1st Teaching Workshop on Environmental Economics

for the Middle East and North Africa

December 5-16, 2005 - ICTP, Trieste, Italy

Irrigation Water Pricing

Lecture I.2

Yacov Tsur

The Hebrew University of Jerusalem

SMR 1684 - 2

A primer on irrigation economics

- Demand
  - Single producer, single crop
  - Single producer, many crops
  - Many producers, many crops
- Supply
  - Fixed, variable and total costs
  - Average and marginal costs
- Efficient Pricing
  - Marginal cost pricing
  - Marginal and average cost pricing
  - Block rate pricing

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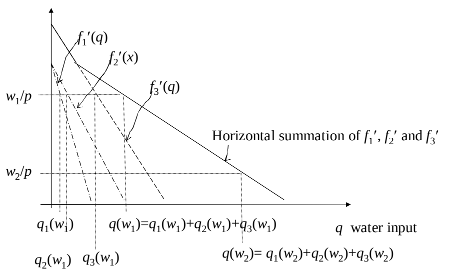
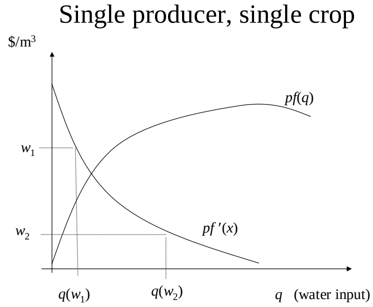
Single producer, many crops



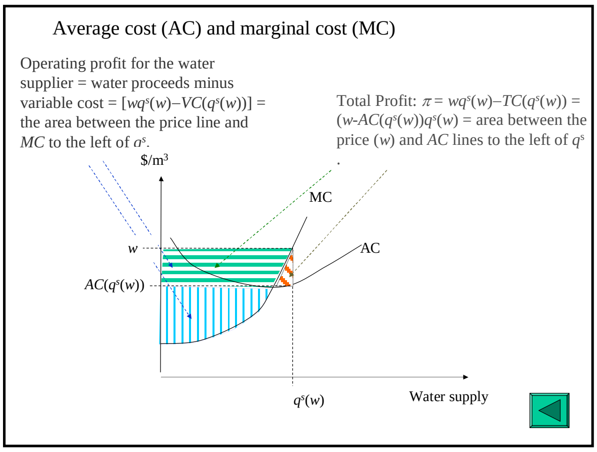
$f_j'(q)$ = marginal water productivity for crop j

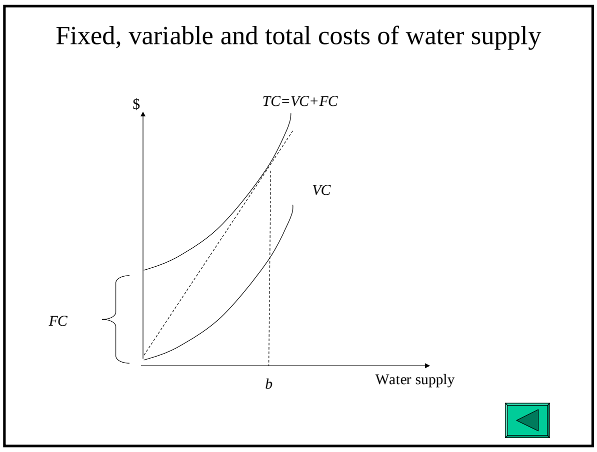
The inverse water demand for all crops is the horizontal summation of the inverse individual crop demands

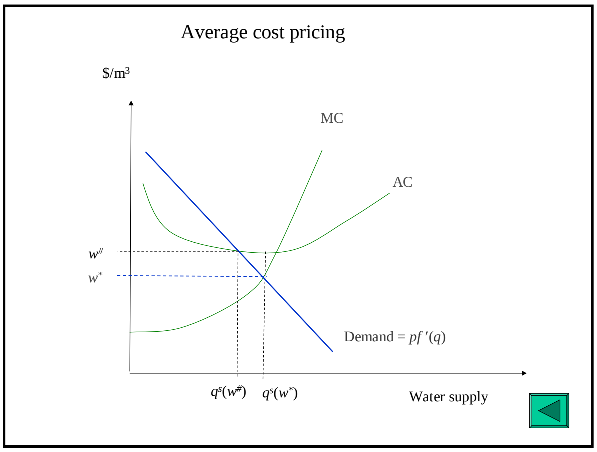
Single producer, single crop

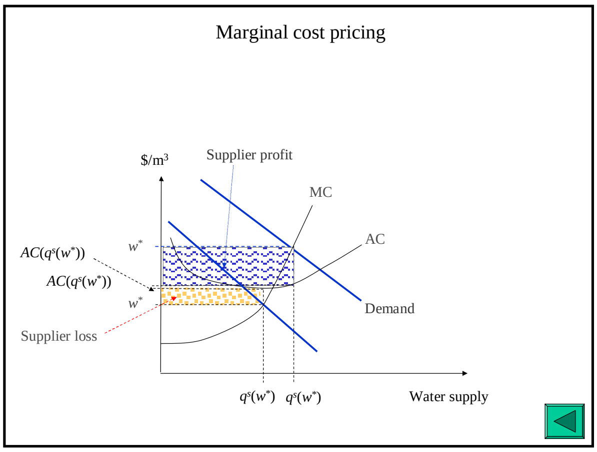


$f(q)$ is water production function; $f'(q) \equiv \partial f/\partial q$ = marginal water productivity; $pf(q)$ is revenue ($); $pf'(q)$ is vmp of water ($/m^3); p is output price; w is water price.

