

# Groundwater

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

## **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.

### *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.

## Groundwater as an Exhaustible Resource (cont.)

### Public vs. Private Conflicts in Groundwater Use

Conflicts arise when individual pumps are not regulated or metered:  
open access => over-extraction

$SW$  = 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:

- Interest rate is lower.
- Water stock is smaller.
- Alternative water sources are costlier at present or future.

Open access costs increase as:

- the area of aquifers is smaller and lift costs are larger.

Inefficient resource use may occur when:

- Water users are myopic or their interest rate is larger than the social rate.
- There are many resource users.

### Corrective Policies:

- 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:

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

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

$X_t$  = pumping in the previous period

= 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:

- Variation in water conditions and
- Variation in output price.

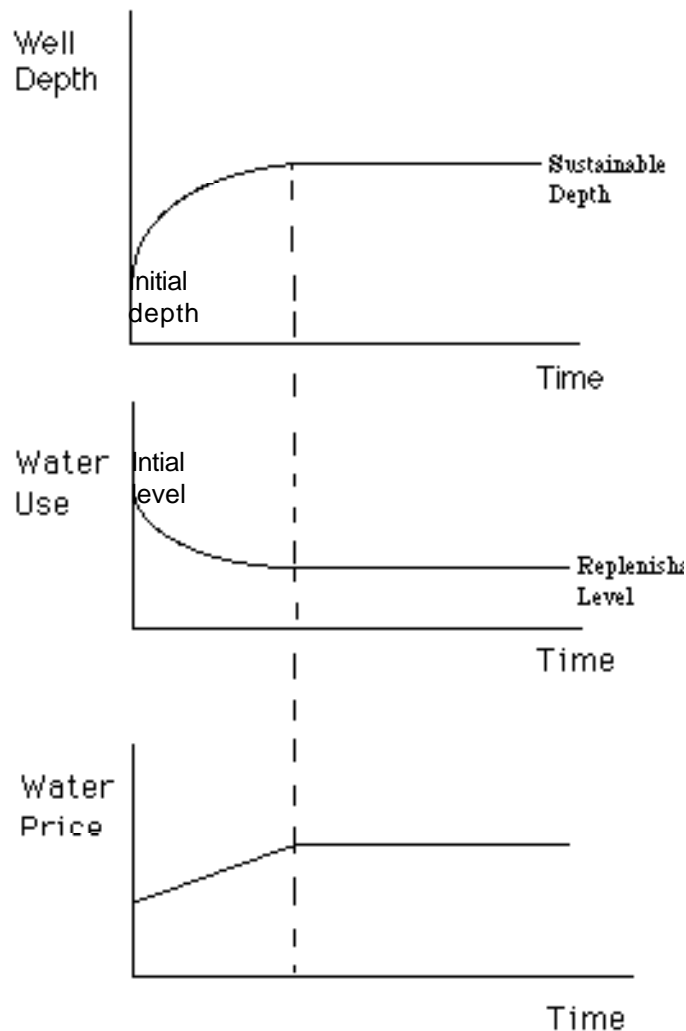
Every steady-state level of the state variable,  $S$ , is associated with a different groundwater table, which will influence the choice of the optimal well depth. Determining of optimal, sustainable, average well depth involves assessing the:

- Risk of prolonged droughts (which is used to set lower bounds).
- Increase in average pumping cost as average depth increases.
- Benefits from mining excessive water un-sustainably in early periods in order to reach the average sustainable well depth.

## Groundwater as a Renewable Resource (cont)

The theory of renewable resources suggests that when water is replenished, and 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.



## **Groundwater as a Renewable Resource (cont)**

### **Modeling Problems**

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

### **Other Issues:**

the stock of groundwater is stochastic due to natural variability in rainfall.

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.

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?

## Conjunctive Use

*Definition:* The simultaneous use of groundwater and surface water.

