 1, for the example utility described in the Teaching Notes. We emphasize that researchers look at all three costs as potentially affecting behavior. The complexity of the calculations is important for students to understand because demand management via pricing requires consumers to know the price they pay for water.

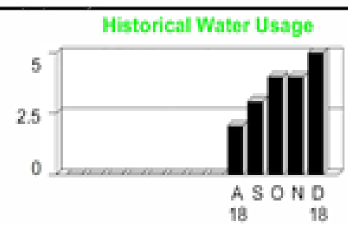
Building on EOD and IBR concepts, we typically transition into discussions of the motivation of water utilities in using different pricing strategies. Most water utilities are not-for-profit and may have rules requiring revenues to not exceed costs. (This may also allow for discussion of monopolies and public oversight or regulation.) As such, IBR pricing allows them to charge high marginal prices to high-volume users while offering prices below marginal costs for low-volume users. Utilities may or may not choose to display pricing information on consumer bills. One way to clearly demonstrate this to students is through the comparison of bills with marginal price information and without. Figure 2 shows a bill comparison we apply in class where the left bill has higher water consumption, less information, and a lower price (see Teaching Notes for additional discussion).

One key sticking point for students beginning to study water economics is the treatment of water as a good with monetary value. For this reason, water pricing is a great opportunity to discuss issues of equity in natural resources use. While water is essential to human life, the concepts from economics still apply to its allocation and use. Studying water as a market-allocated good does not change its essential nature, our moral obligation to allocate it fairly, or the need to preserve water for the natural environment.

The case we provide to study equity in water pricing (see Teaching Notes) focuses on colonias, unincorporated subdivisions along the U.S.–Mexico border without access to urban water supplies. We emphasize two approaches to understanding the problem. The standard policy approach suggests the municipalities are failing because they are not providing water service to these communities.

Service Address: NORTH EAST — Service Dates: 06/01/18 - 06/30/18

Meter Readings			Service	Total Charges
Previous	Current	Usage		
300	346	46	Previous Balance	$211.56
			Last Payment	-$211.56
			Water	$44.00
			Sewer	$50.00
			Garbage	$17.00
			Green Waste	$4.00
			Dispatch	$3.00
			Storm Water	$3.00
			Adjustments	
			Total Due	**$121.00**



Water Tiers: Tier 1 = 0-4 CCF Tier 2 = 5-10 CCF Tier 3 = 11+ CCF 1 CCF = 748 Gallons

Service -

METER #	AVG GALLONS/DAY	SERVICE PERIOD	CURRENT READ	PREVIOUS READ	USAGE
82974220	120.6	11/16/2018 to 12/17/2018	30	25	5

Water Base Charge		$6.26
Water Usage Tier 1	4 CCF @ $2.59	$10.36
Water Usage Tier 2	1 CCF @ $4.32	$4.32
Watershed Protection 5.000 CCF @ $0.1122		$0.56
Water Infrastructure Replacement Charge		$1.50
Waste Water Base Charge		$6.86
Waste Water Usage	5 CCF @ $4.53	$22.65
Waste Water Infrastructure Replacement Charge		$4.50
Metered Total		**$57.01**

Non-metered Charges		
Recycling		$2.60
Stormwater	0.4 SFEU @ $5.00	$2.00
Non-metered Total		**$4.60**

	Current Activity	$61.61

Figure 2: Example Bills from Comparison Exercise

A paper by Olmstead (2004) focuses on the economic incentives facing municipalities, which are legally limited in what they can charge for water. This limitation makes it impossible for municipalities to recoup investment in extending water service to these communities. The case demonstrates the importance of economic analysis in understanding the underlying mechanisms behind policy failures and leads to a nice discussion of potential solutions.

The colonias case study could be fit into a more thorough treatment of equity and affordability in water delivery either through a more elementary discussion of current affordability metrics and indexes (Patterson and Doyle 2021) or more advanced discussion of the unintended consequences of block rates (Agthe and Billings 1987) and theoretical efficiency discussions around marginal users (Schoengold and Zilberman 2014). A more in-depth discussion on equity, emigration in urban areas, and the complex challenges of water delivery with aging infrastructure (Swain, McKinney, and Susskind 2020) and declining population (Faust, Abraham, and McElmurry 2016) could also be included and potentially reference other urban water crises such as Flint, Michigan (Sadler and Highsmith 2016).

4 Discussion and Outcomes

Urban water pricing is an intuitive topic that many audiences easily relate to. A modified version of the material presented in this article has been presented to nonstudent audiences to introduce EOD and conservation pricing. Students and nonstudents alike relate to receiving utility bills, assessing the costs and benefits of various water uses, and making decisions on use. The contrast between a low-cost, low-information bill in arid Utah and a high-cost, high-information bill in humid North Carolina (Figure 2) always spurs interesting discussions. A paper by Luby, Polasky, and Swackhamer (2018) can enhance classroom discussion in its findings that this single observation is an empirical regularity.

In gauging student learning outcomes, we use two quantitative and three qualitative measures. The ability to calculate and apply a concept like elasticity of demand varies depending on the level of the course, so the exact expectation of the calculations can vary, but generally our two quantitative learning outcomes are:

1. Calculate total average price, average variable price, and marginal price for water;
2. Calculate price elasticity of demand for water using the midpoint method.

The first objective is achievable for all student levels, although undergraduates struggle with average price calculations using an IBR pricing schedule. While all undergraduate students can apply elasticity of demand to go from a change in price to change in quantity demanded, only advanced students have the experience in using econometric tools to calculate elasticity of demand using data. For this reason, the qualitative objectives associated with elasticity of demand become critical in evaluating undergraduate learning outcomes. We define three qualitative learning outcomes:

1. Understand determinants of price elasticity of demand and use the concept of price elasticity of demand to explain how water consumers will respond to a change in the price of water.
2. Define different water pricing strategies and explain how water pricing can motivate conservation.
3. Explain some of the complex issues in water pricing, equitable access, and tradeoffs facing water managers in the 21st century.

Student level sets the criteria for mastering these topics. For graduate students, items one and two should be fully and easily addressed. Undergraduates, especially in lower-level courses, will still struggle with elasticity concepts. Mastery of the topic requires they be able to identify urban water demand as inelastic and explain why.

Undergraduate students may or may not fully master the complex and emerging policy issues related to water pricing, but efforts should be made to at least engage them on these topics. Graduate students, however, can be evaluated on how well they can articulate the inherent tradeoffs in conservation and equity related to water allocation: providing cheaper water reduces barriers to access but encourages use. These discussions can be extended to include water pricing choices under increasing scarcity and subsequent management choices for water policy makers.

In advanced undergraduate and graduate courses, the cutting edge of economic research on demand response, real-time pricing, peer effects, and equity can be presented depending on instructor interest and expertise. Students interested in causal empirical analysis will be particularly interested in the quasi-experimental settings offered by rate changes, and how these have evolved (e.g., Nataraj and Hanemann 2011; Ito 2014; Wichman, Taylor, and Von Haefen 2016). Students interested in behavioral economics will enjoy papers that think about what information users receive or what knowledge is required for them to act on price signals (e.g., Brent and Ward 2019).

5 Conclusion

In this paper we present an overview of urban water pricing for an instructor of a class in natural resources and environmental economics or water economics. The basic concepts of EOD and IBR pricing are framed within the context of emerging issues in urban water pricing and equity. We provide classroom-ready material intended to help students understand the complexity of water demand by different user groups. The topic and material enhance prior concepts of marginal analysis and elasticity of demand by providing an intuitive and interesting setting.

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