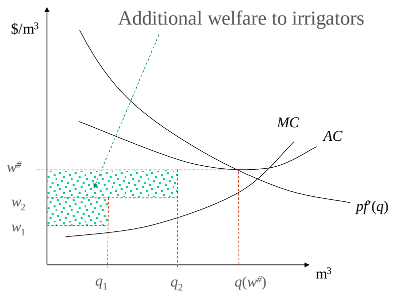

Average cost (AC) and marginal cost (MC)
Operating profit for the water supplier = water proceeds minus variable cost = [wq^s(w)–VC(q^s(w))] = the area between the price line and MC to the left of q^s.
Total Profit: π = wq^s(w)–TC(q^s(w)) = (w-AC(q^s(w))q^s(w) = area between the price (w) and AC lines to the left of q^s
$/m³
MC
AC
w
AC(q^s(w))
q^s(w)
Water supply


Fixed, variable and total costs of water supply
$
TC=VC+FC
VC
FC
b
Water supply


Average cost pricing
$/m³
MC
AC
w#
w*
Demand = pf ′(q)
q^s(w#)
q^s(w*)
Water supply


Marginal cost pricing
$/m³
Supplier profit
MC
AC
AC(q^s(w*))
AC(q^s(w*))
w*
w*
Demand
Supplier loss
q^s(w*)
q^s(w*)
Water supply

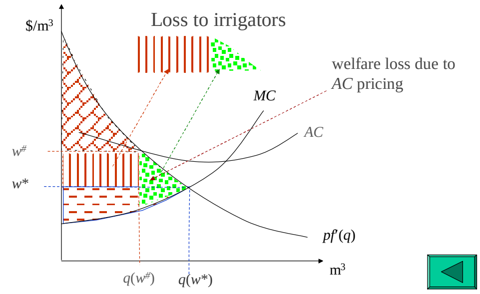
Block rate pricing



Marginal and average cost pricing

$\{q(w^*),w^*\}$ and $\{q(w^\#),w^\#\}$ are the allocations under *MC* and *AC* pricing, resp.

The joint surplus under *MC* pricing is the entire marked area, whereas under *AC* pricing it is the red area.



Empirical analysis

Two main approaches to obtain the derived demand for irrigation water:

- ►Econometric
- ►Programming

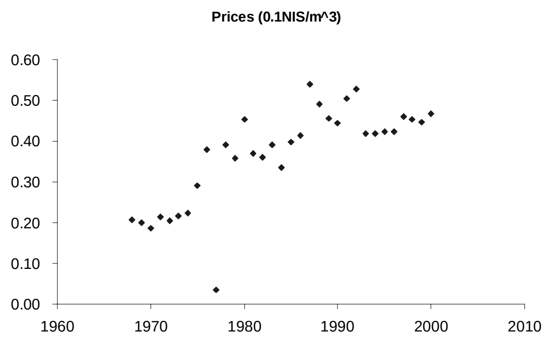
Guidelines:

❑ **1.** *Marginal cost pricing* is efficient - maximizes the joint surplus of water users (farmers) and water suppliers

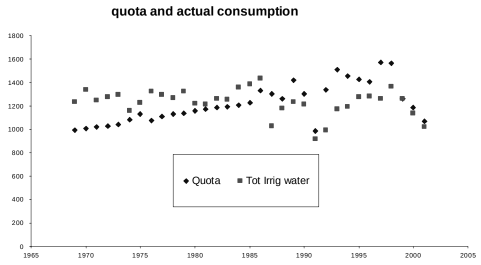
❑ 2. *Average cost pricing* balances the water supply budget but entails a loss in efficiency. The farmers carry the burden of the welfare loss.

❑ **3.** *Block-rate pricing* can retain efficiency while transferring wealth between water users and water suppliers.

