Teaching and Educational Methods

Simulating a Water Market: An In-Class Activity to Compare Market Efficiency under Various Institutions and Relative Advantages of Agents

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Abstract
Water markets are a public policy tool that can help to allocate water to its highest value uses, creating more efficient outcomes. This paper presents a classroom simulation that exposes students to some of the practical ramifications of establishing a water market and the outcomes that result. The activity has students role-playing as various businesses that require water for operation and assigns initial water endowments to some of the agents. Students must buy and sell water on a market and attempt to maximize their individual welfare. The students gain a deeper understanding of the welfare gains from water markets and learn how a lack of information and negotiating power can create inefficiency.

1 Introduction and Background

Water management is a complex problem that requires simultaneously managing uses to households, agriculture, industry, recreation, ecosystem services, and more (Young and Loomis 2014). Water is often allocated inefficiently because it is frequently under priced, leading to overconsumption (Creel and Loomis 1992; Timmins 2003). Water rights are often established according to traditional allocation methods that do not encourage conservation or sustainable use and prevent or restrict trade (Hutchins and Steele 1957; Donohew 2009). Groundwater is often extracted to fill the need, but as aquifers are depleted, new management policies will be required (Gibbons 1986; Dalin, Taniguchi, and Green 2019; Pauloo et al. 2020). Climate change will likely exacerbate these issues because drought is expected to become more prevalent, and water is to become more scarce (Palmer et al. 2008; Mukheibir 2010; Kahil, Dinar, and Albiac 2015; Mehran et al. 2017).

Water markets are a tool that have been proposed to help alleviate these issues (Hartman and Seastone 1970) that Olmstead (2010) has reviewed. They allow low-value users to sell their water to other entities with high-value uses, improving economic efficiency. These benefits are especially pronounced during low supply periods. Various locations around the world have established water markets. Grafton et al. (2012) found that establishing a water market in Australia's Murray-Darling Basin created gains from trade exceeding $2 billion per year and that the potential benefits in the U.S. West of expanding water transfers exceed $175 million per year. Schwabe et al. (2020) report that California had $3.9 billion of water exchanged from 2008 to 2019, but this accounted for only 2 percent of use in the state. The adoption of water markets in new locations is likely to provide economic benefits and alleviate future scarcity issues (Loch et al. 2013; Leonard, Costello, and Libecap 2019; Garrick et al. 2023).

Water markets do have some drawbacks. Most notably, increasing the price of water is likely to place financial burdens on low-income households, particularly people experiencing poverty in low-income countries (Venkatachalam 2015; Grafton, Horne, and Wheeler 2022). Additionally, water markets can increase price uncertainty and introduce risk to users (Zuo, Qiu, and Wheeler 2019).

Another concern is that externalities can be present when there is no market presence for instream flows (Griffin and Hsu 1993). Despite the potential gains highlighted in the U.S. West, Colby, Crandall, and Bush (1993) found significant price dispersion in the U.S. West water markets and that information flows and linkages may be insufficient to allow prices to converge, especially in locations with few potential market participants.

Teaching university students about water markets provides a good opportunity to use an in-class simulation to enhance student learning. Water economics is often toward the end of an environmental and natural resource economics course. At this point in the course, the analytical difficulty of the material on water economics and water markets is less difficult than in other portions of the course. However, several of the nuanced aspects of water markets and the difficulties presented when practically implementing water markets are not obvious from the theoretical classroom material. Students are familiar with retail settings, where buyers are price takers within a market and decide what quantity they will purchase at the set price. Water markets typically function as negotiation, ask/bid, or auction-based markets. Many students have little or no practical experience with these market institutions, and several students have expressed significant learning from active participation in price negotiations.

Several simulation activities and games are available online for principles of microeconomics classes to demonstrate the laws of supply and demand. Software-based economic simulations are available online, such as economics games (economics-games.com), MobLab (moblab.com), and econ class experiments (econclassexperiments.com) that cover competition, markets, externalities, game theory, and more. Mashayekhi et al. (2006), Gold and Gold (2010), Kvasnička (2014), and Riley (2020) have also developed computer-based activities that cover supply and demand and the function of markets.

