Sustainability Economics of Groundwater Usage and Management
An Environmental Macroeconomic Perspective

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Issues

- falling water tables and land subsidence
- pollutant concentrations (salinity, nitrates, pesticides, ...)
- seawater intrusion
- ecosystems
- climate change and conjunctive use

Groundwater economics: general

- Burt; Brown and Deacon: PV-optimality.
- Gisser and Sanchez; Khoundrini: CP vs PV-optimality.
- Negri; Provencher and Burt: Game-theoretic solution.
- Burt; Knapp and Olson: conjunctive use.
- Noel and Howitt; Richard; Brosnivich et al: spatial dynamics.
- Olson and Conrad; Zeitouni: quality.
- Khoundrini; Knapp and Baerenklau: quantity and quality.
- Richard; Roumasset; Reinelt: seawater intrusion.

Economics of groundwater sustainability

Research questions

- What is an economic definition of sustainability?
- How do we achieve it?
- Policy instruments.

This will necessitate a major extension of standard groundwater economic models to include households, consumption and investment, and human-generated capital stocks.

Is SGMA (2016) well-founded?

What is sustainability?

SGMA (2016): Avoid undesirable consequences

- Water table declines.
- Land subsidence.
- Seawater intrusion.
- Ecosystem effects.
- Stream-aquifer interaction.
- Water quality

SGMA (2016) and sustainability (cont.)

SGMA (2016) apparently doesn't consider the following as undesirable consequences:
Foregone value of groundwater locked up in storage?
Potential economic losses associated with ad hoc management?

Physical evaluation of a steady-state/no overdraft policy

All economic production/consumption requires extractions from the environment and emissions back to the environment.

Example 1. Assuming no overdraft with no other justification

- Then this should be true for all resource and environmental stocks at all points in time.
- Implies that there should have been no aquifer drawdown from the late 1800's.
- Can only be satisfied with no production/consumption of goods and services.

Example 2. American economic growth 1800-2000.

- Suppose we allowed no drawdown of natural capital as part of the Constitution.
- Would we have the same economy we have now?

Economic sustainability: economic efficiency

Maximize present value of net benefits.

- High initial water table: drawdown to an optimal steady-state (OSS).
- OSS initial water table: maintain at that level (SGMA).
- Low initial water table: stock increases to an OSS.

Economic sustainability: growth and intergenerational equity

What is coming off an aquifer is income; sustainability is defined over household well-being and consumption. The two are potentially quite different because of investment opportunities in an economy.

Overdrafted water

- This creates economic value.
- Invest in infrastructure, factories, knowledge, solar power...
- Human-generated capital stock $\Uparrow$, groundwater stock $\Downarrow$.
- Done properly, the regional economy can be - on net - better off.

Economic sustainability: growth and intergenerational equity (cont.)

Two economies:

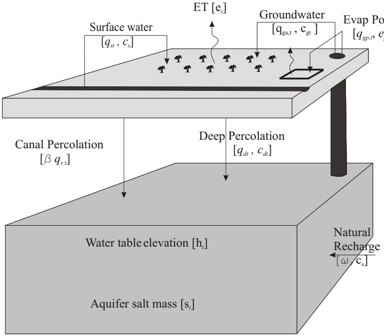
- Hydrologic steady-state economy: maintain groundwater stock and agricultural operations indefinitely.
- Modern growth economy: gw stock and farming decline, but there are hospitals, universities, high-tech industries, etc.

Model

- Agricultural region overlying a groundwater aquifer.
- Surface water imports and groundwater extractions.
- Canal and agricultural deep percolation to the aquifer.
- Investment in a risk-free financial asset.

Coupled agricultural production/water table model

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



Households

Representative household utility

$$\sum_{t=1}^{T} \alpha^t u(c_t) \tag{1}$$

$\alpha = 1/(1 + r_h)$ = discount factor, r_h = household subjective discount rate, and c_t = consumption. Instantaneous utility $u(c) = c^{1-\rho}/(1-\rho)$, $\sigma = 1/\rho$ is IES.

