Salinity and Drainage Management in Irrigated Agriculture

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- **Salinity/drainage is a worldwide problem in irrigated agriculture,** *but relatively little studied in water economics*.
- **Synthesis of research for San Joaquin Valley, California, USA:** *this is a solvable problem over at least intermediate time scales.*
- **Ideas, concepts, methods, results are (hopefully) of more general validity for other water issues and regions.**

1. Soil and Groundwater Salinity

Historical

- **Ancient Mesopotamia**. Irrigation initiated approximately 6,000 BC with decline in agricultural productivity during the period 2400 BC - 1700 BC. [Scarre (1993), Jacobsen and Adams (1958), Gelburd (1985)]
- **Viru Valley in Peru**. Irrigation systems were developed during the period 400 BC - 0 BC. Population peaked in 800 AD with a precipitous decline after 1200 AD [Tanji (1990)].
- **Salt River basin, Arizona.** Native Americans (Hohokam, 300 BC - 1450 AD). Water logging and salinization on the valley floor causing crop damages, with no record of habitation after this period. [Tanji (1990)].

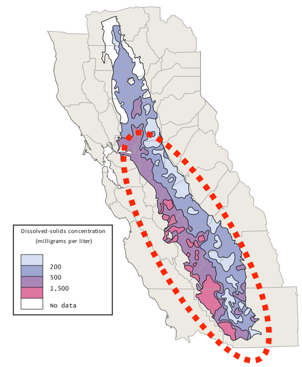
Current

- **Irrigated agriculture** provides 40% of worldwide food production [United Nations (2003)]..
- **Salinity/drainage impacted lands** = 1/3 worldwide irrigated land [United Nations (2003)].

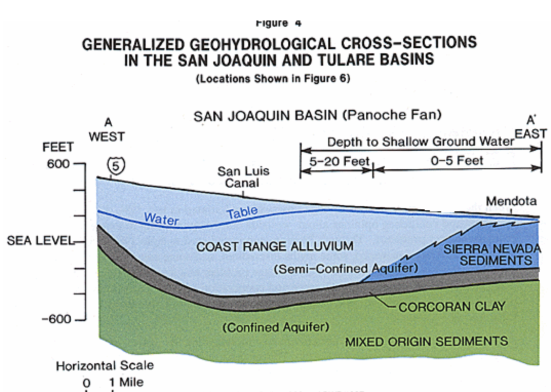
Table 1. Salinity and Drainage Affected Regions Worldwide

Region	Irrigated Acreage: Total (hectares)	Irrigated Acreage: % affected by salinity or waterlogging	Drainage, Environmental, and Additional Irrigation Issues	Current Disposal Options: Reuse	Current Disposal Options: Evap. Ponds/ Basins	Other Management Options Considered
Murray-Darling River Basin[a]	2.1 million	70-80%	Rising salinity levels in rivers and tributaries from agricultural drainage and shallow saline watertable.	Yes	Yes	Land retirement; Agroforestry; Irrigation upgrades;
Aral Sea Basin[b]	7.9 million	50%	Aral Sea drying up due to increasing water use by agriculture. River water quality decreasing due to drainage discharge. Water shortages. Evaporation basin at capacity.	Yes	Yes	Land retirement; Decrease cotton / Increase rice production; Irrigation canal upgrades
Nile Delta[c]	3 million	33%	Saline drainage waters threatening fisheries in Northern Lakes. Water resources under severe stress. Projected water demand by 2025 cannot be met by new water source projections. Plan to increase reuse of agricultural drainage water from 4400 million m^3 to 8000 million m^3.	Yes	No	Revegetation with salt-tolerant crops; Irrigation and drain upgrades
Indus Plain[d]	15.8 million	25%	Pumping of groundwater may lead to seawater intrusion. Seepage from evaporation ponds affecting adjacent lands. Low water allowances for irrigation.	Yes	Yes	Irrigation canal upgrades; Well additions; Conjunctive use; Source Control; Groundwater pumping
USA[e]	24 million		Increasing salinity in rivers due to seepage and return flows from irrigated agriculture (e.g., Pecos River, Arkansas River, Rio Grande, Yakima River, Snake River). Rising salinity levels in Colorado River and drainage disposal sites (e.g., Salton Sea) which threaten ecosystem health and wildlife.	Regional		Source control; Reuse; Conjunctive use
Great Basin	997,000	58%		Yes	No	
Rio Grande	782,000	75%		Yes	No	
Upper Colorado	651,000	41%		Yes	No	
Lower Colorado	616,000	66%		Yes	Yes	