Irrigation water price data



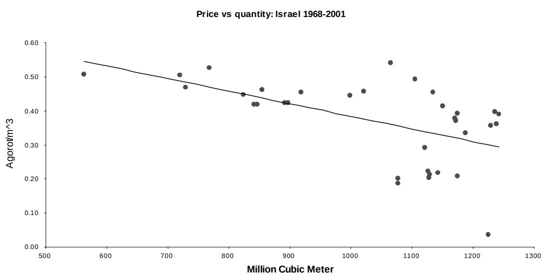
Econometrics: Data:



Problems with the econometric approach:

- ➢Price – Quantity data are rare (require volumetric pricing, which is used in only 25 % of irrigated land worldwide)
- ➢When *P-Q* data are available, price variation is typically small ➔ inaccurate estimation (large variance)
- ➢Watch out for quota restrictions (disequilibrium)

Price - quantity



Special case: LP

π_j = crop j profit per hectare, j = 1,2,…,n (calculated from data)

L_j = crop j land allocation (decision variable)

Max $\pi = L_1\pi_1 + L_2\pi_2 + \ldots + L_n\,\pi_n$

Subject to — Shadow Prices

$a_{11}L_1 + a_{12}L_2 + \ldots + a_{1n}L_n \le x$ (water constraint) ········> λ

$L_1 + L_2 + \ldots + L_n \le L$ (land constraint) ········> μ_L

$a_{21}L_1 + a_{22}L_2 + \ldots + a_{2n}L_n \le b$ (family labor) ········> μ_f

Non-negativity, crop rotation, etc.

The shadow price of the water constraint is the vmp of irrig water

Change water constraint from zero until irrig water is not binding to get derived demand for irrig water

Programming approach

$$\pi(x,b,p,r) = Max_{\{q,z,s\}}\; pf(q,z,s) - (r_1z_1 + r_2z_2 + \ldots + r_kz_k)$$

water input

purchased inputs (fertilizer, hired labor, machinery, pesticide)

fixed inputs (land, family labor, some capital)

subject to:

$q \le x$ (water constraint)

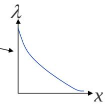
$s \le b$ (land, family labor constraints)

(possibly other, e.g., nonnegativity, constraints)

Shadow price

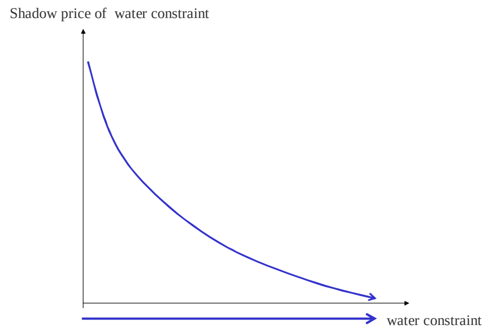
$\lambda(x) = \partial\pi/\partial x$

$\mu = \partial\pi/\partial b$



LP Example (Moroccan ORMVA)

Model R'Mel/Loukkos	Groudnut, early planting	Groudnut late planting	Soft wheat	Sugar cane	Strawberry (under plastic tunnel)	Barley as fodder	Corn as fodder	Melon (under plastic tunnel)	Water melon	Pepper	Potatos season crop
Yield per hectare (product1)											
September	29.6										
October		22									
November											
December					31						
January					42	1882					
February					52	470					
March					62						
April				623	62			149			
May								185			193
June			20				661	103		62	
July							2643		266	103	
August							2203		89	41	
Yield per hectare (product2& byproduct)											
September											
October	705.6	560									
November											
December					5						
January					5						
February					10						
March					10						
April					10						
May					62						
June			498.4		31						
July											
August											
Output1 price (Dh/unit)	588	683	242	25.6	900			280	65	130	130
Output21 price (Dh/unit)					303						
Output22 price (Dh/unit)											
Gross product/unit cost (Dh/unit)	17404.8	15026	4840	15948.8	264399	0	0	122360	23075	26780	25090



