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Groundwater, Water Logging, Drainage and Water Quality

Groundwater can be viewed as both an exhaustible resource and as a renewable resource:

Groundwater as an exhaustible resource

Aquifer that is not being replenished.

Examples: (a) Groundwater aquifers in deserts.

(b) Fossil water (water trapped in prehistoric periods).

- Ogalalla in Western Kansas, Ok, Texas a fossil source

Relevant Economic Factors

Pumping Costs

CP = pumping cost per unit of water

$CP = h_i U_i d$

U_i = unit price of energy service (fuel, electricity)

h_i = energy source requirement per unit of lift

d = well depth.

Example: The case of electric pump.

Energy lift requirement = 1.4 kwh per A-F per foot

Energy price = 15 cents per kwh

Energy lift cost = 21 cents per acre-foot per foot

Well depth = 100 feet

Pumping cost = $21 per acre-foot

Pumping cost depends on well depth, energy price, pump fuel efficiency.

Increase in energy price:

(1) Reduces pumping with existing equipment.

(2) May lead to modernization of pumps.

(3) Likely to reduce groundwater demand.

(4) Will lead to adoption of modern technologies.

Public vs. Private Conflicts in Groundwater Use

Conflicts in groundwater use arise when individual pumps are not regulated or metered. In this case, no one knows for certain how much other people are pumping, but can only observe the change in the groundwater table. As with other open access resource problems, when use of the aquifer is not regulated, the groundwater is overdrawn.

SW = social cost of groundwater pumping

$SW = CP + CS + CE$

CP = pumping cost

CS = user cost (cost of exhaustibility of the water stock; shadow price of the resource stock constraint)

CE = open access cost associated with common pool problem (increased cost of pumping associated with reduction in water level as stock is depleted).

The user cost increases as:

(1) Interest rate is lower.

(2) Water stock is smaller.

(3) Alternative water sources are costlier at present or future.

Open access costs are likely to increase as the area of aquifers is smaller and lift costs are larger.

Inefficient resource use may occur when:

(1) Water users are myopic or their interest rate is larger than the social rate.

(2) There are many resource users.

Manifestation of inefficiency:

In the short run:

(1) Over-drafting

(2) Under-use of conservation technologies

(3) Overproduction of water-intensive crops.

In the long run:

(1) Water shortages and earlier depletion of resources.

Corrective Policies:

The optimal policy is a water tax or a pumping quota. However, water use is difficult to monitor, and enforcement of these policies is difficult. Alternative policies include:

- Tax based on crop and technology choices.
- Regulation restricting crop/technology choices.
- Subsidy of conservation technologies.
- Limitations on pumping capacity per acre.

Groundwater as a Renewable Resource

Rain and deep percolation can renew the groundwater stock.

The model:

The equation of motion for the groundwater stock is:

$$S_{t+1} = S_t - X_t + \delta X_t + R_t$$

where

S_{t+1} = water stock at period $t+1$

X_t = pumping in the previous period

δ = deep percolation of water pumped onto field

R_t = replenishment by rain.

In the long run average water pumping has to be equal to average rainfall in order to sustain optimal water stocks. Actual water use may vary from year to year to reflect:

(1) Variation in water conditions and

(2) Variation in output price.

Every steady-state level of the state variable, S, is associated with a different groundwater table, which will influence the choice of the optimal well depth. Determining of optimal, sustainable, average well depth involves assessing the:

(1) Risk of prolonged droughts (which is used to set lower bounds).

(2) Increase in average pumping cost as average depth increases.

(3) Benefits from mining excessive water un-sustainably in early periods in order to reach the average sustainable well depth.