Salinity/Drainage on the Westside of the San Joaquin Valley of California



Source: USGS Groundwater Atlas



Historical salinity/drainage management: Westside SJV, California

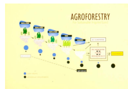
- **Master Drain (mid 1950's - 1964).** Plan = drain westside with system running north, emptying into San Francisco Bay/Delta.
- **San Luis Interceptor Drain (1968 -1975).** Construction of partial system terminating at Kesterson reservoir which was joint use (wildlife and drainage evaporation.)
- **Kesterson reservoir (1983).** Bird-deformities from SE in drainage inflows.
- **Northern subarea:** some outflow to the San Joaquin river. **Westlands and other districts:** closed drainage basins. **Tulare Lake Drainage Basin:** sustainable evap basin system.
- **Closed basin drainage management over intermediate time scales.**
- **Long-run agricultural production:** salt export from region.

Management Strategies

Source Control

Water application rates
Crops, land allocation, irrigation systems

Reuse



Water application rates and salt concentrations
Crops, land allocation, irrigation systems

Treatment

Se removal strategies

Disposal

Evaporation and solar ponds
Compensating and mitigating habitat
External salt and drainage disposal

Questions

(1) Efficient management

Bio-physical management strategies to maintain:
Agricultural production + Environmental quality

(2) Policy instruments

Collective action to solve the drainage problem:
District, watershed, or regional level
Technology standards vs. charges/subsidies vs. TDP markets

(3) Sustainability

Can agricultural production be maintained at profitable levels
over the short, intermediate and long-runs while also protecting EQ?
Agribusiness, communities and the larger socio-economic system

(4) Information and dynamics

Uncertainty, spatial variability, heterogeneity, asymmetric information
Dynamic processes in both the human and natural systems

2. Field-level dynamics and management

- ***Social net benefits***

  Crop revenue – production costs – environmental costs

- ***Production functions***

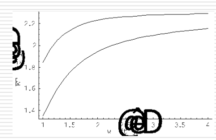
  Crop yield, quantity and salt concentration = f (applied water depth and salt concentration)

- ***Decision problem***

  Select management variables to Maximize SNB subject to various constraints and given prices and environmental conditions.

Plant-level dynamics

- ***crop yield***
  y = f[b(T)]
- ***ET***
  e(t) = f[b(t), m(t), s(t)]
- ***biomass dynamics***
  b(t+1) = f[b(t), e(t)]
- ***moisture dynamics***
  m(t+1) = m(t) - e(t) + w(t) - d(t)
- ***salt dynamics***
  s(t+1) = f[m(t), s(t), w(t), c(t)]



Field-level spatial variability

- ***Infiltration coefficients***

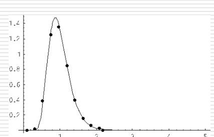
  b = fraction of field-level water depth infiltrating at a point

  $$w_t = \beta \bar{w}_t$$

- ***Spatial density function***

  $f(\beta)$ $\int f(\beta)d\beta = 1$ Lognormal

  E[b] =1, SD[b] depends on irrigation system



- ***Field-level averages***

  Integrate variables of interest over spatial density function.

  $$\bar{y} = \int_0^\infty y f[\beta] d\beta \qquad \bar{d}_t = \int_0^\infty d_t f[\beta] d\beta$$

Empirical findings

- ***Field-level spatial variability is fundamental to understanding water management***.
  [Seginor (1978); Feinerman, Letey, Vaux (1983); Berck and Helfand (1990); Knapp (1992a,b,c)]
- ***Multiple irrigation sources differing in cost and salt concentration.***
  Typically find near linear isoquants implying corner solutions (no blending).
  [Rhoades (1989); Dinar, Letey, and Vaux (1983); Kan, Schwabe, Knapp (2002)]
- ***Crop rotations and sequences affect water management for individual crops in the sequence.***
  [Knapp (1992a,b,c)]
- ***Irrigation systems***.
  Plausible water and drainage prices imply moderate upgrades to furrow, rarely imply switches to high-cost systems such as linear move or subsurface drip.
  [Caswell and Zilberman (1985); Dinar and Zilberman (1991); Weinberg, Kling, and Wilen (1993); Knapp, Stevens, Letey, and Oster (1990)]

3. Regional Management

Hydrologic balance in drainage-impacted areas

- Water Management
- Irrigation Systems
- Crop Selection and Rotations
- Reuse
- Treatment
- Evaporation Ponds

Economic Efficiency *Average conditions in WWD*

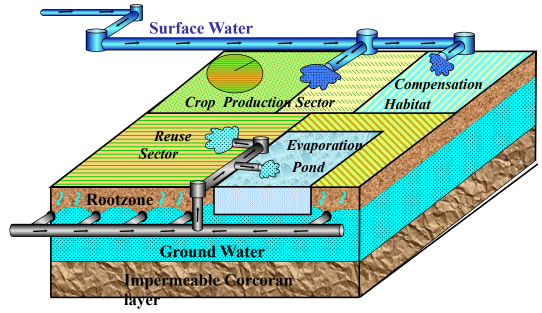


Figure 1 - Regional agricultural production with a shallow water table and no external drainage facilities.