LP tableau -- water requirement

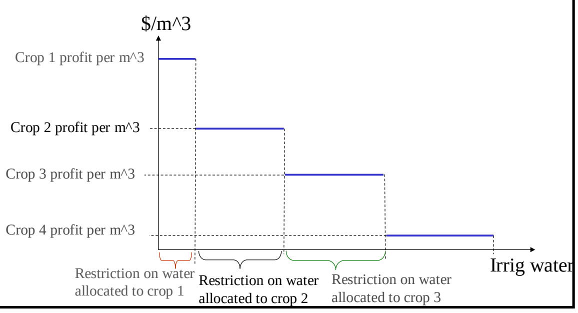
Model R'Mel/Loukkos		Groudnut, early planting	Groudnut late planting	Soft wheat	Sugar cane	Strawberry (under plastic tunnel)	Barley as fodder	Corn as fodder	Melon (under plastic tunnel)	Water melon	Pepper	Potatos season crop
Land use	September1	1	1		1	1			1			
	September2	1	1		1	1			1			
	October1		1		1	1	1		1			
	October2				1	1	1		1			
	November1				1	1	1		1			
	November2				1	1	1		1			
	December1				1	1	1		1			
	December2			1	1	1	1		1			1
	January1			1	1	1	1		1			1
	January2			1	1	1	1		1			1
	February1			1	1	1	1		1			1
	February2			1	1	1	1		1			1
	March1			1	1	1			1	1	1	1
	March2			1	1	1			1	1	1	1
	April1			1	1	1		1	1	1	1	1
	April2	1		1	1	1		1	1	1	1	1
	May1	1		1	1	1		1	1	1	1	1
	May2	1	1	1	1	1		1	1	1	1	
	June1	1	1	1	1	1		1	1	1	1	
	June2	1	1	1	1	1		1	1	1	1	
	July1	1	1		1	1		1	1	1	1	
	July2	1	1		1	1		1	1	1	1	
	August1	1	1		1	1		1	1	1	1	
	August2	1	1		1	1		1	1	1	1	
Rotation	Groundnuts-limits	1	1									
	Groundnuts-diversification	2	-1									
	Potatos-diversification											1
	Céréales-limits			1			1	1				
	Sugar cane-limits				1							
	Strawb+Melon+w.melon-limits					1			1	1		
	Solanacées limits										1	1
	Open field végétable limits									2	-3.3	
	Intensification limits (med.ter	1	1	1	1	1	1	1	1	1	1	1
	Diary-limits											
Succession	September	1	1		1	1	1		1			
	October		0.5		1	1	1		1			
	November			0	1	1	1		1			
	December			0.5	1	1	1		1			0.5
	January			1	1	1	1		1			1
	February			1	1	1	1		1			1
	March			1	1	1	1		1	1	1	1
	April	0.5		1	1	1	1	1	1	1	1	1
	May	1	0.5	1	1	1	1	1	1	1	1	0.5
	June	1	1	1	1	1	1	1	1	1	1	
	July	1	1		1	1	1	1	1	1	1	
	August	1	1		1	1	1	1	1	0.5	1	

LP tableau -- water requirement

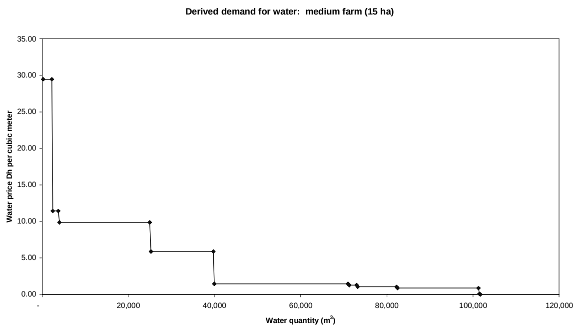
Model R'Mel/Loukkos		Groudnut, early planting	Groudnut late planting	Soft wheat	Sugar cane	Strawberry (under plastic tunnel)	Barley as fodder	Corn as fodder	Melon (under plastic tunnel)	Water melon	Pepper	Potatos season crop
Water use in m3	September	530			1400	800						
	October				900	600	1300					
	November				300	500	700					
	December					300			700			
	January					200			300			
	February					200		900	500			700
	March			700	800	700		900	1000	500	300	1600
	April	370	300	1000	500	700		1200	2000	800	600	1700
	May	1100	1000	1000	900	800		1400	2000	800	900	500
	June	1800	1700		1300	1000			1500	1300	1000	
	July	2400	2300		1700	1200				1600	1000	
	August	1800	1570		1700	1200					700	
	Water supply constraint											
	Tot.water charge											

Generalization:

If production function $f(q,z,s)$ admits CRS (long run) with exogenous constraints (marketing, water quota) the derived demand for water will have the step function form:



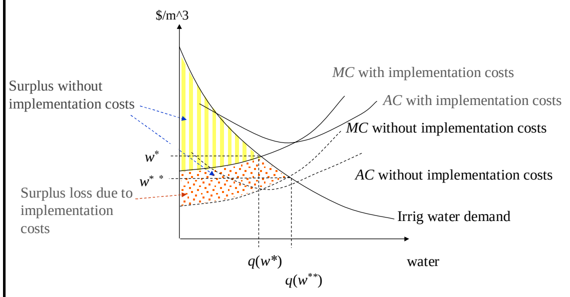
Derived demand for water via LP



Implementation Costs:

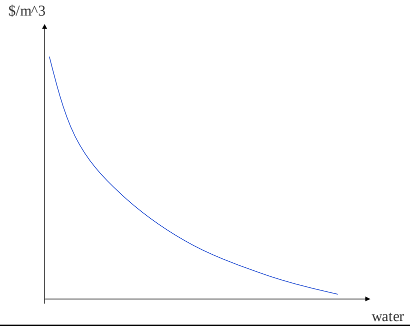
Fixed implementation costs affect the AC curve

Variable implementation costs affect the AC and MC curves



In the short run

There are fixed factors and production function typically admits DRS. The short-run derived demand for water is smooth:



Guidelines cont.

- 4. *Implementation costs* are part of the cost of water supply and should affect the marginal cost (*MC*) price accordingly.

- 5. From efficiency standpoint, the desirable pricing method to use is the one that yields the highest welfare when implementation costs are accounted for.