Two components differentiate this water market simulation from standard market simulations. The first is that supply is represented by a fixed total quantity constraint with the endowment of water rights to specific agents rather than a production function. Second, the market functions through private negotiation for determining prices and quantities. Third, students have an implicit tendency to try to lower the cost of water. Experience running the simulation has shown that students are more hesitant to charge efficient (high) water prices than "widgets" in a principles of microeconomics course, likely due to the necessity of water for basic human needs. Participation in the simulation reinforces to students that active water markets can support essential human needs while increasing economic efficiency. This activity focuses on face-to-face peer interaction and does not include software or computer augmentation. Students must negotiate and trade during class time, similar to activities on barter trading (Karpoff 1984), supply and demand (Lin 2018), land conservation (Dissanayake and Jacobson 2016), and ecosystem services (Abidoye, Dissanayake, and Jacobson 2021).

The in-person nature of the activity can improve student outcomes by reducing student passivity (Senthamarai 2018), motivating students, and improving critical thinking skills (Laal and Ghodsi 2012). Additionally, Eppich and Chang (2015) found that in-person debriefing can promote professional collaboration and practical decision-making. Farolfi and Erdlenbruch (2020) have developed a class activity that illustrates the common-pool dilemma aspect of water management. The activity presented in this paper uses a setting where water rights are established, avoiding the common-pool dilemma, and focuses on how trading can increase the welfare of market participants.

This paper introduces an in-class activity that simulates a water market. The simulation is targeted at a "300" level environmental economics or environmental and resource economics course. At this level, the student will have completed a principles of microeconomics course and an introductory calculus course as prerequisites. However, they will not necessarily have completed an intermediate microeconomics course where they have applied calculus in an economics setting. This simulation has been conducted in an undergraduate, 300-level environmental and resource economics at the University of Oregon and in a master's level environmental economics course at Duke University's Nicholas School of the Environment. The simulation is conducted as part of the unit on water economics, generally placed toward the end of the course so that students are already familiar with marginal analysis from other units already covered. The students should be familiar with problems that involve two or more agents and understand how to compute the marginal benefits (MB) or marginal costs (MC) given total benefits or costs. They should recognize that to find an efficient outcome they must set marginal costs and benefits equal to each other and solve for equilibrium quantity and price. The simulation presented here gives costs and benefits in tabular form, similar to the Chapter 18 exercise in Harris and Roach (2017). The scenario handouts could be readily modified to give the costs and benefits in a functional form for use in classes where students are comfortable with differential calculus.

2 Learning Objectives

There are two broad categories of learning objectives for this activity: (1) Gaining a deeper understanding of the material presented in the class and (2) Demonstrating the practical functioning of a water market and showing how the practical application can deviate from theoretical results derived in lectures and homework. The second category is not germane to many environmental economics courses. However, the simulation demonstrates results that economists have observed and verified empirically. Menkhaus, Philips, and Bastian (2003) have found that private negotiations disadvantage sellers (particularly small sellers) compared to open auctions. Kristensen and Gärling (2000) found that irrelevant anchoring information influenced negotiated offers and prices. Bazerman, Magliozzi, and Neale (1985) established that under negotiation, a market converges toward a Nash equilibrium with experience, but that initial outcomes are not at the Nash equilibrium. Students will find these insights useful as they embark on their careers and consider the application of the knowledge they have gained in the classroom.

The following list includes these objectives and some potential additions that could be included if desired.

- Homework problems and lecture examples have demonstrated how to solve for efficient equilibrium outcomes with information on all participants. In practice, buyers do not have information on seller costs, and sellers do not have information on buyers' preferences. Market transactions help reveal this information over time, and during this transition, the market typically has some deadweight loss.
- Understanding that inefficient outcomes can result in a market setting, even when other factors discussed in the course are absent. There are no externalities, property rights are established, and it is not a common property or public good. However, private negotiation and the initial market phase, where agents must learn other parties' preferences, costs, and benefits, will push the market toward an inefficient outcome.
- Even though the simulation will likely not lead to an efficient outcome, it will lead to welfare gains compared to a situation where no trading is allowed.
- Understanding that markets typically reach an efficient outcome only after some time has passed. Markets typically require time for buyers and sellers to observe prices and price variability before an efficient equilibrium can be reached. Over time, the price will move toward the price that will allow the fixed supply to meet demand.
- Recognizing that market power and negotiating power can alter the dynamics of a market and favor certain agents in the market.
- Reinforcing how uncertainty plays a role in market outcomes—fixed prices or taxes create quantity uncertainty, while fixed quantities (as demonstrated in the simulation) create price uncertainty.

