Irrigation Economics

The economics of irrigation is an important part of water economics in the U.S., because irrigation accounts for the majority of agricultural water use and agriculture uses 80% of annual water supply. The analysis of irrigation water demand requires a basic knowledge of the hydrologic cycle as it affects agricultural production.

![The Hydrologic Cycle](image)

The use of irrigation water depends on:

- Economics (prices and costs)
- Crop Selection
- Land Quality and Environmental Conditions
- Irrigation Technology

Water Management Choices depend on:

- Type of Crops
- Irrigation Technology
- Level of Water Availability

**Some Stylized Facts About Irrigation:**

Irrigation water is measured in "acre-feet," AF, which is the amount of water needed to cover one acre of land to a one foot depth (before water is lost to percolation).
Irrigation Efficiency measures the percentage of water that is actually consumed by the crop.

Typical Water Use of Common Crops:

- **Heavy water users:**
  - Alfalfa: 5-7 AF/year
  - Rice

- **Medium water users:**
  - Fruits: 2.5-4 AF/year
  - Cotton: 2.5-4 AF/year
  - Vegetables: 2-3.5 AF/year

- **Low water users:**
  - Wheat: 1.8-2.5 AF/year

Notice that there are big water savings moving from Rice / Alfalfa to Wheat.

Irrigation efficiencies of several irrigation technologies:

<table>
<thead>
<tr>
<th>Method</th>
<th>Example</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational</td>
<td>Furrow</td>
<td>.65</td>
</tr>
<tr>
<td></td>
<td>Border</td>
<td>.65</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>Manual move</td>
<td>.8</td>
</tr>
<tr>
<td></td>
<td>Center pivot</td>
<td>.8 With field crops</td>
</tr>
<tr>
<td>Low volume</td>
<td>Drip</td>
<td>.95 Not used with alfalfa, wheat</td>
</tr>
<tr>
<td></td>
<td>LEPA</td>
<td>.9 Used in field crops</td>
</tr>
<tr>
<td></td>
<td>Mini-sprinkler</td>
<td>.9 Used with trees</td>
</tr>
</tbody>
</table>

Water Saving Technology is initially very expensive to install.

- Over the lifetime of the system, the farmer pays for the technology through higher irrigation efficiency which defrays some of the cost of water.

However, the correct incentives may not exist to stimulate investment in water-saving technology, since:

- water is not sold in markets (price does not necessarily reflect MB)

Currently, the price of water is set administratively and is not the result of the maximizing behavior of economic agents. Water in agricultural uses is also heavily subsidized, which has the following implications:

- **Low water prices benefit users** by providing a cheap source of water
- Low water prices creates an inefficient incentive to adopt new, water-saving technologies.

How The Choice of Irrigation Technology Affects Output:

Water is applied to the surface, percolates through the soil and is taken up by the root system.

- If the soil is dry and a bucket of water is poured on it, most of it will fail to permeate the soil, but will instead exit the land in the form of runoff.
- If the soil is first moistened, then it much more readily absorbs water
This is the principle behind drip irrigation: it applies water much more slowly so that the crop can absorb it better

- Most of the water applied in a drip irrigation system is absorbed by the plant.
- On the other hand, drip irrigation systems are very expensive to set up.

In contrast, a sprinkler distributes water much more unevenly (through space and time)

- Less of the water applied is utilized by crops; greater evaporation and runoff

- Yet sprinkler systems are relatively inexpensive to set up.

Finally, the least efficient forms of irrigation are gravitational systems such as flood or furrow, which use the concept of acre foot quite literally by pooling water on a portion of land. Gravitational systems are less water efficient than sprinkler or drip irrigation, because of greater evaporation and surface runoff.

A simple model of irrigation technology choice:

Agricultural production is a function of the effective water taken up by the crop.

- It does not matter how much water is applied, because what matters is the water available to the roots.

Effective Irrigation Water is the quantity of water actually taken up by the crop.

- Effective water is the product of two components:
  - applied irrigation water (the quantity of water applied), and
  - irrigation efficiency (the fraction of applied water taken up by the crop):

Let the per-acre production function for an agricultural product be:

\[ y = f(e) \]

where:

- \( y \) = agricultural output per acre
- \( e \) = effective irrigation water per acre

and where we assume \( f_e > 0 \) and \( f_{ee} < 0 \)

- i.e., water has a positive marginal product that increases at a decreasing rate.