- 6. Any charge aimed at covering the fixed costs of water supply should be levied in a way that does not affect farmers' water input decisions.

Numerical illustration (Tsur and Dinar 1997)

2 crops x 2 inputs: Cotton-Wheat, water-nitrogen

Quadratic approximation for per-hectare water-nitrogen production functions:

Parameters estimates from Hexem and Heady (1978)

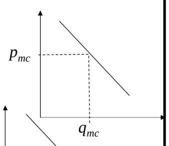
Linear MC

Implementation cost = % of water proceeds

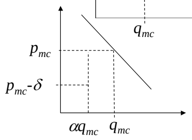
Area pricing optimal at 10 % implementation costs

Set up: Three farm types: small, medium and large. Calculate the Gini index under three pricing schemes

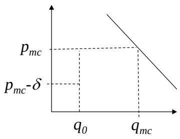
- Scheme 1: Flat rate Marginal Cost pricing



- Scheme 2: Proportional block rate pricing characterized by α and δ: pay p_{mc}- δ for αq and p_{mc} for the remaining water:



- Scheme 3: Absolute block rate pricing



Income distribution

Improving income distribution comes at the expense of efficiency ➔

Efficiency – Equity tradeoffs

- Is water pricing an effective policy tool?

- Empirical evidence doesn't support (Tsur and Dinar 1997, Tsur et al. 2004)

Farm profits and income distribution MC pricing at 0.46 Dh m^{-1} (source: Tsur et al. 2004)

Pricing scheme	$\mathbf{P_{mc}}$	α	δ	π^3	π^2	π^1	$\pi^1+\pi^2+\pi^3$	μ	*G*
1				173,967	433,836	5,784,108	6,391,910	452,502	0.575
	0.46	0.75	0.5Pmc	180,982	452,753	5,952,928	6,586,663	468,148	0.577
	0.46	0.5	0.5Pmc	177,877	450,166	5,952,928	6,580,970	465,248	0.577
	0.46	0.25	0.5Pmc	176,267	442,978	5,883,928	6,503,173	459,959	0.576
	0.46	0.75	Pmc	187,997	471,671	6,121,748	6,781,415	483,794	0.58
	0.46	0.5	Pmc	181,787	466,496	6,121,748	6,770,030	477,994	0.578
2	0.46	0.25	Pmc	178,567	452,121	5,983,748	6,614,435	467,416	0.577
		Q **(m^3)**	**δ**						
	0.46	10,000	Pmc	178,567	438,436	5,788,708	6,405,710	457,102	0.569
	0.46	10,000	0.5P	176,267	436,136	5,786,408	6,398,810	454,802	0.572
	0.46	20,000	Pmc	183,167	443,036	5,793,308	6,419,510	461,702	0.563
3	0.46	20,000	0.5P	178,567	438,436	5,788,708	6,405,710	457,102	0.569

The Gini index:

Arrange incomes in descending order ($\pi_1 \geq \pi_2 \ldots \geq \pi_n$)

$$G = 1 + \frac{1}{n} - \frac{2}{n^2 \mu} \sum_{i=1}^{n} i\pi_i$$

G = 0 under perfect equality (when $\pi_i = \mu$ all i)

G = (n-1)/n ≅ 1 under perfect inequality (one gets all, the rest get none)

In our case:

$$G = 1 + \frac{1}{n} - \frac{2}{n^2 \mu}\left[\pi^1 \sum_{i=1}^{103} i + \pi^2 \sum_{i=104}^{425} i + \pi^3 \sum_{i=426}^{2375} i\right]$$

$$= 1 + \frac{1}{2375} - \frac{2}{2375^2 \mu}\left[5356\pi^1 + 85{,}169\pi^2 + 2{,}730{,}975\pi^3\right]$$

Guidelines cont.

❑ **7.** Water prices have limited effect on income distribution within the farming sector and are therefore poor means to address income distribution goals

❑ **8.** How to allocate the fixed cost of water supply can be determined based on income distribution criteria (the urban population can carry (some of) the burden of the fixed costs of irrigation water supply (they will get some of it back in the form of fresh and cheap ag products and in environmental amenities)

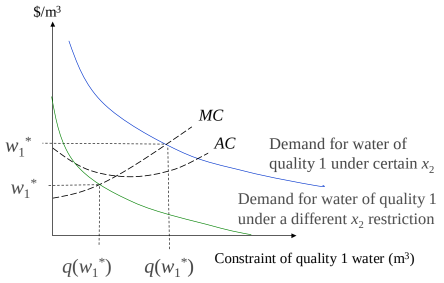
Farm profits and income distribution under MC pricing at 3 Dh m^{-1}

(Source: Tsur et al. 2004)