- The activity can be repeated with the same values to allow students to observe the market approaching a more efficient outcome over time. When implementing a second round, the instructor should record the prices and quantities from trade for the initial market on the blackboard but complete both rounds before conducting the debrief. Typically adds 5 minutes to the activity.
- The activity can be repeated with different water supply values (included in the accompanying spreadsheet) but with the same costs and benefits. This round will confirm students' understanding of how resource shortages impact a market by raising the price and reducing consumption. This demonstrates some of the impacts of drought and reinforces concepts from a unit on renewable or nonrenewable resources. Similarly, record prices and quantities from the previous round(s), but complete this round before conducting the debrief and discussion. This typically adds 10 minutes to the activity.

3 Simulation Description

The water energy nexus has received considerable attention over the past two decades, as well as This section describes the process of running the simulation. Appendix A includes a copy of each handout, and Appendix B includes copies of the text shown on PowerPoint slides displayed during the simulation. This simulation has been run during the lecture on a day when a homework assignment is due that includes a structurally similar problem (included in Appendix B) with two agents. Completing the homework question before the simulation ensures that the students are familiar with calculating marginal costs and benefits, that they should set MB = MC to find the solution, and that Price = MC at the solution. The major difference between the simulation and their homework is (1) they have information about their own costs and benefits but do not know anything about other agents' cost or benefit functions, and (2) there are five agents, increasing the complexity through multiple trading possibilities, and establishing an efficient outcome is more difficult. Table 1 outlines the simulation and the expected time that will be needed.

3.1 Pre-Simulation Setup

Divide the class into five groups of approximately 3–4 people and assign each group to be an agent. The collection of five groups will form a market. Larger classes will have multiple, noninteracting markets. There should be a clear delineation between markets to ensure that they are not buying and selling with the wrong market and that information is not being shared between the markets. The simulation has been run successfully with up to 70 students and three simultaneous markets.

Give a handout to each group that will assign them an "agent" (municipality, hay farm, berry farm, beverage plant, and textile factory). Each agent is given their total costs or benefits in table form. Then, they calculate MB/MC in table form by subtracting the current row from the previous row and dividing by the difference in usage. Within each market, two agents have a water endowment who will be the sellers. Two sellers are included to alleviate the potential for monopoly power. The two sellers have not colluded in prior experiences running the simulation. However, there is potential for astute groups to engage in monopolistic or monopsonistic behavior with the limited number of participants.

3.2 During the Simulation

Give students approximately 15 minutes to complete all transactions. During the simulation, I answer questions that help clarify instructions but defer most questions that ask about a solution technique. I will refer the students to the relevant homework question and reiterate that this is conceptually similar, but that they only have information on one agent and must negotiate with other groups. A question that typically comes up early in the simulation after groups have successfully computed the MBs is, "Where

Table 1: Outline of the Components of the Simulation and Their Requisite Time

Activity Component	Approximate Expected Time	Comments
Initial Instructions	5 minutes	Reviewing announcements or homework questions at the beginning of class may be useful. Assigning groups and providing instructions to latecomers will encumber the activity.
Group Setup	5 minutes	The time taken will depend on the group assignment method.
Simulation Phase 1	15–20 minutes	Prior experience has shown that the groups take 15–20 minutes to conclude their negotiations. Giving people a 5-minute warning at 15 minutes may be helpful to encourage them to wrap up. If all negotiation has concluded, end this phase.
Simulation Phase 2 (optional)	5 minutes	Repeating the simulation with the same supply quantity, costs, and benefits will likely see an equilibrium closer to efficiency that requires less negotiation time. Prior experience has shown that the initial simulation results in a low price and volume of water traded. This phase will likely see a higher price with greater volumes traded, leading to a more efficient outcome.
Simulation Phase 3 (drought scenario, optional)	10 minutes	Repeating the simulation with new supply values will require less time than the first round but more than the second. The efficient price is higher than in the standard simulation. The negotiated price(s) are likely to increase, reflecting the supply shortage and student learning.
Debrief and Discussion	10–15 minutes	Allow time for questions relating to the simulation or the simulation's application to the class material.

are the MCs that I should set these equal to?" resulting in a need to guide them to negotiate and begin trade with other groups.