Effective water equation:

\[ e_i = a^*h(i,q,c) \]

where:

- \( a \) = applied water per acre
- \( h(i, q, c) = \text{irrigation efficiency} \)

\( i = \text{irrigation technology}, \) where we assume two possible irrigation technologies, labeled with an index variable \( i \):

- Traditional technology: \( i=1 \)
- Modern technology: \( i=2 \)

\( (dh/di) > 0: \) an increase in irrigation technology increases irrigation efficiency (higher \( i \) results in higher irrigation efficiency).
q = quality (of land or water). Land quality has many dimensions, such as water-holding capacity, soil quality and topographical conditions such as slope.

- \( h_q > 0 \), thus, an increase in land or water quality increases irrigation efficiency.

c = climate variables (temperature, humidity, etc.)

\( h_c \) is ambiguous, thus, an increase in a climate variable may increase or decrease irrigation efficiency, depending on the particular climate variable considered. (High wind and sun energy, for example, tend to decrease irrigation efficiency, due to greater evaporation rates).

The farmer’s per-acre profit-maximization problem can be expressed as the following **discrete/continuous choice problem**:

\[
\max_{i,a} \Pi = Pf(e) - (w + z_i)a - k_i \\
\max_{i,a} \Pi = Pf(ah(i,q,c)) - (w + z_i)a - k_i
\]

where: \( \Pi \) = profit  
\( P \) = output price  
\( z_i \) = cost of water pumping and pressurization  
\( k_i \) = fixed cost of technology \( i \)  
\( w \) = price of water

Assumptions:

(a) \( h(i=1) > h(i=0) \) Irrigation efficiency is higher with modern technologies.

(b) \( k_1 > k_0 \) Modern technology requires higher fixed cost.

(c) \( z_1 > z_0 \) Pumping and pressurization cost may be higher with modern technology.

For a given \( i \), optimal water use is determined by the F.O.C.:

\[
\frac{d\Pi}{da} = Pf_e e_a - (w + z_i) = Pf_e h(i,q,c) - (w + z_i) = 0
\]

where \( f_e \) and \( e_a \) are the appropriate partial derivatives.

Note the use of the chain rule.

Rearranging:

\[
\frac{w + z_i}{h(i,q,c)} = Pf_e
\]

which says that at the optimum: **MC of effective water = MVP of effective water.**
We next outline some of the economic implications of the model:

The Technology Adoption Decision

The decision to adopt modern irrigation technology depends on a number of parameters in the model, for example, land quality. At some level of land quality, all else being equal, switching technologies will maximize profits. This level of land quality is called the switch point. (Similarly, other parameters in the model have other, analogous switch points.)

Figure 14.2

- Figure 15.2 shows that it is not profitable to farm land of quality \( q_{m(i=1)} \) regardless of the type of irrigation technology. On the other hand, with high-quality land, either technology is profitable, although the traditional technology is more profitable. This is because on high quality land, the increase in yield with the modern technology is not worth the fixed cost of installing it. Where the modern technology makes a difference is on land of moderate quality, i.e., the land between \( q_{m(i=0)} \) and \( q_s \). The modern technology increases profits on land between \( q_{m(i=0)} \) and \( q_s \), and makes profitable land that was previously not worth farming, i.e., the land between \( q_{m(i=1)} \) and \( q_{m(i=0)} \).

- The switch point is based on a comparison of Profit\((i=0)\) with Profit\((i=1)\).

Crop selection

The selection of agricultural crops may be viewed as another, parallel type of “technology adoption”.

- **Crop selection depends on the levels of economic parameters** such as land quality and water prices.

- If the price of water increases, farmers are more likely to increase their acreage water-saving crops such as wheat, sorghum, vegetables, and nuts.
  - This process is called a switch in “biological technology.”
In general, farmers *simultaneously* choose crop type, irrigation technology and applied water use levels to maximize profits, based on the levels of economic parameters such as land quality. **Modern technologies are more likely to be adopted in regions with:**

- Moderate to low quality land
- High value crops (fruits, nuts and vegetables)
- Low quality water
- High price water.