Pricing Scheme	P_{mc}	α	δ	π^3	π^2	π^1	$\pi^1+\pi^2+\pi^3$	μ	G
1	3			126,083	286,867	3,819,806	4,232,756	308,073	0.552
	3	0.75	0.5Pmc	153,427	346,867	4,914,073	5,414,367	386,115	0.564
	3	0.5	0.5Pmc	151,583	346,867	4,920,806	5,419,256	384,893	0.568
	3	0.25	0.5Pmc	141,083	346,492	4,470,806	4,958,381	356,705	0.564
	3	0.75	Pmc	217,583	533,617	7,742,414	8,493,614	586,771	0.589
	3	0.5	Pmc	177,083	499,867	6,021,806	6,698,756	474,322	0.583
2	3	0.25	Pmc	156,083	406,117	5,121,806	5,684,006	405,338	0.573
		Q (m^3)							
	3	10,000	Pmc	156,083	316,867	3,849,806	4,322,756	338,073	0.503
	3	10,000	0.5P	141,083	301,867	3,834,806	4,277,756	323,073	0.527
	3	20,000	Pmc	186,083	346,867	3,879,806	4,412,756	368,073	0.462
3	3	20,000	0.5P	153,427	316,867	3,849,806	4,320,100	335,892	0.508

❑ No dramatic change in the Gini index

The demand for quality 1 water depends on restriction of quality 2 water:



Water quality

Suppose there are H sources of water of different quality (e.g., fresh, saline, reclaimed) with the (annual) capacity limits x_h, $h = 1,2,\ldots,H$.

$f(q_1,q_2,\ldots,q_H,z,s)$ = the water production function of the H water inputs $q_1,q_2,\ldots,q_H$, the purchased inputs z, and other limited inputs s.

The derived demands for the H water inputs stem from:

$$Max_{\{q,z,s\}} \{\pi = p\, f(q_1,q_2,\ldots,q_H,z,s) - r{\cdot}z\}$$

subject to:

$$q_1 \le x_1,\ q_2 \le x_2,\ \ldots,\ q_H \le x_H$$

$$s \le b$$

Intertemporal considerations:

$$Max_{\{q_0,q_1,\dots,q_T\}} \sum_{t=0}^{T} \frac{B(Q_t, q_t, t)}{(1+r)^t}$$

$$s.t. \quad Q_1 - Q_0 = R(Q_0) - q_0 \quad \cdots\to m_0$$

$$Q_2 - Q_1 = R(Q_1) - q_1 \quad \cdots\to m_1$$

$$\vdots$$

$$Q_{T+1} - Q_T = R(Q_T) - q_T \quad \cdots\to m_T$$

Feasibility constrains, $t = 0,1,\dots,T$

Q_0 *given*

Q_{T+1} *restricted*

Shadow prices (user cost): m_0, m_1, …, m_T

❑ **9.** When water derived from sources of different quality (e.g., fresh, saline or reclaimed water) has different effect on crop yield, each water quality is treated as a separate input and must be priced separately. The demand for each water quality depends on the available supply as well as demands for other water types. Given the set of water demands, pricing should be determined simultaneously for all types of irrigation water

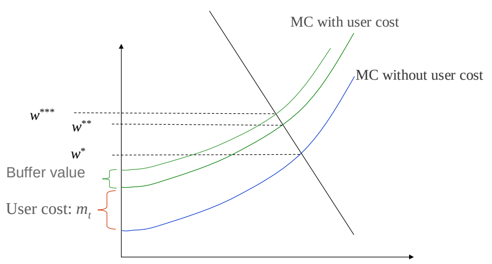
Guideline – cont.

❑ **10a. When irrigation water is derived from a stock source (lake, reservoir, aquifer) in an unsustainable fashion (the stock shrinks over time or water quality deteriorates), the price of water must reflect also the scarcity value and stock externality (effect of stock size on withdrawal cost). These effects show up via the user cost of water, calculated within an intertemporal management framework. The user cost of water should be added to the price of water.**

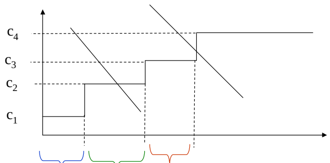
❑ **10b. When irrigation water is derived from a ground and surface sources conjunctively and surface water supply (e.g., rainfall) fluctuates, groundwater acts also as a buffer that mitigates the fluctuations in surface water supplies. This role has economic value that should be added to the price of groundwater.**

Intertemporal effect:

Supply and demand at a specific time period



❑ **13.** If the same water (quality) is derived from a number of sources (e.g., various surface and ground sources), then the change in the supply cost of each source implies that the marginal cost of water supply increases when supply shifts from one source to the other. The cheaper sources will be used first and the water price should reflect the marginal cost of the most expensive source under use



Miscellaneous guidelines…..