3.3 Post-Simulation Debrief and Discussion

After completing the simulation, record each agent's outcome and write them on the classroom blackboard. At the beginning of this portion of the simulation, let students know that classes rarely or never find an efficient outcome for all five groups in the market to set them at ease with sharing their results. During this phase, it is critical to make students comfortable with the learning process and not to be concerned that they "got it wrong." Try to be gentle and humorous during this portion of the simulation and avoid critical comments.

The most common outcome observed is that the price of water is lower than MB/MC, indicating that more trade should occur and that the price of water should be higher for an efficient outcome. Most markets will not have multiple prices, which leads to some discussion points to reinforce the learning objectives.

First, discuss the differential price. Why did some agents pay more? Typically, some sellers will have multiple transactions at different per-unit prices. Ask them why they sold at lower prices if higher prices were available.

Second, bring up the solution technique used throughout the class to solve problems of setting MB = MC. Then identify 1–2 groups where the price they bought/sold at is higher than their MB or MC and discuss their specific outcome. Ask how their profit would change if they bought or sold one more unit of water at the same price and show that they could have increased their benefits. Often the buyers note that sellers would only sell them more water by increasing the price of all previous units, an outcome that would lower their benefits. In that case, choose the seller as the second group to analyze and see if their benefits would have increased from being willing to sell more.

Then discuss some of the learning objectives and discuss how the activity demonstrates some results covered in class and how the actual markets do not always achieve some of the results derived analytically.

- In class lectures and homework problems, cap-and-trade markets have a single clearing price and generate an efficient outcome. Discuss how negotiation and market power can prevent an efficient outcome. Also, discuss how markets tend to approach more efficient outcomes as time progresses and the agents learn, but that market changes, perhaps due to drought, reduce or reset this learning. Show a slide that shows price evolution for a real market, such as Figure 1 in Rimsaite et al. (2021), Figure 7 in Brown (2006), or Figure 1 from Hitaj and Stocking (2016).
- Quantity instruments, such as cap-and-trade programs that have been discussed earlier in the course, create price uncertainty. This is comparable to the simulation they have just finished, where the total water supply is fixed. Discuss verbally how a simulation with a slightly different setup, a fixed price, would result in an uncertain quantity consumed. In a practical setting, a fixed price would lead to uncertain instream flow remaining and the potential for overuse.
- In previous simulations, the sellers typically do not wish to sell efficient quantities of water. Relate this to the endowment effect (Kahneman, Knetsch, and Thaler 1991) many students have seen from a behavioral economics course or unit in a different class.
- A final point for discussion is equity concerns. A common outcome in prior simulations has been that the municipality does not maximize its total welfare/profit. They sell less water than would be efficient to ensure their citizens have access to plenty. Discuss the idea that the high MB at low quantities represents critical water uses such as drinking, sanitation, and cooking. The low MB at high quantities could represent nonessential uses such as watering lawns and washing cars. If the municipality in the simulation sold a low quantity of water, this likely resulted in low agricultural output. In a practical setting, this would result in higher food prices. While the simulation simplifies reality, the trade-off between agriculture and urban use is a tangible public policy issue.

Some caveats can be mentioned during the simulation or the debrief to elucidate some areas where the simulation deviates from actual water markets. These include:

- The simulation includes the municipality as the primary water seller. In practice, municipalities are often purchasing from agricultural water rights holders (Shupe, Weatherford, and Checchio 1989; McLane and Dingess 2013).
- The simulation abstracts away from other costs that must be incurred in practice. The cost to treat and distribute water in residential and commercial settings is particularly important for

water economics. The end-user price of municipal water can be significantly higher than the price required for the initial purchase (Varela-Ortega et al. 1998).
- The simulation does not account for differential water quality requirements. Agricultural water supply will generally require treatment before use in a city or a beverage plant.

4 Conclusion

This paper includes an in-class simulation to engage students in how water markets function. The activity has students play the role of economics agents who require water for their business or operation, and students must trade with each other to maximize their net benefit. This activity reinforces many of the concepts learned in an environmental or natural resource economics course on water economics. Also, it presents some of the barriers that prevent or impede the practical implementation of markets in public policy.