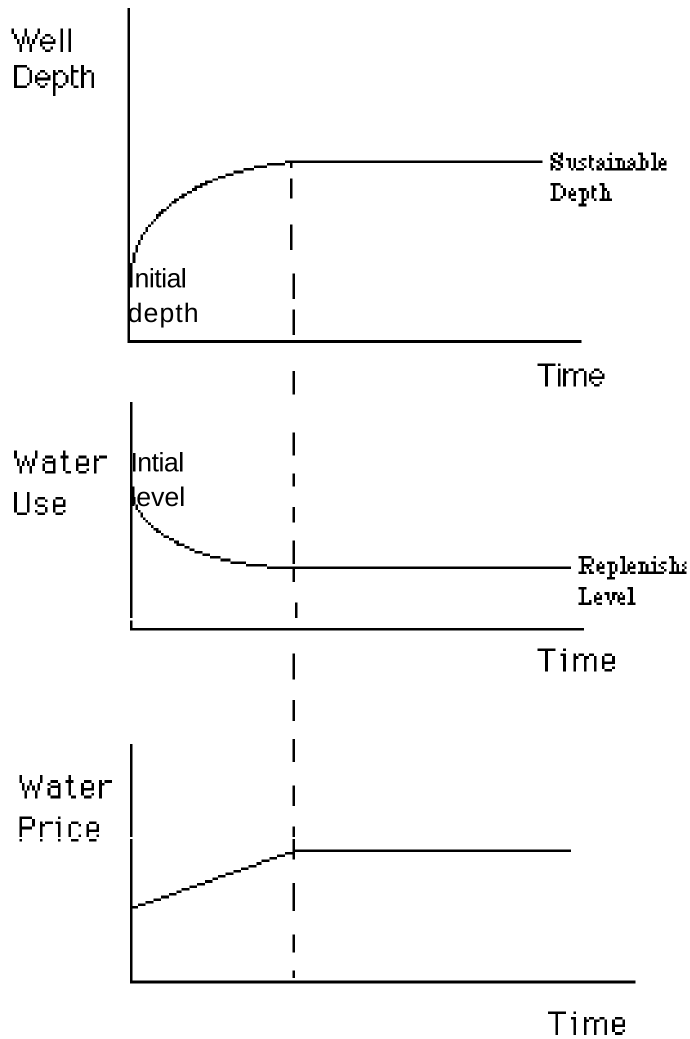
The theory of renewable resources suggests that when (1) water is replenished, and (2) optimal sustainable depth is lower than the initial water table, the optimal water pumping strategy consists of two phases:

(i) Mining of excessive stock until sustainable depth is reached; and then
(ii) Pumping of water at the rate of replenishment (R_t) for the remainder of time.

Modeling Problems

(1) Deep percolation may lead to reduction of water quality due to leaching of nitrates, phosphates and pesticides.
(2) There is a time lag between rain and water use and replenishment.
(3) Rain is randomly distributed.

Figure 15.1



Other Issues:

A problem with any steady-state harvest of groundwater is that the stock of groundwater is stochastic due to natural variability in rainfall.

- Cyclical variability needs to be considered as well

If a system has a high degree of variability, the system has the potential to collapse (that is, send groundwater stock to zero)

- Underneath Pheonix, Az. Is an elaborate system of irrigation canals built by the Anasazi Indians.
    - the irrigation technology used was nearly identical to that used today
    - about 500 years ago, a severe drought caused a collapse of this Indian Civilization

Several other issues involved in the type of model outlined above can best be seen by looking at a few examples of surface water management.

A few decades ago, water in the Colorado River was divided up for use in 6 Western States; Wyoming, Utah, Colorado, Arizona, Nevada, New Mexico, and California.

- Water used for agriculture in California is more productive than water used in other states such as Wyoming, due to favorable soil and climate characteristics.

- When we solve for the optimal well depth, we implicitly assume that all farms are the same, even though water uses over a groundwater source will vary greatly based on cropping patterns, and irrigation technology.

- Farms with inefficient irrigation technologies and/or farms that grow water-intensive crops will have a different optimal well-depth than those with efficient irrigation technologies and grow crops that are not water-intensive.

A few decades ago, the Mississippi River Basin was dredged by the conservation corps., then in 1994 there was a huge flood. This raises questions such as:

- Should the government build a levy to protect farmland from flooding?
- Or should these lands be allowed to revert back to wetlands?
  - This choice generates 2 types of ecology.
- Similarly, alternative management practices for groundwater can affect ecology.