**What are some of the effects of technology adoption?**

Recall that profit maximization requires:

\[
\frac{W + Z_i}{h(i)} = P f_e
\]

Now assume for simplicity that \(z_0 = z_1\), (that is, pumping costs are the same) and recall from page 2 that \(f_e > 0\). This implies that:

\[
h(i=0) < h(i=1) \implies f_e(i=0) > f_e(i=1) \implies e_0 < e_1
\]

Thus, **modern technology increases the optimal level of effective water use.**

But note that a higher level of effective water use does not imply a higher level of applied water use. This is because the ratio \((a/e)\) is smaller with modern technology, so that greater effective water can be utilized with lower applied water.

In most cases, **modern technology REDUCES the optimal level of applied water use**, and is therefore water-saving.

**If** \(e_0 < e_1\), **then** \(q_0 < q_1\). Thus, **modern technology increases crop output.**
If (a) Land quality is high 
and (b) Water quality is high 
and (c) Weather is mild
Then \( h(i=1) \) and \( h(i=0) \) are not very different and the adoption of modern irrigation technology does not change the optimal levels of crop output or applied water use by very much.

If Either (a) land quality is low 
or (b) water quality is low 
or (c) weather is hot
Then adoption of modern irrigation technology may affect optimal crop output and applied water use significantly. When land quality is low and temperature is high, the effect of adopting new technology depends on water price:

<table>
<thead>
<tr>
<th>Water Price</th>
<th>Increase In Crop Output</th>
<th>Decrease In Applied Water Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low ($15/AF)</td>
<td>Minimal (0-5%)</td>
<td>High (30-40%)</td>
</tr>
<tr>
<td>Med ($15-$80/AF)</td>
<td>Medium (5-15%)</td>
<td>Medium (15-20%)</td>
</tr>
<tr>
<td>High ($80+/AF)</td>
<td>High (25-50%)</td>
<td>Low or negative (&lt;5%)</td>
</tr>
</tbody>
</table>

An Example of Technology Choice Under Markets:

Say an individual farmer is growing a crop, Y

- Crop Production Function: \( Y = 30e - 0.2e^2 \)
- The price of y is: \( P = $80/\text{ton} \)
- The price of water is: \( V = $400 / \text{A-F} \)
- \( \pi = PY - Va - F \), where \( a \) = the input ‘applied water’, and \( F \) = fixed costs

The farmer is trying to decide between two technologies:
- Sprinkler Irrigation is 50% efficient and costs $10,000 to install
- Drip Irrigation is 75% efficient and costs $20,000 to install

We first calculate profits under each system, then compare:

Under Sprinkler Irrigation:

\[
\underset{a}{\text{Max.}} \left\{ \pi^s = 80(30e - 0.2e^2) - 400a - 10,000 \right\}
\]

subject to: \( e = 0.5a \)
• substituting in the constraint relating effective water to applied water:

\[ \max_a \{ \pi^S = 800a - 4a^2 - 10,000 \} \]

• Foc:

\[ \frac{d\pi^S}{da} = 800 - 8a = 0 \]

which yields: \( a^* = 100 \) A-F.

• Substituting the value \( a^* \) into the profit expression we get:

\[ \pi^S = 800(100) - 4(100)^2 - 10,000 = 30,000 \]

Under Drip Irrigation:

\[ \max_a \{ \pi^D = 80(30e - 0.2e^2) - 400a - 20,000 \} \]

subject to: \( e = 0.75a \)

• substituting in the constraint relating effective water to applied water:

\[ \max_a \{ \pi^D = 1400a - 9a^2 - 20,000 \} \]

• Foc:

\[ \frac{d\pi^D}{da} = 1400 - 18a = 0 \]

which yields: \( a^* = 77.78 \) A-F.