	Historical	*No Reuse*		*Reuse*
		No CH	CH	
Crop Production				
Area (acres)	0.83	0.762	0.789	0.514
Furrow 0.5 miles (%)	95			90
Furrow 0.25 miles (%)		75	22	
Linear move sprinklers (%)		20	73	
Drip (%)	5	5	5	10
Surface water (ft/yr)	3.23	2.44	1.99	3.17
Deep percolation (ft/yr)	1.17	0.48	0.14	1.21

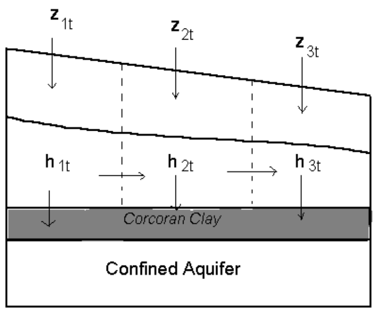
	Historical	*No Reuse*		*Reuse*
		No CH	CH	
Reuse				
Area (acres)	0	0	0	0.32
Crop/Irrigation system				Cotton/F4
				Wheat/F4
Ground water (ft/yr)				3.81
Deep percolation (ft/yr)				1.87
Land Disposal				
Evaporation pond (acres)	0	0.07	0.02	0
Compensation Habitat (acres)			0.02	
Region				
Social Net Benefits ($/yr)	311	258	196	294
Drainage shadow value ($/af)	0	80.68	393.86	18.69

- Absent reuse, a high level of **source control** is efficient due to high evaporation pond cost. This is accomplished via adoption of high uniformity/high cost irrigation systems.
- **Reuse** is extremely promising. Evaporation ponds are not used and per-acre source control is minimal. High net returns are achieved.
- The analysis finds modest use of **evaporation ponds**. Pond areas range from zero to 7% of land area. If birds and wildlife are kept off the ponds, then CH may be an environmental benefit.
- The estimated **drainage price** is a relatively modest $19/af but is sensitive to the assumptions made. Given the risk and uncertainty of reuse, the true value is likely higher.
- **Sustainability**. A high level of agricultural production may be possible for some period of time while still maintaining environmental quality.

4. Upslope-downslope transport

- High water tables in the drainage-affected areas are generated by deep percolation from overlying land
- There can also be lateral flows into the area from upslope areas
- Should these upslope flows should be regulated?

Side profile of a west to east transect on the westside of the SJV



Agricultural Production

Social net benefits (profits)

$$\sum_i \sum_j [p_j y_{ij} - p^w w_{ij} - \gamma_{ij}] x_{ij} - (e\gamma_e + \gamma_p) x_p \qquad (5)$$

x_{ij} = land area, w_{ij} = applied water, y_{ij} = yield, d_{ij} = deep percolation.

Production functions

$$y_{ij} = f_{ij}(w_{ij}) \qquad (6)$$
$$d_{ij} = g_{ij}(w_{ij}) \qquad (7)$$

Land allocations

$$\sum_i \sum_j x_{ij} + x_p \le \overline{x} \qquad (8)$$
$$\underline{x_i} \le \sum_j x_{ij} \le \overline{x_i} \qquad (9)$$

Net deep percolation flows

$$\sum_i \sum_j d_{ij} - e\, x_p \le z \qquad (10)$$

Cotton-cotton-tomatoes rotation. Five irrigation systems (F2, F4, linear move, LEPA, subsurface drip). Letey et al (1985) production function model w/lognormal infiltration distribution.

Finite-difference groundwater model

Freeze and Cherry (1979); Viessman et al (1989).