Conjunctive Use

Definition: The simultaneous use of groundwater and surface water.

The economic implication of conjunctive water use is similar to the idea of using strategic oil reserves to dampen the volatility of oil prices.

- When oil is cheap, we build up reserves

- If oil becomes expensive (such as when an oil embargo occurs), we use reserves

Similarly, we also need to maintain a certain capacity of water to provide agricultural output, serve urban and residential water consumption, and to satisfy recreational and environmental uses, such as waterfowl preservation.

A Model of Conjunctive Use:

Say there are three types of events occurring with equal probability:

W - Wet Seasons

N - Normal Seasons

D - Dry Seasons

S = the level of surface water = a with probability 1/3

$2a$ with probability 1/3

$3a$ with probability 1/3.

Assume water stock is infinite

Cost of surface water: m\$/AF

Cost of groundwater: n\$/AF

$m < n$

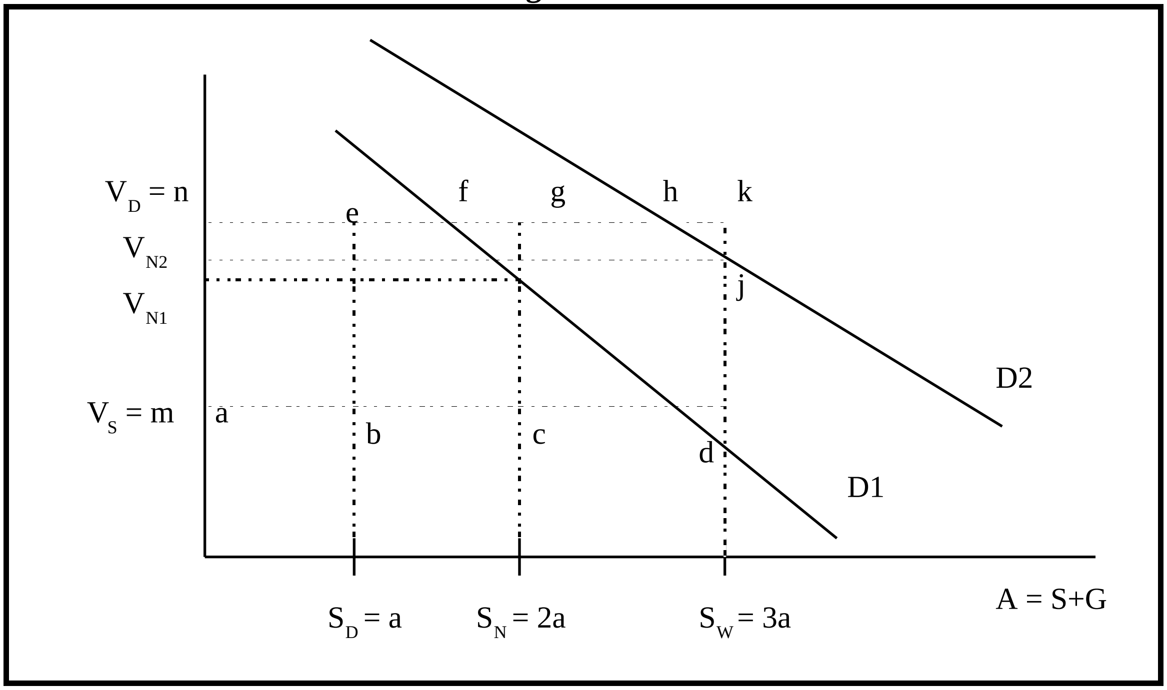
Let: $B(A)$ be the benefit from water and applied water be denoted by:

$$A = S + G$$

where: S = amount of surface water applied,

G = amount of groundwater applied.