❑**11**. Under volumetric pricing, efficiency requires that the price of water reflects the marginal cost of water supply disregarding water allocation between crops (i.e., water price should not change across crops)

❑ **12.** Under per area pricing, changing the (per hectare) water fee across crops can be used to improve efficiency by affecting farmers' crop selection

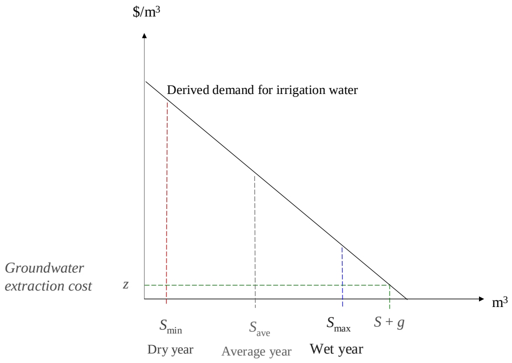
Properties of pricing methods

Pricing Scheme	Implementation	Efficiency Achieved	Time Horizon of Efficiency	Ability to Control Demand
Volumetric	Complicated	First-best	Short-run	Easy
Output	Relatively easy	Second-best	Short-run	Relatively easy
Input	Relatively easy	Second-best	Short-run	Relatively easy
Per area	Easiest	None	N/A	Hard
Block rate (Tiered)	Relatively complicated	First-best	Short-run	Relatively easy
Two part	Relatively complicated	First-best	Long-run	Relatively easy
Water Market	Impossible without pre-established institutions	Potentially First-best	Typically Short-run	N/A

Prices vs. Quantity: the role of asymmetric information:

❑ **14.** Due to the prevalence of asymmetric information, water allocation and pricing rules should be designed in order to minimize the limitations imposed on farmers' input-output decisions

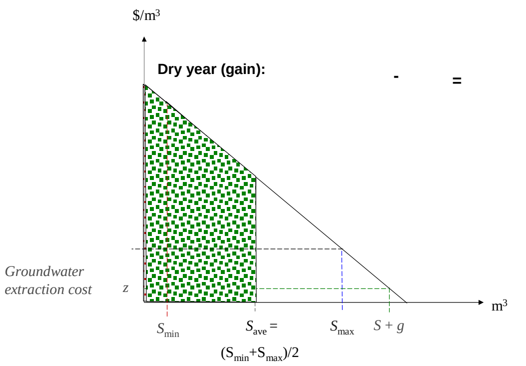
Conjunctive management of ground and surface water



Additional aspects:

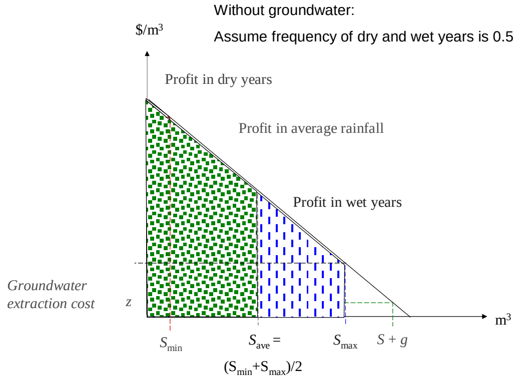
- ➢Externalities (Ag as provider of environmental amenities and of negative externalities)
- ➢Irrigation technology (changes yield response to water)
- ➢Using markets to price water
- ➢Economy-wide considerations
- ➢Conjunctive management of ground and surface water

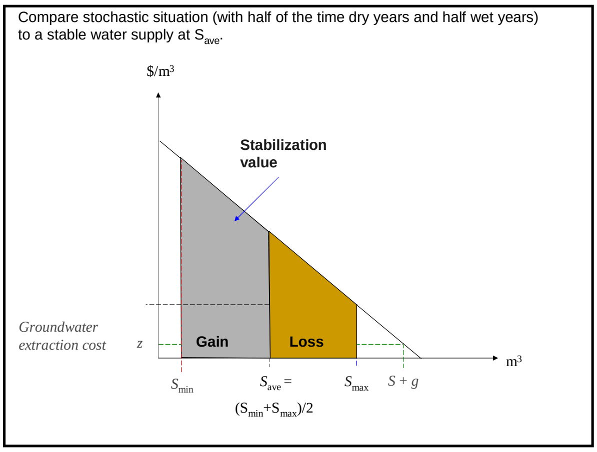
Compare stochastic situation (with half of the time dry years and half wet years) to stable water supply at S_{ave}.

