Spatial dynamics of water management in irrigated agriculture

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Introduction

- Irrigated Agriculture
  - 16% of world arable land is irrigated
  - accounts for 1/3rd of world's food production
  - uses 40% of world's freshwater withdrawals
  - has considerable waste emissions (salinity and drainage, nutrients, toxic chemicals…)
- Future
  - world population is growing at the rate of 1.3%/yr, but arable land comprises only 10% of world land area, most already exploited
- Question
  - how do we maintain agricultural production while minimizing water use and waste emissions

Objectives

- Develop a dynamic optimization model for irrigation management that includes a daily model of plant growth, spatial variability, and fundamental scientific principles
- Analyze sensitivity of water demand and drainage to water price change and when deep percolation costs are included
- Find the optimal irrigation technology to be used given specific costs for water and deep percolation flows

Method

- Data used is from San Joaquin Valley
- The study is conducted for cotton
- The dynamic model described is algorithmic, and requires an iterative procedure for solution
- The model was solved using GAMS CONOPT nonlinear optimization procedure
- There is 1 control variable and 11 state variables
- Five of the equations described are solved for 11 cells for 187 days of plant growth – m, e, w, d, and h

Model

- *Objective function*

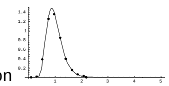
$$\underset{w}{Max} \quad \pi = p^y \sum_i y_i(w) \cdot pr(\beta_i) - \gamma - p^w \sum_{t=t_1}^{t_2} w_t - p^d \sum_{t=t_1}^{t_2} \sum_i d_{i,t}(w) \cdot pr(\beta_i)$$

- *Spatial variability*

β – infiltration coefficient

β ~ lognormal distribution over the field

E(β) = 1, SD(β) depends on irrigation system

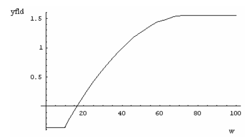


Marketable yield is a function of vegetative plant yield:

$$y_i = \mu_1 + \mu_2 y_i^{veg} + \mu_3 (y_i^{veg})^2$$

Vegetative yield is a function of seasonal evapotranspiration:

$$y_i^{veg} = \frac{z_{i,t_2+1} - \underline{z}}{\overline{z} - \underline{z}} \cdot \overline{y}^{veg}$$



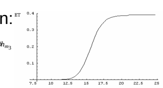
- *Daily model of plant growth*

Daily Evapotranspiration:

$$e_{i,t} = \frac{\overline{e}}{1 + \left(\frac{h_{i,t}}{h_{50}}\right)^{\phi e_1}}$$

Matric pressure head function:

$$h_{i,t} = \frac{1}{\phi h_{m_1}} \left(\left(\frac{(m_{i,t}/120) - m_{res}}{m_{sat} - m_{res}} \right)^{-1/\phi h_{m_2}} - 1 \right)^{1/\phi h_{m_3}}$$



Daily deep percolation flows:

$$d_{i,t} = Max\,[m_{i,t} - e_{i,t} + \beta_i w_t - \theta_f, 0]$$

Equations of Motion:

For soil moisture – $m_{i,t+1} = m_{i,t} + \beta_i w_t - e_{i,t} - d_{i,t}$

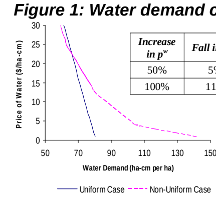
For cumulative ET – $z_{i,t+1} = z_{i,t} + e_{i,t}$

Results

Table 1: Spatial dynamics of water management

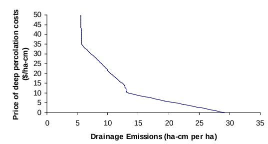
Variables (p^w = $3.9/ha-cm)	*Uniform Case*	*Non-uniform Case* (Furrow ½ Mile)
Total applied water (ha-cm per ha)	78	105 (35% increase)
Deep percolation flows (ha-cm per ha)	0	29
Marketable lint yield (Mg/ha)	1.556	1.497 (4% fall)
Profit ($/ha)	910	680

Figure 1: Water demand curve



Increase in p^w	***Fall in w^****	***Fall in Net Benefits***
50%	5%	2.5%
100%	11%	6%

Figure 2: Irrigation and the environment



Tables 2.1 and 2.2: Choice of optimal irrigation system

(Systems compared – Furrow ½ mile, Furrow ¼ mile, Sprinkler, LEPA, Linear, Sub-surface Drip)

Table 2.1: No deep percolation costs

Price of Water	*System Chosen*
0	Furrow ½ Mile
5	Furrow ½ Mile
10	Furrow ½ Mile
15	Furrow ½ Mile
20	Furrow ½ Mile
25	**Furrow ¼ Mile**

Table 2.2:With deep percolation costs and pw = $3.9/ha-cm

Price of DP	*System Chosen*
0	Furrow ½ Mile
5	Furrow ½ Mile
10	**Furrow ¼ Mile**
15	Furrow ¼ Mile
20	Furrow ¼ Mile
25	Furrow ¼ Mile

Conclusions

- Model incorporates
  - dynamic plant growth over the season
  - spatial variability
  - fundamental principles of subsurface hydrology
- There are increases in *w** and *d** with the introduction of spatial variability
- Water price increases by 50% and/or quantity reductions of 5-10% are possible without much loss in social net benefits
- Better water management at field-level helps water conservation more than fallowing land, changing crops, or changing irrigation technology

Symbols used

π - returns to land and management
p^y - market price of the crop
w - total irrigation water applied over the season in the field
y_i - marketable yield in cell i
γ - non-water production and harvest costs
p^w - price of applied water in irrigation
p^d - price of deep percolation flows
$d_{i,t}$ - deep percolation losses in cell *i* on day *t*
y_i^{veg} - vegetative crop yield at point *i*
$z_{i,t}$ - cumulative evapotranspiration in cell *i* on day *t*

$\underline{z}$ - minimum cumulative ET
$\overline{z}$ - maximum cumulative ET
$\overline{y}^{veg}$ - vegetative plant yield obtained at maximum ET
$e_{i,t}$ - evapotranspiration on day *t* in cell *i* on the field
$\overline{e}$ - maximum ET under non-stressed conditions
$h_{i,t}$ - matric pressure head
h_{50} - stress at which the yield is reduced by 50%
$m_{i,t}$ - soil moisture in cell *i* on day *t*
m_{res} - residual water content
m_{sat} - saturated water content
θ_f - field capacity

Reference

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