Figure 15.2



The idea of conjunctive use is to combine the management of surface and groundwater using groundwater supplies as storage. Total water available is the sum of groundwater and surface water, but surface water is used first (because it is cheaper) and groundwater reserves are used only to stabilize variability in the annual supply of surface water.

The optimal water use strategy can be found by solving:

$$\max_{\substack{S_D, G_D, S_N \\ G_N, S_W, G_W}} \frac{1}{3}\{B(S_D + G_D) + B(S_N + G_N) + B(S_W + G_W)\} - m(S_D + S_N + S_W) - n(G_N + G_D + G_W)\}$$

where the FOCs for a dry year are:

(1) $$\frac{dL}{dS_D} = \frac{1}{3}B_{S_D} - m = 0$$

(2) $$\frac{dL}{dG_D} = \frac{1}{3}B_{G_D} - n = 0,$$ and similar for wet and normal years.

When surface water and groundwater are of homogeneous quality, $B_{G_D} = B_{S_D}$, and we can combine the two equations to get m = n, which is a contradiction, because we know that: m < n. The implication is that we **do not have an interior solution to L**; instead, we have a **corner solution**. That is, it cannot be optimal to use both surface and groundwater at the same time when both sources are available. In fact, the optimal solution is to use all surface water first, since it is the cheaper source, and then use groundwater only when we run out of surface water.

Say that aggregate demand for water is D_1.

The optimal choices (when benefits are based on Demand = D_1) are:

Year	Groundwater	Surface Water	Water Price
Dry	*ef*	*ab*	$V_D = n$
Normal	0	*ac*	V_{N1}
Wet	0	*ad*	$V_S = m$

If demand is D_2,

The optimal choices (when benefits are based on Demand = D_2) are:

Year	Groundwater	Surface Water	Water Price
Dry	*eh*	*ab*	$V_D = n$
Normal	*gh*	*ac*	$V_D = n$
Wet	0	*aj*	V_{N2}

If groundwater price declines with stock, and stock can be adjusted, there will be a steady state where groundwater is used in dry years; where excess water is added in wet years, so that the average groundwater level is stabilized at the desirable steady-state level.

Note that the price of groundwater will be determined by the appropriate steady-state solution. If demand is high, such as at level D2, groundwater is used in 2 out of 3 of the possible seasons at an annual average level of:

$$\frac{eh + gh}{2}$$

The other 33% of the time, in wet years, the rate of groundwater replenishment is only at level *hk* (the surface water not used in a wet season). Therefore, the optimal solution will be to deplete the stock of groundwater in early years, which pushes up the price of groundwater, say to n', and lowers the use of groundwater in all seasons until a new steady-state is achieved.

Groundwater contamination and water quality

Good water quality is a necessary feature of a healthy environment. Poor quality drinking water can lead to adverse health effects in humans, animals, birds and fish.

- Water Quality is typically measured in "% of junk per volume"

Water quality is adversely effected by inputs of both urban and agricultural waste. A good way to improve water quality in natural environments is to increase the flow of water, since this will tend to dilute pollutant concentrations.

There are 2 criteria that go into determining the level of fresh water that flows into the environment:

(1) **Legal Action**: the Clean Water Act and Endangered Species Act each have provisions which allocate a portion of water to environmental uses.

- An example is the recent action taken to preserve water quality problems in the San Francisco Bay - Delta region. A few years ago, California had a severe drought so that the Sacramento River had a lower natural flow *and* farmers diverted greater amounts of water for irrigation. As a result, runs of Chinook Salmon and Delta Smelt were extremely small. The Delta Smelt is an endangered species.
  - In 1992, G. Bush mandated a minimum flow requirement for Sacramento River water between the Delta and Sacramento Bay to improve freshwater habitat.

(2) **Economic Action**: When a certain quantity of water is removed from production, either Urban or Agricultural uses, the effect of additional scarcity is to raise water prices.