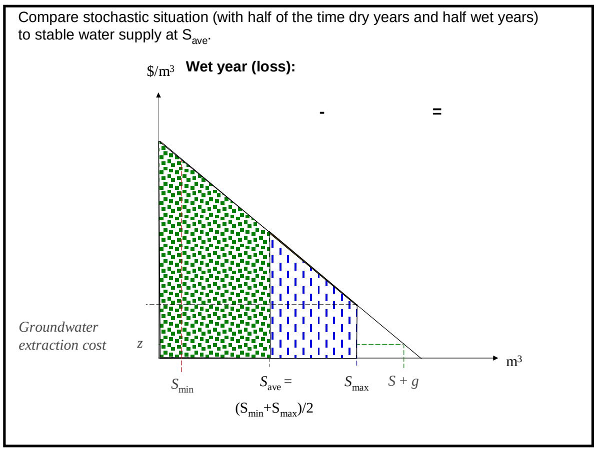


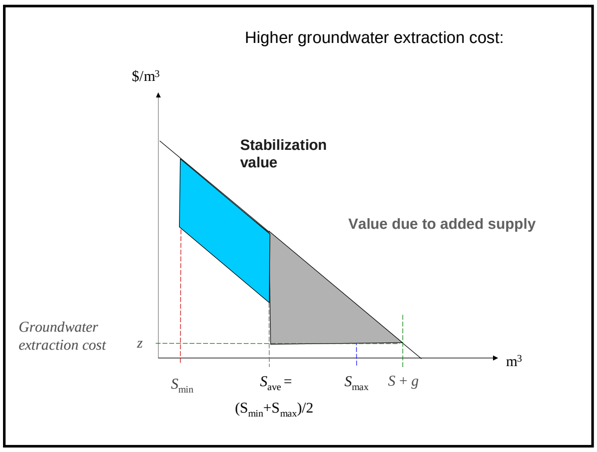
Without groundwater:

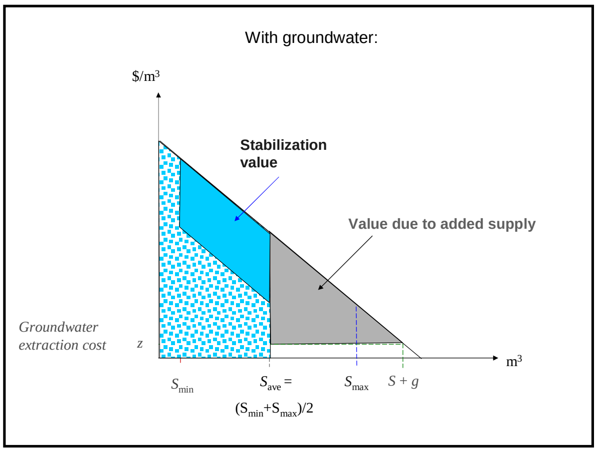
Assume frequency of dry and wet years is 0.5



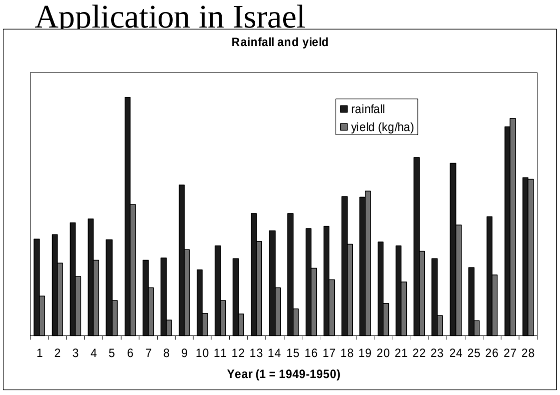

Compare stochastic situation (with half of the time dry years and half wet years) to a stable water supply at S_ave.
$/m³
Stabilization value
Groundwater extraction cost
z
Gain
Loss
m³
S_min
S_ave =
(S_min+S_max)/2
S_max
S + g


Compare stochastic situation (with half of the time dry years and half wet years) to stable water supply at S_ave.
$/m³
Wet year (loss):
-
=
Groundwater extraction cost
z
m³
S_min
S_ave =
(S_min+S_max)/2
S_max
S + g

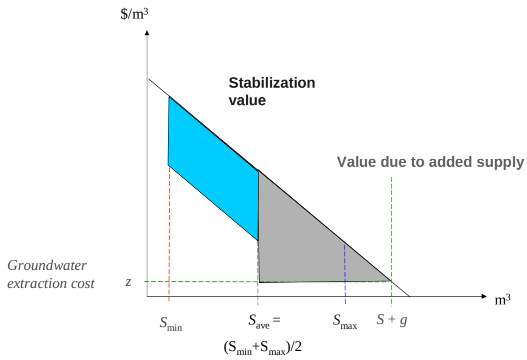

Higher groundwater extraction cost:
$/m³
Stabilization value
Value due to added supply
Groundwater extraction cost
z
m³
S_min
S_ave =
(S_min+S_max)/2
S_max
S + g


With groundwater:
$/m³
Stabilization value
Value due to added supply
Groundwater extraction cost
z
m³
S_min
S_ave =
(S_min+S_max)/2
S_max
S + g

Application in Israel



Higher groundwater extraction cost:



Stabilization values in Israel

	Z ($ m^{-3})			
	0.05	0.1	0.15	0.2
Stabilization value ($/ha)	52.6	48.4	33.3	14.7
Value due to increase supply ($/ha)	91.9	20.9	0.5	0
Tot GW vlaue	144.4	69.3	33.8	14.7
Percent SV of Tot Value	36%	70%	98%	100%

Yield vs. rainfall