No formal assessment has been conducted to assess the impact of the activity. However, multiple students self-reported in the comments of their course evaluation that they found the active participation to be beneficial or helpful in improving their understanding of water markets, that the activity helped them understand how the application of the course material to actual policy can be difficult, and that it was a highlight of the course. No comments to date have self-reported that the activity was a negative experience. However, as this was not asked directly on the evaluation, it is possible that some students have a negative opinion but did not express it.

There are some pitfalls that the instructor should avoid while implementing this activity. First, the students need to be prepared for the simulation by having a foundational understanding of marginal analysis and how to use it to solve for economically efficient outcomes. They should also understand the concept of water markets and how they function, i.e., this activity is not recommended for the first class on water markets as an introduction to the concept. Second, the instructor must provide a balance of assistance. If too much solution assistance is given, the students will learn less than if they arrive at the solutions with their group. However, the instructor should guide any groups that are unsure how to progress during the simulation.

This activity aims to aid the instruction of an environmental economics, resource economics, or agricultural economics course that includes a unit on water economics. However, the simulation could be applied to other classroom settings where simulating a market establishment would benefit student understanding and aid student engagement.

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Appendix A – Group Assignment Sheets

Group A: Municipality
You are the city council for Hydroville. The city owns the property rights for 20 acre-feet (af) of water. You must provide water for the citizens of your town. The water is used by the citizens for residential and general commercial purposes (drinking, washing, landscaping, etc.). The marginal benefits are decreasing due to the citizens placing a higher value on drinking than on washing and landscaping. You can use all 20 af for your city or sell some of the water to other users.

The table below lists the marginal benefit of the water to the citizens of your town.

Water Used (af)	Total Benefit	Marginal Benefit
0	0	
2	200	
4	380	
6	540	
8	680	
10	800	
12	900	
14	980	
16	1,040	
18	1,080	
20	1,100	

Names of group members:

For each group you are trading with, record the group, the quantity of water sold, and the price per af.

Provide a brief (2–3 sentences) explanation of how you arrived at the amount(s) that you bought or sold.

Group B: Hay Farm

You are the owners of a family hay farm. You have installed gutters on the farm buildings that collect 2 acre-feet (af) of water for yourself. You have the option of installing an irrigation system to the river that will allow you to participate in the market for $20. This will allow you to sell your 2 af on the market, or it will allow you to buy additional water.

You produce hay that you can sell on the market for $10 per bale. Assume you have no costs other than water.

Hay Produced (bales)	Water Used (af)	Total Benefit	Marginal Benefit
0	0		
16	1		
30	2		
42	3		
52	4		
60	5		
66	6		
70	7		
72	8		
72	9		

Names of group members:

Are you choosing to install the irrigation to allow you to buy and sell water?

How much water are you buying or selling, and what is the price per af?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Group C: Berry Farm

You are the managers of a berry farm. You own the property rights to 10 acre-feet (af) of water by virtue of owning property next to the river. You can use your water to grow berries. You can install a drip system for $100 that will reduce your water usage by 2–3 for all amounts of berries produced. You can buy or sell water on the market. Berries sell for $4 per pound on the market.

The table below represents the number of pounds of berries that you can grow. Assume you have no costs other than water.

Berries Grown (pounds)	Water Used with No Irrigation (af)	Water Used with Irrigation (af)	Total Benefit	Marginal Benefit
0	0	0		
25	3	1		
45	6	2		
60	9	3		
70	12	4		
75	15	5		
75	18	6		
70	21	7		

Names of group members:

Are you choosing to install the irrigation system?

How much water are you buying or selling, and what is the price per af?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Group D: Textile Factory
You are the management team for a textile factory. The water you use in the factory to clean and cool equipment ultimately becomes wastewater and is unavailable for reuse. You have the option of two different production processes: one that uses more water and one that uses more labor. You do not have any prior rights to water, so you must buy the water you use. Choose a production process and the amount of water.

The table below represents your two production processes.