- Since water is heavily subsidized, moving to a market system can have the same effect as legal action by raising water prices to lower water use.
  - However, environmental uses of water provide many public goods.
- Because water quality has many features of a public good, water markets may not encourage water users to maintain large enough environmental stocks.
- Even a water market system may require farm subsidies to encourage lower water use in agriculture.
  - This can perhaps be done with cross-subsidization with revenue from fishing and hunting licenses or with other forms of recreation taxes.
- Note that reducing agricultural uses (which may occur through adoption of modern technologies and yield increases) has a dual effect on water quality.
  - lower agricultural use implies more surplus water for environmental uses
  - lower agricultural use implies less runoff of nitrates and phosphates.

Major Water Quality Problems:

Agricultural Runoff
Water logging

Waterlogging occurs when agricultural land is located over underground layers of material that are impenetrable to water (such as heavy clay) and which impede natural percolation of water and leads, over time, to rising groundwater levels

Waterlogging and the runoff of nitrates and phosphates from farmland are examples of externalities and are thus problems of market failure that may require government intervention. Analyses of policies to correct water contamination should consider:

(1) Heterogeneity of producers.

(2) Multiplicity of policy objectives:
- efficiency
- equity
- solvency
- environmental quality

(3) Multiplicity of policy tools
- taxes
- standards
- education
- R&D.

(4) Uncertainty about behavior and physical phenomena.

(5) Dynamic elements of the problem

Runoff Problems

Example 1: Kansas Dairy Producers:
(animal waste from dairy production contaminates surface and groundwater)

Policy Alternatives:
(1) Limit cows/acre to meet overall targets on per acre waste.
(2) Tax waste/acre.
(3) Tax on milk or tax on Fed Cattle

*Example 2***:** Water Quality Standards in the Blue River.

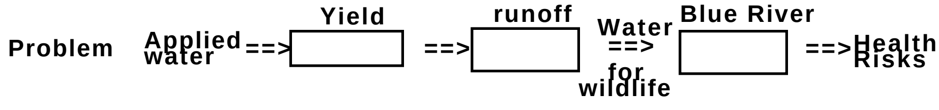
Management Challenges:
- phosphate contamination occurs at many nonpoint sources
- Randomness of weather => variability in nitrate concentration

Say:

S = standard limiting phosphates/gallon in the Blue River

α = percent of time S is met, due to random weather fluctuations.

$C(S, \alpha)$ cost of compliance
- where, in this case: $C_S > 0$ $C_\alpha > 0$.



Policy alternatives:
(1) reduce agricultural runoff by improving irrigation efficiency and
(2) remove phosphates from the water with cleanup facilities, evaporation ponds.

Policy impacts depend on interest rates and output prices in the national market:

- Low prices — Kansas producers will exit the market

- High prices, Low Interest — Kansas farmers use drip irrigation
  — cleanup facilities can be built.
  (future benefits higher relative to the investment today when r is small)

- High prices, High interest — Kansas farmers use drip irrigation
  — build evaporation ponds
  (future benefits lower make smaller clean-up investments optimal)

Water Logging

Waterlogging impedes agricultural productivity by creating wetlands and swamps.

- Water logging is responsible to the demise of Mesopotamian agriculture.