### A Model of Conjunctive Use:

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:  $n\$/AF$

$m < n$

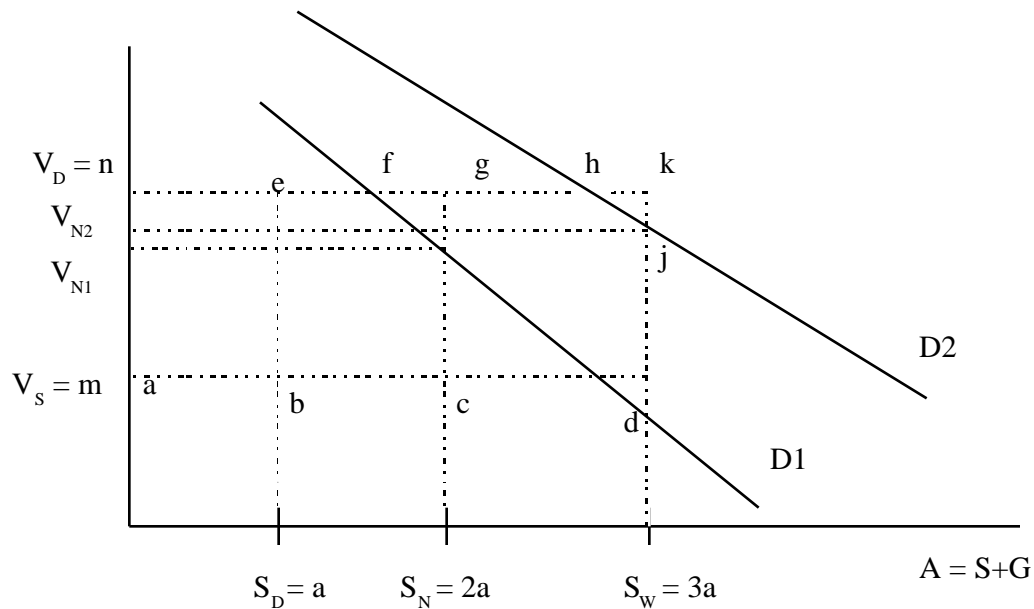
Let:  $B(A)$  be the benefit from water and applied water be denoted by:

$$A = S + G$$

$S$  = amount of surface water applied,

$G$  = amount of groundwater applied.

## Conjunctive Use (cont)



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:

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

where the FOCs for a dry year are:

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

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

## Conjunctive Use (cont)

When surface water and groundwater are of homogeneous quality, it is not optimal to use both surface and groundwater at the same time. => use all surface water first, since it is the cheaper source, and then use groundwater only when we run out of surface water.

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

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

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

<u>Year</u>	<u>Groundwater</u>	<u>Surface Water</u>	<u>Water Price</u>
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 avg. groundwater level is stabilized at the desirable steady-state level.

the price of groundwater is determined by the appropriate steady-state solution. If demand is high ( $D_2$ ), 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).



## Groundwater contamination and water quality

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 determine fresh water flows:

- (1) **Legal Action:** the Clean Water Act and Endangered Species Act each have provisions which allocate a portion of water to environmental uses.
- (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.
  - Because water quality has many features of a public good, water markets may not encourage water users to maintain large enough environmental stocks.
  - 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:**

**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.

### **Runoff Problems**

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

Policy Alternatives:

- Limit cows/acre to meet overall targets on per acre waste.
- Tax waste/acre.
- 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

Policy alternatives:

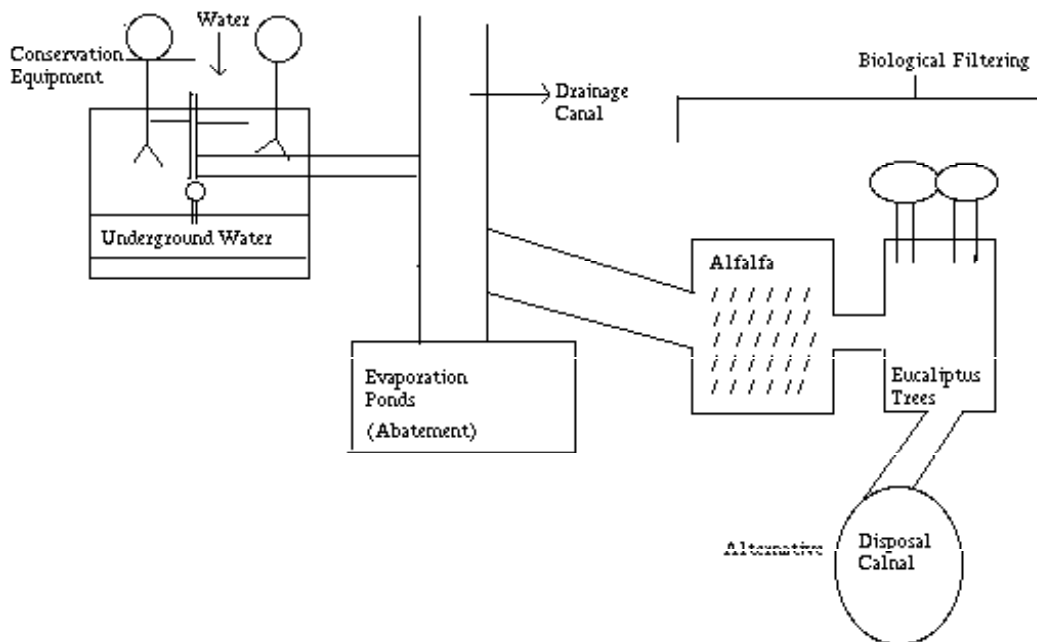
- reduce ag. runoff by improving irrigation efficiency and
- remove phosphates from the water with cleanup facilities, evaporation ponds.

# Water Logging

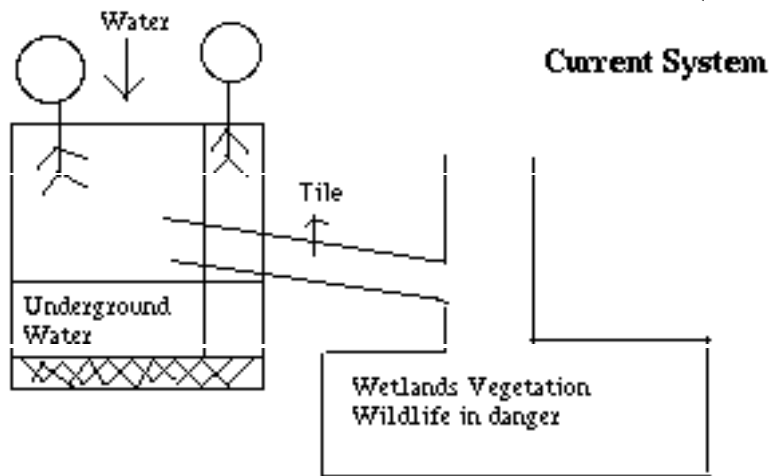
Waterlogging impedes agricultural productivity by creating wetlands and swamps.

## Solutions:

- A drainage system consisting of underground tiles leading to drainage canals.
- Water Conservation practices at the farm level



## Example: Problems in the Kesterson Reservoir (in California)



Water logging in Central Valley was mitigated by installing tiles

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

Water containing selenium, which accumulated in vegetation, harmed ducks and waterfowl at Kesterson Reservoir.

Policy Solutions:

- Longer disposal canals ending at
  - (a) San Francisco Bay (environmental side effects)
  - (b) Monterey Bay (too long, too costly)
- Source reduction—reduction of deep percolation.
  - (a) Change crops
  - (b) Adopt irrigation technologies, by way of
    - (i) taxation of drainage, and by
    - (ii) subsidies to conservation.
- Abatement by evaporation ponds
- Reuse of water by pumping tile water back onto fields (for a limited time)
- Biological filtering—Alfalfa or Eucalyptus trees to absorb selenium