Revenue from Textiles ($)	Water Used by Process A (af)	Labor Costs from Process A ($)	Water Used by Process B (af)	Labor Costs from Process B ($)	Total Benefit	Marginal Benefit
0	0	0	0	0		
540	2	100	1	1,000		
960	4	200	2	2,000		
1,260	6	300	3	3,000		
1,480	8	400	4	4,000		
1,620	10	500	5	5,000		

Names of group members:

Are you choosing process A or process B?

How much water are you buying or selling, and what is the price per acre-foot (af)?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Group E: Beverage Plant
You own a beverage plant. You require water to make your beverages and to clean and cool plant equipment. You are the farthest downstream, so you have access to two water markets. You can obtain water from this market, or from another water market that has a fixed price of $90 per acre-foot (af). You cannot sell water from the other market because you do not have a way to transport it upstream.

The table below represents the water input required to produce beverages. You can sell your beverages at a price of $15 each. Assume you have no costs other than water.

Number of Beverages Produced	Water Used (af)	Total Benefit	Marginal Benefit
0	0		
8	1		
15	2		
21	3		
26	4		
30	5		
33	6		
35	7		
36	8		
36	9		

Names of group members:

Are you buying water from this market or from the alternative market at $90 per af?

How much are you buying or selling, and what is the price per af?

Provide a brief (2–3 sentences) explanation of how you arrived at the amount that you bought or sold.

Appendix B – Slides and Graphics Presented

B.1 Slides during the Simulation

The following text should be presented before the simulation has begun, and before the handouts have been distributed. Phrases set aside with square brackets [] should be modified to include information specific to your course. Include details on the first bullet that instruct the students on how their groups will be determined (random assignment, find their own partners, etc.). I prefer assigning the groups randomly to encourage discussion with students they do not typically work with, but allowing them to form their own groups will save time.

- We will be conducting an in-class simulation. [Instructions on how to form groups]
- You will be assigned some details on the costs, benefits, revenues, etc., regarding the operation of your business or agency.
- This simulation is similar to [question #3] on the recent homework. The primary difference is that you only have information on your own operations and must negotiate with the other parties.

The following text should be displayed as the simulation is beginning. I provide oral instruction over these points as the simulation is beginning and leave them up as a quick reference for the students during the simulation.

- Your group must decide the level of output that you are going to produce.
- You should obtain the correct amount of water for the output that you choose.
  - For some groups, this will require buying water.
  - Some groups will be able to sell water to other groups.
- Your goal is to maximize the profits/benefits of your business.
- For each transaction with another group, you should record the amount of water sold and the price per acre-foot (af).

B.2 Actual Water Market Data Figure

I show this figure on a slide as part of the debrief, such as Figure 1 in Rimsaite et al. (2021, p. 5). The data is from transactions in a nine-state water market sample that includes AZ, CA, CO, ID, NM, NV, TX, UT, and WA. The figure shows some volatility that can likely be explained by drought conditions such as the simultaneous price increase to leases and transfers in 2003. It also shows some price variability where lease price increases in 2006, but the transfer price remains level, indicating there is likely to be some other cause.

Appendix C – Other Class Materials

C.1 Sample Course Outline

Table C1 presents the timeline of an environmental and resource economics course that is suited for this activity that shows the context for the activity. This timeline is for a 10-week quarter-length class. The schedule would require some modification for a semester-length or a condensed summer course.

