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

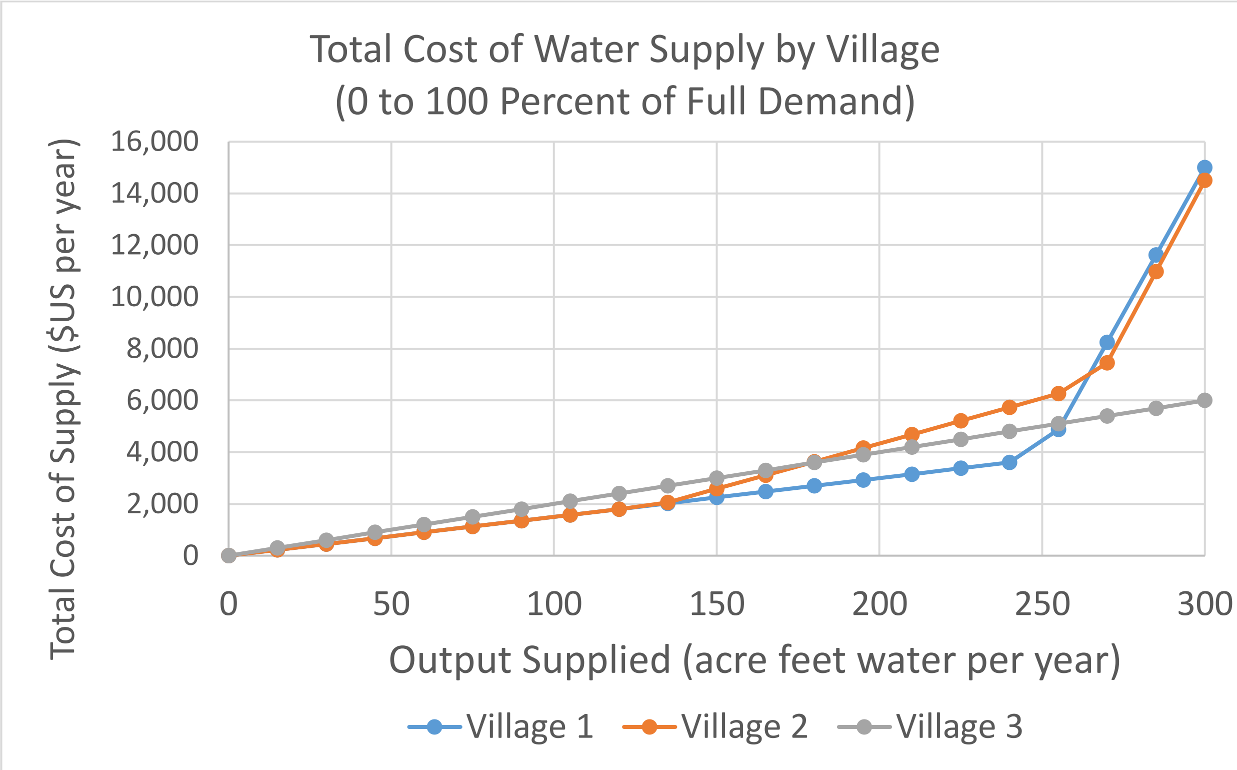

Figure 1: Total Cost of Water Supply by Village (0 to 100 Percent of Full Demand)

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.

```
$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;
```

```
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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