• Substituting the value \( a^* \) into the profit expression we get:

\[ \pi^D = 800(77.78) - 4(77.78)^2 - 20,000 = 34,444 \]

Since \( \pi^D > \pi^S \), the farmer is better off investing in a drip irrigation system

Notice:

• Drip Irrigation Uses Less Applied Water: \( 77.78 < 100 \)

• Drip Irrigation Uses More Effective Water: \( 0.75(77.78) = 58.34 > 50 = 0.5(100) \)

• Output Per Acre is Higher Using Drip Irrigation: \( Y^D > Y^S \)
Comparing Irrigation Under Water Markets and Queuing Systems

Suppose land quality is given as \( q \).

Suppose also that we have two technologies denoted by \( i \in \{0, 1\} \), and

\[ h_i = \text{irrigation efficiency}, \]
\[ a_i = \text{applied water per acre}, \] and
\[ e_i = \text{effective water per acre}. \]

Total water available for all acreage in a watershed is \( A \).
Total acreage of productive agricultural land in the region is \( L \).

The production function is:

\[ y = f(e) \]
\[ e = ah_i \]

\( e = \) effective water per acre
\( a = \) applied water per acre
\( y_m = f(e_m) = \) maximum output per acre
\( e = e_m, \) effective water associated with maximum yield

\( \frac{d}{de} f(e_m) = 0. \)

Under a queuing system

Water trading is disallowed. There is no incentive to adopt modern technology, since there is no water price. Water is simply diverted, as needed, according to the queue.

- Senior rights owners use water until the VMP of water = 0, which is the level that will maximize yields.
- applied water use is \( a_m = \frac{e_m}{h_0} \) per acre, the amount of applied water associated with the maximum effective water absorbed by the crop
- Junior rights owners downstream use whatever water is left.

Under a queuing system of water rights:

- water price = 0
- per acre fee for water use = \( \mu \)

Total acres under a water rights system:

\[ \frac{A}{a_m} = \frac{Ah_0}{e_m} < L \]

Total output = \[ \frac{Ah_0 y_m}{e_m} \]
Output price = \( P \)
Producer surplus = \[ P \frac{Ah_0 y_m}{e_m} - \mu \frac{Ah_0}{e_m}. \]
Is the queuing system efficient?

Junior rights owners do not get enough water if scarcity exists.

• A unit of water would provide positive MVP on junior owners land
• The last unit of water on a senior owners land provides MVP = 0.

- Therefore, The Queuing System is Inefficient. \( \text{MVP}_J \neq \text{MVP}_S \)

The queuing system leads to under-utilization and over-irrigation of land.

• A market system may offer a better solution, depending on transaction costs.

The switch to a market system involves costs of \( t \) dollars per acre annually in transaction costs. They include improved piping and improved monitoring.

Under a Market System

When all land quality is the same, the efficient solution involves applying water uniformly across all land to equate the MVP. Thus, under a market system that all land is utilized and each owner faces the choice of technology \( i \).

• water per acre = \( \frac{A}{L} \)

• yield per acre = \( y_i = f \left( h_i \frac{A}{L} \right) \)

• price of water = VMP of applied water = \( Pf_i h_i \)

• \( k_i \) = the fixed cost of implementing the technology (\( k_1 > k_0 \))

The producers' annual profits per acre are:

\[ \pi_i = Py_i - \frac{A}{L} Pf_i h_i - k_i - \mu - t \]

so that:

\[ \pi_1 = Py_1 - \frac{A}{L} Pf_1 h_1 - k_1 - \mu - t \]

\[ \pi_0 = Py_0 - \frac{A}{L} Pf_0 h_0 - k_0 - \mu - t \]

\[ (\pi_1 - \pi_0) = P(y_1 - y_0) - \frac{A}{L} Pf_i(h_1 - h_0) - (k_1 - k_0) \]

Technology 1 is selected if:

\[ (\pi_1 - \pi_0) > 0 \]

Both technologies require the same water per acre, because water is evenly distributed across all acres as a result of equating the MVP. When each farmer is a small unit, the farmer does not believe that her choice of technology will affect the market price of water. When the market price of water is taken as a constant in the problem, the choice of technology can be expressed as:

Select technology 1 when: \( P(y_1 - y_0) > k_1 - k_0 \)
Both technologies result in the same water use per acre, but the modern technology increases the yield by raising the amount of effective water received by the crop.

If the market value of the increase in yield is greater than the extra capital costs involved with investing in the new technology, the farmer should invest.