Flow between cells is computed according to Darcy's law:

$$q''_{i,i+1}(\tau) = -K_{i,i+1} \frac{(h'_{i+1}(\tau) - h'_i(\tau))}{b} A \qquad (A1)$$

where $q''_{i,i+1}$ denotes lateral flow from cell i to cell i+1 per unit time.
Vertical flow through the clay layer is also calculated by Darcy's law:

$$q''_{i,v}(\tau) = -K^c \frac{(h^c - h'_i(\tau))}{b^c} A^c \qquad (A2)$$

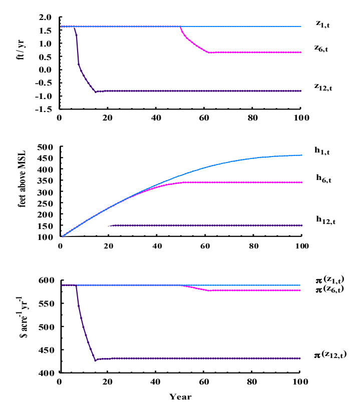
where h^c is the hydraulic head for the confined aquifer, b^c is the clay layer thickness, and A^c = a Bb is the horizontal cell area.

Equation of motion for the aquifer during the year:

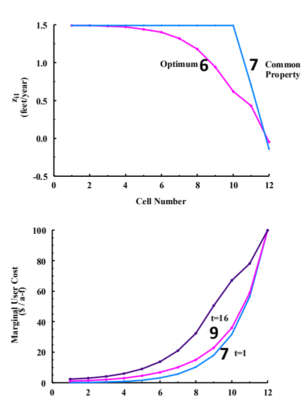
$$h'_i(\tau+1) = h'_i(\tau) + \frac{z'_i(\tau)}{s^y} + \frac{q'_{i-1,i}(\tau) - q'_{i,i+1}(\tau) - q'_{i,v}(\tau)}{A^c\, s^y} \qquad (A3)$$

where z'_i(J) is deep percolation in cell i during subperiod J .

Spatial dynamics of the agricultural production/groundwater aquifer system under common property usage.



Spatial dynamics of the agricultural production/groundwater aquifer system: common property vs economic efficiency.



- Net deep percolation flows are progressively reduced as the water table rises under economic efficiency.

- Efficient upslope source control is minimal. Finite transmissivity implies a time delay between upslope emissions and downslope impacts. Positive discounting implies that the PV of marginal damages is lower for upslope areas than downslope, implying lower source control upslope. This is robust to changes in the interest rate, hydraulic conductivity, and boundary conditions.

- Optimal emission charges increase as the water table rises, and are higher downslope than upslope.

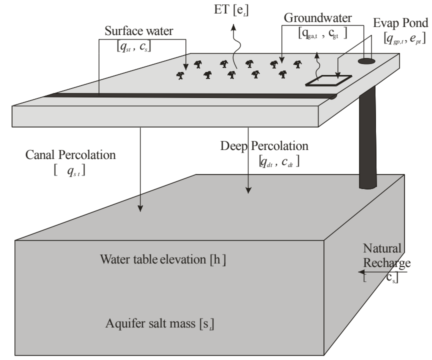
- Agricultural production in the region is long-run sustainable, dependent on the availability and salt-removal of evaporation ponds.

- Widespread land retirement is not necessary for a sustainable system.

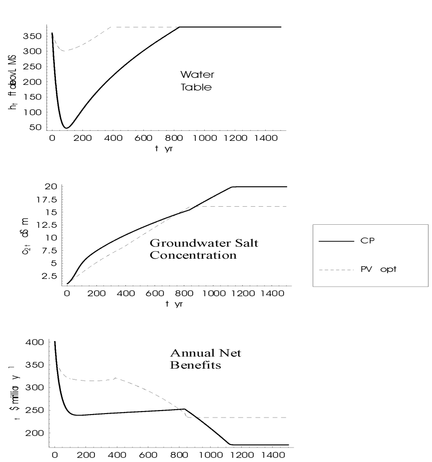
5. Saline groundwater systems

- Basins import surface water (and salts), but limited or no salt exports in some cases.
- Reuse potentially major remedy for drainage-limited regions, but it has a concentrating effect (ET but no salt uptake/removal).

Figure 1. Regional agricultural production with surface water supply and overlying an aquifer system with salinity. Variables are q=water quantity, c = salt concentration, e = evaporation/transpiration, h=hydraulic head, s = aquifer salt mass.



Common Property vs. Economic Efficiency



Saline Groundwater Systems

- Salt buildup under reuse occurs – on average – relatively slowly.
  Reason = small DP flows relative to aquifer size.
  This implies reuse is likely a solution for considerable time periods.
- Salt and DW emission shadow prices are fairly low in general aquifers where drainage is not necessarily limiting (e.g. eastside SJV).
  This implies relatively small incentives for management.
- Analysis shows that various groundwater problems (falling water tables, high water tables, salinity/drainage) can be viewed as different stages of the same overall dynamic process.
- Incomes are generally declining over time implying <u>nominal</u> unsustainability. However, when investment in physical/social capital is factored in, then this may or may not hold true.