Table C1: Example Timeline of an Environmental and Resource Economics Course	
Class Day	**Topic**
Week 1 Class 1	Introduction to environmental economics and review of principles of microeconomics
Week 1 Class 2	Externalities I: Markets and market failures—positive and negative externalities
Week 2 Class 1	Externalities II: Computation of equilibrium given supply, demand, and externality and welfare analysis
Week 2 Class 2	Pollution Management I: Introduce a model of polluting firms, and solve the model with command-and-control (quota) policy
Week 3 Class 1	Pollution Management II: Solve model with taxes and cap-and-trade; examine welfare implications of different policies
Week 3 Class 2	Pollution Management III: Discuss implications of uncertainty with the policy instruments; discuss the real-world application of policy; review for Midterm
Week 4 Class 1	Midterm I
Week 4 Class 2	Common Property Resources I: Description of types of goods, and example solved of market outcome and efficient outcome for a common property resource
Week 5 Class 1	Public Goods and Discount Rates: Theory of public goods and example solved to find market equilibrium and efficient outcome for a public good; introduce discount rates
Week 5 Class 2	Resource Allocation over Time I: Description of how economics uses dynamic models for resource allocation over time; review discount rate, and show how it enters dynamic economic models; introduce two-period model (simplified overlapping generation model) and solve for resource allocation
Week 6 Class 1	Resource Allocation over Time II: Conclude solving the two-period model; discuss extension to infinite time horizon; discuss how changes in parameters such as discount rate, demand in period 2, and uncertainty will change the allocation across time
Week 6 Class 2	Resource Allocation over Time III: Discuss the application of model results to real-world situations, the Hotelling's rule, and the Hartwick rule; review for Midterm II
Week 7 Class 1	Midterm II
Week 7 Class 2	Valuing the Environment: Total economic value, type of value; begin methods used to quantify nonmarket benefits; cost of illness, replacement cost, and travel cost model
Week 8 Class 1	Valuing the Environment: Conclude methods used to quantify nonmarket benefits; hedonic pricing, stated preference methods; introduce cost-benefit analysis, and solve dynamic cost-benefit example. **Homework assigned with problems over material from Week 7 Class 2 to Week 8 Class 2 Due Week 9 Class 1.**
Week 8 Class 2	Renewable Resources I: Discuss the real-world application of models developed earlier in the course to fish, surface water, and wildlife
Week 9 Class 1	Renewable Resources II: **Water market activity**. **Homework on renewable resources and valuing the environment Due.**
Week 9 Class 2	Nonrenewable Resources I: Discuss the real-world application of models developed in the course for mining and minerals; solve an example of recycling vs. virgin resource use of a mineral.
Week 10 Class 1	Nonrenewable Resources II: Discuss the real-world application of models developed in the course for groundwater and fossil fuels; cover the transition from fossil fuels to renewable energy and other energy and electricity trends
Week 10 Class 2	Climate Change and Review: Discuss how the topics covered relate to and interact with climate change; review for Final
Week 11	Final

C.2 Sample Homework Problem

The following problem is a sample problem that has been included on the homework assignment due the day that the water market activity is conducted. This problem gives students familiarity with the solution technique that they will need to use for the in-class activity. Students have also completed other problems that require them to convert total benefits/costs/product to marginal values and set those equal to find the efficient solution such as Harris and Roach (2017) exercises 4.1 and 13.2. This problem is assigned after covering different methods that have been used to assign water rights in lecture, so the students must recognize that prior appropriation assigns the water right to the earliest settler, and that who is upstream is not used. The solution is included in *italics*.

There are two farmers that have settled and built farms along a river. Jack settled and established his irrigation in 1954, and Kate settled and established her irrigation in 1960. Kate is upstream from Jack.

Acre-Feet of Water Used	Total Benefit to Jack	Total Benefit to Kate	Marginal Benefit to Jack	Marginal Benefit to Kate
1	100	150	*100*	*150*
2	180	270	*80*	*120*
3	240	360	*60*	*90*
4	280	420	*40*	*60*
5	300	450	*20*	*30*
6	300	450	*0*	*0*

a) Complete the table by computing the marginal benefit to each farmer.

b) If there are 15 acre-feet (af) of water available, if water is not tradeable, and if water rights are given by prior appropriation, how many units of water will be used by each farmer?

Both farmers would use 5 af. There is no scarcity constraint with this level of supply. Both farmers get zero MB from a 6th unit of water, so they would not bother.

c) If there are 7 af of water available, if water is not tradeable, and if water rights are given by prior appropriation, how many units of water will be used by each farmer?

Jack has the water right by prior allocation, so he will use the same 5 af as in part (b). However, this leaves only 2 af for Kate.

d) If a water market is established and if water is tradeable, how many af of water will be used by each farmer when 15 af are available, and what price will water sell at?

With no scarcity constraint, establishing the water market will not change the outcome. Same as part (b) where both farmers will use 5 af. With no actual sales, the price is zero.

e) If a water market is established and if water is tradeable, how many af of water will be used by each farmer when 7 af are available?

With 7 af available, there is a constraint to supply, and water trading provides an opportunity for greater benefits. Find the allocation where the marginal benefits are equal, and the total amount used is 7. By inspection, this occurs at 3 af for Jack and 4 af for Kate. Water will be sold at their mutual marginal benefit price = $60 per af.

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