Comparing Market and Queuing Outcomes

Assume that, under market conditions, technology $i$ is optimal and adopted by all farmers. Under a market system all arable land is utilized. The transition to market will increase irrigated land from

$$\frac{A}{e_m h_0}$$

to $L$.

Output will increase by:

$$\Delta Y = Lf\left(h_i \frac{A}{L}\right) - \frac{Ah_o}{e_m} f(e_m) > 0$$

as water is shifted from low MP land to the high MP lands of junior rights holders.

- Output per acre of senior rights owners will decrease, and
- water per acre of all users will decrease.

The reduction in output per acre is from $f(e_m)$ to $f(A/L e_i)$. The reduction in water use per acre is from $e_m h_0$ to $A/L$.

In the transition to the market, \( \left( e_m - h_i \frac{A}{L} \right) \frac{A}{h_0 e_m} \) units of water which were used to produce the output associated with area B in the figure are allocated to irrigate new lands. Overall, output is increasing because the water that was used under queuing to produce output associated with region B of the figure is used under markets to produce output in
region A on new land that is brought into production. Obviously, the marginal productivity of this water increases.

If the senior rights owners have to buy water under markets, they are losing from the transition. Under water markets, they now have lower yields, they now have to pay for water, and they also must pay to adopt the new technology, since doing so is now optimal. Their loss per acre is:

$$Pf (e_m) - Pf \left( h_i \frac{A}{L} \right) + Pf h_i \frac{A}{L} + k_i + u.$$  

But if the senior rights are given the property rights to the water, they may win. They still have lower output than under queuing, but the gain from selling excess water may overcome this output loss. Their income per acre will be:

$$Pf \left( h_i \frac{A}{L} \right) + (e_m - h_i \frac{A}{L}) Pf h_i \frac{A}{L} - t - k_i$$

If the transaction costs are high, there is no incentive to switch to a system of water markets. Namely, if:

$$t > \frac{P \Delta Y + k_i L - k_{o} A / (h_0 \cdot e_m)}{L}$$

When transaction costs per acre exceed the per acre change in output plus the cost of adopting the optimal modern technology less the cost savings of senior owners not adopting the conventional technology, water markets may be inefficient.

Because markets for final products have negatively sloped demand, the transition from queuing to markets will also reduce the market price of agricultural commodities. Senior rights owners may thus lose, even if they sell water because of the price decline of their output. Producers as a whole may actually lose, but consumer surplus will increase.
Numerical Example of Market vs. Queuing (based on a Study by Zilberman)

In this example we have:
- 4 technologies;
- 2 demand elasticities for output; and
- 2 transaction cost levels:

<table>
<thead>
<tr>
<th>Land Base (10³ acres)</th>
<th>Demand Elasticity</th>
<th>900</th>
<th>900</th>
<th>1050</th>
<th>1050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>50</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Queuing Outcomes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output (10⁶ lbs.)</td>
<td></td>
<td>936</td>
<td>936</td>
<td>936</td>
<td>936</td>
</tr>
<tr>
<td>Output Price ($/lb.)</td>
<td></td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Irrigated Land (10³ acres)</td>
<td></td>
<td>720</td>
<td>720</td>
<td>720</td>
<td>720</td>
</tr>
<tr>
<td>Producer Profits (10⁶ dollars)</td>
<td></td>
<td>342</td>
<td>342</td>
<td>342</td>
<td>342</td>
</tr>
<tr>
<td>Market Outcomes</td>
<td>Adjustment Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjustment Costs = $/acre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output (10⁶ lbs.)</td>
<td></td>
<td>1159</td>
<td>1161</td>
<td>1161</td>
<td>1344</td>
</tr>
<tr>
<td>Output Price ($/lb.)</td>
<td></td>
<td>0.572</td>
<td>0.746</td>
<td>0.57</td>
<td>0.744</td>
</tr>
<tr>
<td>Water Price ($/AF)</td>
<td></td>
<td>62.0</td>
<td>73.75</td>
<td>63.7</td>
<td>118.4</td>
</tr>
<tr>
<td>Irrigated Land (10³ acres)</td>
<td></td>
<td>900</td>
<td>900</td>
<td>902</td>
<td>1050</td>
</tr>
<tr>
<td>Technologies</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Senior Rights Net Profits (10⁶ dollars)</td>
<td></td>
<td>5.3</td>
<td>139</td>
<td>0</td>
<td>43.4</td>
</tr>
<tr>
<td>Senior Rights Gross Profits (10⁶ dollars)</td>
<td></td>
<td>191</td>
<td>361</td>
<td>191.1</td>
<td>398.5</td>
</tr>
<tr>
<td>Percent Gain in Social Welfare</td>
<td></td>
<td>5.4%</td>
<td>16.3%</td>
<td>5.4%</td>
<td>23.8%</td>
</tr>
<tr>
<td>Market Outcomes</td>
<td>Adjustment Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjustment Costs = $/acre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output (10⁶ lbs.)</td>
<td></td>
<td>1150</td>
<td>1160</td>
<td>1150</td>
<td>1342</td>
</tr>
<tr>
<td>Output Price ($/lb.)</td>
<td></td>
<td>0.579</td>
<td>0.746</td>
<td>0.579</td>
<td>0.744</td>
</tr>
<tr>
<td>Water Price ($/AF)</td>
<td></td>
<td>53.5</td>
<td>81.0</td>
<td>53.5</td>
<td>118.4</td>
</tr>
<tr>
<td>Irrigated Land (10³ acres)</td>
<td></td>
<td>890</td>
<td>900</td>
<td>890</td>
<td>1050</td>
</tr>
<tr>
<td>Technologies</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Senior Rights Net Profits (10⁶ dollars)</td>
<td></td>
<td>0</td>
<td>107</td>
<td>0</td>
<td>10.9</td>
</tr>
<tr>
<td>Senior Rights Gross Profits (10⁶ dollars)</td>
<td></td>
<td>160.7</td>
<td>328.2</td>
<td>160.7</td>
<td>366.1</td>
</tr>
<tr>
<td>Percent Gain in Social Welfare</td>
<td></td>
<td>-0.5%</td>
<td>4.6%</td>
<td>-0.5%</td>
<td>10.3%</td>
</tr>
</tbody>
</table>

The example shows:
(1) Under markets, acreage and output grow and output prices go down.
(2) If demand elasticity is low, the decline in output price may be substantial and producers may lose.

- **The percent gain in social welfare is highest in elastic demand markets**
(3) If transaction costs are high, the introduction of markets may not be worth while.
Figure 5.4
demonstrates gains in social welfare from transition to markets as a function of
total water. It assumes zero transaction costs. When 2.1 million AF are available, social
surplus increased by 130 million dollars (30%). There is no gain in welfare when total
water exceeds 3.8 million AF, because, at this point water scarcity is not a problem.

Figure 5.5
The Figures hold Social Welfare Constant

Figures 5.5 and 5.6 show the amounts of reduction in agricultural water that will keep welfare unchanged if industry moves from queuing to markets - as a function of output price and transaction cost.

- Outcomes in the region below the lines are welfare improving.

We can think of reductions in water as a result of increasing scarcity.

The demand functions for water can be derived according to the price of output and the available technology. The demand function has several steps and each is associated with a different technology.
Figure 5.7 shows that when urban demand is small (D1), gains from markets are not spectacular, and traditional technology is optimal since the MVP of water in alternate uses is small. When water demand is high (D2), however, introduction of markets will lead to adoption of modern technologies and will reduce agricultural water use substantially.

Today we have a transition from queuing to markets in other environmental amenities, including air quality.

Polluters have assumed they have pollution rights which were established "de facto" chronologically. Now, as air quality becomes scarce, they need pollution permits, and there is trading. Introduction of pollution trading will increase efficiency - if welfare gains from markets are sufficient to offset transaction costs.