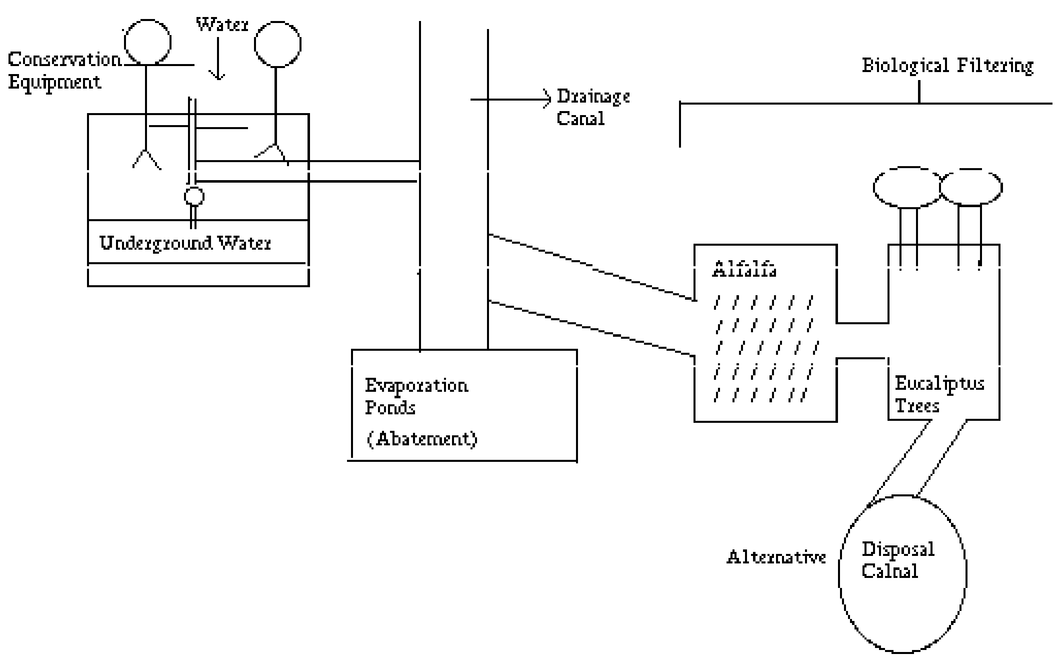
Solutions:

(1) A drainage system consisting of underground tiles leading to drainage canals.

- A drainage canal which is parallel to the Nile River is responsible for the sustainable production in Egypt for 4,000 years.

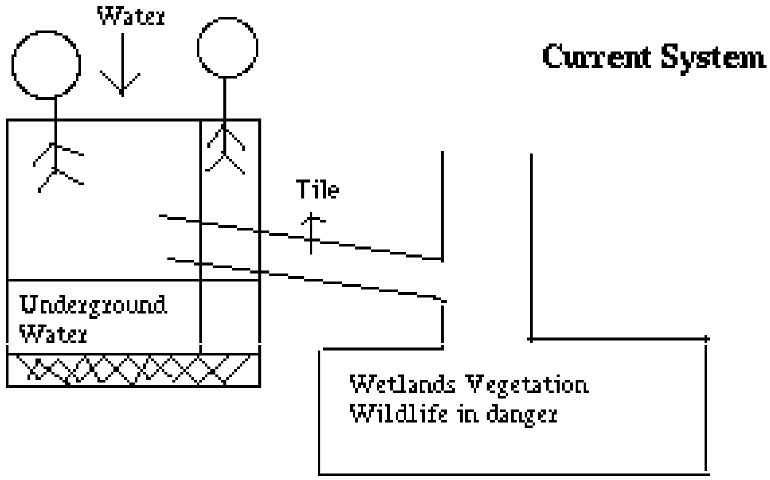
(2) Water Conservation practices at the farm level

Figure 15.3



Example: Problems in the Kestersen Reservoir (in California)

Figure 15.4



Water logging in the Central Valley was mitigated by installing tiles

- Tile Water led to drainage canals.
- The canal eroded at the Kestersen Reservoir where wildlife (ducks) roamed.

Water containing selenium, which accumulated in vegetation, harmed ducks and waterfowl at Kesterson Reservoir. The government disallowed further disposal of selenium-contaminated water at Kestersen

Alternative Solutions:

(1) Longer disposal canals ending at
   (a) San Francisco Bay (unlikely because of environmental side effects on the Bay ecosystem)
   (b) Monterey Bay (too long, too costly)

(2) Source reduction—reduction of deep percolation.
   (a) Change crops
   (b) Adopt irrigation technologies

   This solution could be induced by
   (i) taxation of drainage, and by
   (ii) subsidies to conservation.

(3) Abatement by evaporation ponds

(4) Reuse of water by pumping tile water back onto fields (for a limited time)

(5) Biological filtering—Alfalfa or Eucalyptus trees to absorb selenium
   - Biological filtering using wetlands is used in many areas to treat water from urban sewage.