6. Policy instruments

- Traditional environmental policy specifies technology standards.
- Pricing policies
- TDP markets
- Cross-policy effects

Drainage prices

Crop producers are charged for emissions

$$\pi^c = \left(p_1^c y_1 - p_1^w w_1 - \gamma_1 - p^l - p^d d_1\right) x_1$$

Reusers are paid for extractions and charged for emissions.

$$\pi^r = \left[p_2^c y_2 + \left(p^d - p_2^w\right) w_2 - \gamma_{21} - \gamma_{22} x_2 - p^l - p^d d_2\right] x_2$$

Pond operators are paid for water table extractions

$$\pi^p = \left(p^d e_3 - \gamma_3 - p^l\right) x_3$$

The correct drainwater charge induces efficiency.

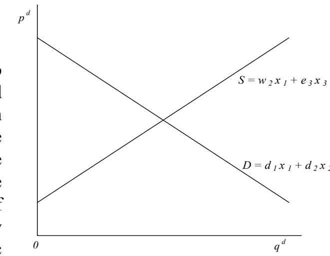
Drawbacks are accuracy and dynamics in charge-setting, and possible adverse equity impacts.

Tiered water pricing
Wichelns (1991)

- Broadview water district, 1988-1989
- P= 16 w<q(crop) P=40 w>q(crop)
- q(cotton)=2.9 af/yr q(melons)=1.9 af/yr
- Drainwater reduction = 23%
- Demonstrates viability of pricing schemes

Permit Markets

An alternative to a pricing scheme is to establish a market for the unpriced services. Here reusers and evaporation pond operators supply permits, while emissions to the water table must be covered by a permit. Competitive equilibrium occurs where the quantity of permits supplied equals the quantity demanded and this achieves hydrologic balance by definition.



Drainage permit market with endogenous

supply and demand.

Cross-policy effects

- ***Weinberg, Kling, and Wilen*** (***1993***)
  Water market effects on drainage problem area (68,000 acres).
  Open water market ($96/a-f) implies 30% decrease in DW.
  Market not an efficient solution; efficiency loss = $33/acre/yr.
- ***Weinberg and Kling*** (***1996***)
  Crop subsidies and environmental policies are implemented by different agencies. Welfare implications of each considered independently depend on the other policy. In principle could get an overall welfare loss from independent action but not in this particular case.

7. Conclusions
Agricultural production management

- Modest source control (improved furrow systems).
  Minimal crop switching and moisture stressing.
- Reuse is very promising. Likely viable over several decades at the very least.
- Evaporation pond policy should be re-evaluated. Yes, they cause damage but so does everything. Also, CH may actually imply net environmental benefit.
- Land retirement or land fallowing not generally economically efficient.
- Convex drainage reduction costs: initial reduction relatively cheap.

Basin management and policy

- The drainage problem involves a dynamic interaction between agricultural production and groundwater. Efficiency requires progressive reduction in net deep percolation flows as the water table rises.
- Upslope source control is not necessarily economically-efficient depending on location due to finite hydraulic conductivity and discounting.
- Salt externalities not necessarily large and reuse not likely to alter aquifer salt concentrations very fast on average.
- Tradeable permit markets for drainage flows with endogenous supply should be investigated.
- Provision of external drainage facilities needs to be investigated. Waste emissions into the environment are an inevitable consequence of all production and consumption activities. The current effective zero-discharge policy facing agriculture is inconsistent with other sectors of the economy

Agricultural sustainability on the westside SJV

- **Short to intermediate run (several decades)**
  modest source control + reuse + modest evaporation ponds + treatment?
- **Long-run**
  management + salt removal from ponds and/or external disposal
- **Producers**
  Future = increasing resource and environmental scarcity.
  Historical reaction to scarcity (e.g. copper and mercury) is recycling and other management strategies.
- **Environmentalists**.
  All economic production and consumption of goods and services has implications for the environment. Zero discharge is impossible. Agricultural environmental regulation should balance benefits and costs consistent with regulation in other sectors of the economy.

Collaboration

- ***Soil Scientists***

  John Letey, Jim Oster, Jim Rhoades

- ***Economists***

  Ken Baerenklau, Ariel Dinar, Eli Feinerman, Iddo Kan, Judy Posnikoff,
  Kurt Schwabe, Marca Weinberg, Dennis Wichelns

- ***Research Assistance***

  Phyllis Nash