**In general, there will be less objection to markets among users of scarce resources if existing users of the resource (senior rights holders or polluters) are given the right to sell permits.**
<table>
<thead>
<tr>
<th><strong>Comparison of Water Rights (Queuing) and Water Markets</strong>*</th>
<th><strong>Queuing</strong></th>
<th><strong>Market</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Allocation mechanism</strong></td>
<td>Uses are assigned by seniority. Trading is disallowed. No limit on consumption use</td>
<td>Water is traded at going price.</td>
</tr>
<tr>
<td><strong>Water pricing</strong></td>
<td>Fixed fee per acre ((u)). Zero price per acre feet.</td>
<td>Fixed fee per acre ((\eta)) determined by supply and demand ((W = pf^\prime h_1)).</td>
</tr>
<tr>
<td><strong>Water choice problem</strong></td>
<td>[ \max_{a,i} Pf(a_i h_i) - u - c_i ]</td>
<td>[ \max_{a,i} Pf(h_i q_i) - Wq_i - c_i - t - \mu ]</td>
</tr>
<tr>
<td><strong>Transaction costs</strong></td>
<td>0</td>
<td>(t) per acre</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>Traditional, (i = 0)</td>
<td>Modern may be adopted, (i &gt; 0), if (c_i - c_0 &lt; P(y_i - y_0) - W(a_i - a_0))</td>
</tr>
<tr>
<td><strong>Water per acre</strong></td>
<td>Maximizing yield per acre, (a = e_m).</td>
<td>Aggregate water/ag. land, (a = A/L)</td>
</tr>
<tr>
<td><strong>Output per acre</strong></td>
<td>(y = y_m)</td>
<td>(y = f\left(\frac{A}{L} \cdot h_i\right)) Smaller than under queuing</td>
</tr>
<tr>
<td><strong>Acreage</strong></td>
<td>Not fully utilized, (L_Q = A h_0 / e_m)</td>
<td>Fully utilized, (L_M = L)</td>
</tr>
<tr>
<td><strong>Aggregate output</strong></td>
<td>Smaller than under market, (Y_Q = \frac{A h_0}{e_m} y_m)</td>
<td>(Y_M = L f\left(\frac{A}{L} \cdot h_i\right))</td>
</tr>
<tr>
<td><strong>Output price</strong></td>
<td>(D(Y_Q)) Greater than market if demand is negatively sloped.</td>
<td>(D(Y_M))</td>
</tr>
<tr>
<td><strong>Social welfare</strong></td>
<td>Lower if transaction costs are not high.</td>
<td>Higher if transaction costs are sufficiently low:* [ t &gt; \frac{P \Delta Y + c_i L - c_0 (A h_0 / e_m)}{L} ]</td>
</tr>
</tbody>
</table>

---

*Under the limiting assumptions of the model presented in class. Namely, there is one land quality. Its irrigation efficiency under traditional technology is \(h_0\) and under the modern one is \(h_1\). Under the modern technology, there is a unique optimal solution. Aggregate land \(L\) and water \(A\) are given.
Income of senior rights owners under transferable rights.

\[
\frac{A h_0}{e_m} \left[ P f(e_m) - \mu \right]
\]

Income of senior rights owners when they do not retain water rights.

\[
\frac{A h_0}{e_m} \left[ P y_i - t - c_i \right] - u + W \left( \frac{e_m}{h_0} - a_i \right)
\]

Incomes under market are higher if demand is not very inelastic, and transaction costs are sufficiently low.

\[
\frac{A h_0}{e_m} \left[ P y_i - W a_i - t - c_i - u \right]
\]

lose from transition to market

\[a_i = \text{applied water}, \; e = \text{effective water}, \; c_i = \text{per acre cost of technology} \; i, \; \text{and} \; t = \text{transaction cost}.
\]

\[\dagger \text{Assuming that the modern technology is adopted.}\]
Queuing Vs. Markets: A Numerical Example

Say the farm production function is: \( y = 8e - 2e^2 \)

There are two technologies available:
- The traditional technology has a 50% water efficiency: \( h_0 = 0.5 \)
- The modern technology has a 60% water efficiency: \( h_1 = 0.6 \)

Suppose for two technologies: \( P = 125, \mu = 100, t = 50. \)

Total water stock is, \( A = 6000 \text{ A-F}, \)

Total land stock, \( L = 2000. \)

