Feature Article

Teaching Water Economics Using Dynamics and a Political Economy Framework

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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
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)
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)
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)
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)
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)
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

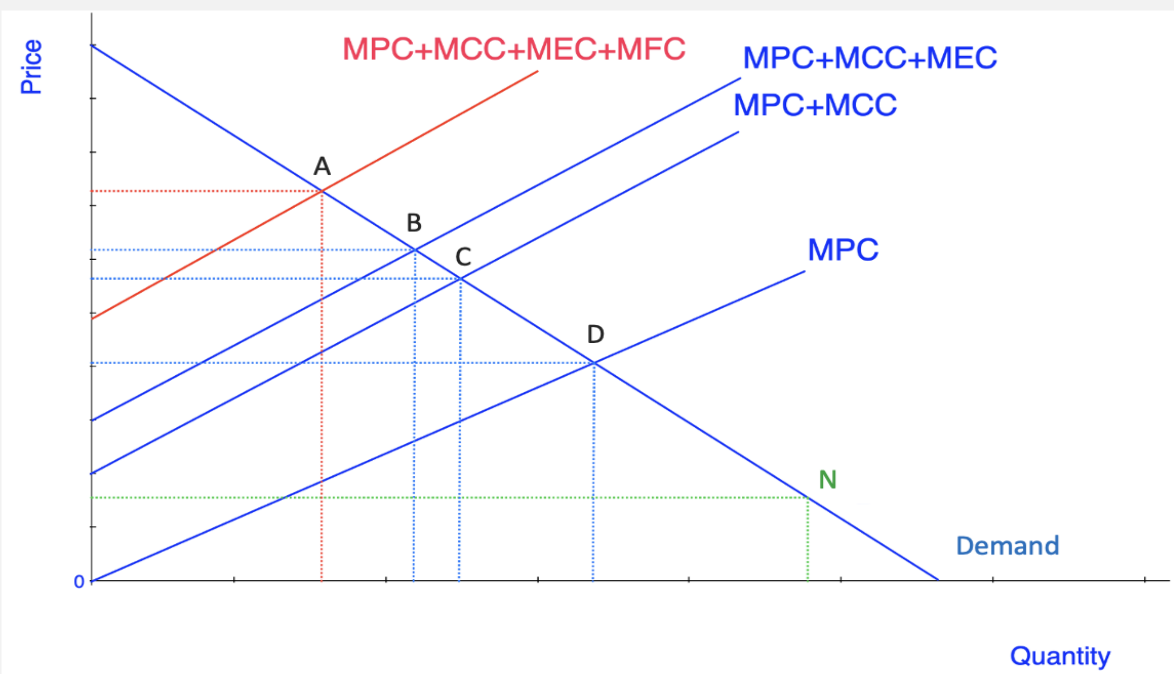
Engage the students in a water rights game. The students are divided into different sources and different water users. Water suppliers have a given amount of water and have a cost function. Water users have water rights and are given a revenue function. Assess resource allocation under different water 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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