**Queuing Outcome:**

- Technology 0 is chosen.
- Senior water rights holders maximize yield:

  \[ \begin{align*}
  \max_e \{ y = 8e - 2e^2 \}
  \end{align*} \]

  which has the FOC:

  \[ \frac{f_y}{f_e} = 8 - 4e = 0 \]

  implying that: \( e_m = 2, y_m = 8. \)

- Water applied per acre is: \( a_m = \frac{e_m}{h_0} = \frac{2}{0.5} = 4. \)

- Acreage utilized simply depends on how far down the river the water flows:

  \[ A_Q = \frac{6000}{4} = 1500. \]

- Aggregate output: \( Y_Q = y_m(A_Q) = 8(1500) = 12,000. \)

- Income per acre: \( \pi_Q = 8(125) - 100 = $900. \)

- Total Farm Income = (1,500 acres)($900/acre) = $1,375,000.

**Market Outcome:**

**First consider the case when only the traditional technology is available.**

- Declining MVP of water and homogeneous land quality implies it is optimal to distribute water evenly across all land...
applied water per acre: \( a = \frac{6000}{2000} = 3 \)

• Effective water: \( e^* = 3(0.5) = 1.5 \)

• Output per acre: \( y^* = 8(1.5) - 2(1.5)^2 = 7.5 \)

• Aggregate Output: \( Y_M = 2000 \cdot 7.5 = 15000 \).

(Yield per acre is smaller than under queuing but total output is greater.)

• Total income:

\[
2000[7.5 \cdot 125 - 100 - 50] = 1575000
\]

• Water price = VMP =

\[
p \frac{\partial f}{\partial e} h_0 = 125(8 - 4 \cdot 1.5) \cdot .5 = 125.
\]

Say Senior rights owners are given the right to sell surplus water:

• Senior rights owner owns 4 A-F of water foot per acre, uses 3 A-F under a system of water markets and sells the remaining A-F for $125:

\[
\pi^* = 125(7.5) - 100 - 50 + I(125) = 912.50
\]

The senior rights owner makes greater profit than under a queuing system.

• Junior rights owners' profit per acre is:

\[
\pi^* = 125(7.5) - 100 - 50 - 3(125) = 537.50
\]

- The junior rights owner earns zero profit under a queuing system.

Now consider the case when the traditional technology is available

If modern technology is available, it will be adopted because of extra output it generates, provided the fixed costs of adopting it are sufficiently small.

• Effective water: \( a = \frac{e}{h_1} \Rightarrow 3 = \frac{e^*}{0.6} \Rightarrow e^* = 18 \)

• Output per acre: \( y^* = 8(18) - 2(18)^2 = 792 \)

• Aggregate output under market: \( Y^* = (2,000 \text{ acres})(7.92/\text{acre}) = 15,840 \)

• Total income:

\[
1500(7.92 \cdot 125 - 100 - 50 - 30) = 1620000
\]
• Water price = \( p = \frac{\partial f}{\partial e} \)  
  \[ h = 125[8 - 4(1.8)] \cdot 0.6 = 125 \cdot 0.8 \cdot 0.6 = 60. \]

Assuming, as before, that Senior rights owners are allowed to sell their surplus water:

• Senior rights owners' income = 
  \[ 792 \cdot (125 - 100 - 50 - 30 + 60) = 870 \]

• Junior rights owners' income = 
  \[ 7.92 \cdot 125 - 100 - 50 - 30 - 180 = 630. \]

Implications:

1) Establishing water markets is welfare improving.

2) The adoption of modern technology is in the best interest of society.
   • total farm income is higher when farmers adopt new technology.

3) Adopting modern technology is in the interest of junior rights holders

4) Adopting modern technology is not in the interest of senior rights holders
   • senior rights owners profit from a market system, but only when modern technology is not adopted.

Now Say the Government Appropriates the Water Rights

If the government is given the water rights, then both senior and junior rights holders must purchase water. The water price is still \( P = VMP \) in either case.

Profit per acre is now the same for the both senior and junior rights holders, which is what we already calculated for junior rights holders above. Therefore, it is now in the best interest of senior rights holders to invest in the new technology.

• Although the allocation of property rights achieves the same result in terms of allocative efficiency: \( P = MVP = \text{marginal profit per acre} \)
  - (an application of the Coase Theorem)

• Different incentives are created for technology investment