Output balance

$$c_t + \Delta k_t = \pi_t \tag{2}$$

Δk_t = net saving, π_t = agricultural income. Non-negative consumption $c_t \geq 0$ implies $\Delta k_t \leq \pi_t$.

Agricultural production

Annual net benefits from agricultural production are

$$\pi_t = b(q_t) - p_{sw} q_{st} - \gamma_e(\bar{h} - h_t) w_t \tag{3}$$

$b(q_t) = \int_0^{q_t} p(q)dq =$ benefits, $p(q) =$ water demand curve, $p_{sw} =$ surface water price, $\gamma_e =$ energy cost.

Total water use

$$q_t = q_{st} + w_t \tag{4}$$

q_{st} and w_t are surface and groundwater quantities respectively.

Deep percolation

$$q_{dt} = \beta_q q_t \tag{5}$$

$\beta_q =$ percolation coefficient.

Surface and ground water

Surface water use

$$q_{st} = (1 - \beta_s)\bar{q}_s \tag{6}$$

$\beta_s =$ surface water infiltration, $\bar{q}_s =$ surface water availability.

Water table equation of motion

$$h_{t+1} = h_t + \frac{\beta_s \bar{q}_s + \beta_q[(1 - \beta_s)\bar{q}_s + w_t] - w_t}{A s^y} \tag{7}$$

with $w_t \leq s^y(h_t - \underline{h})A$ and $\underline{h} \leq h_t \leq \bar{h}$, specific yield $= s^y$ and $\underline{h} =$ the aquifer bottom relative to MSL.

Investment and financial capital

Net savings are constrained by $-k_t \leq \Delta k_t$ where k_t represents financial capital. Borrowing is not allowed in this model, so dissaving cannot exceed the available capital stock k_t.

Capital stock equation of motion

$$k_{t+1} = (1 + r_m)(k_t + \Delta k_t) \tag{8}$$

with r_m the market interest rate. The constraint on net savings implies a non-negative financial capital stock in all periods ($k_t \geq 0$).

Data

The analysis is for Kern country, California, although some data values are from macro-economic data. Aquifer area is 1.29 million acres, although agricultural production is limited to 0.9 million acres. Data values are given in Table 1.

Household parameters

Empirical estimates for the IES (σ) are available from the macroeconomic literature. Hall (1988) finds elasticities of substitution ranging from $0.03 \leq \sigma \leq 0.48$, while Epstein and Zin (1991) report values in the range $0.18 \leq \sigma \leq 0.87$. Results from more recent studies include those of Favero (2005), in which the author estimates an IES in the range of 0.77 to 0.84. A baseline value of $\sigma = 0.4$ is used here, but with sensitivity analysis. Also assumed is a real rate of return for a risk-free financial asset of $r_m = 0.04$.

Discount rate

A variety of subjective discount rates are considered; however, the baseline value is $r_h = 0.05 > r_m = 0.04$. The reasoning for this is as follows: Due to transaction costs associated with banks and other financial institutions, there must be a positive gap between the borrowing rate and the saving rate. For borrowing to equal savings in an economy with heterogeneous agents, then, roughly speaking, the subjective discount rate for an average household would need to lie within this gap. Otherwise, assuming away strong non-convexities and income disparities, there would be either positive or negative net saving, and so the market rate would need to adjust for zero net saving in equilibrium. In any case, we will also consider $r_h = r_m$ and $r_h < r_m$ for completeness.

Surface and groundwater

Surface water in Kern County is high quality (low salinity) and comes from three major sources: the California State Water Project, the federal Central Valley Project, and the Kern River. Surface water costs are estimated from data in Vaux (1986) and Kern County Water Agency (1998) with inflation adjustment, and reflect differential costs of alternate sources within the region. Total diversions $\bar{q}_s = 1.97$ acre feet per year reflecting water deliveries in a normal year (Kern County Water Agency, 1998). Pumping costs are \$15.04 per acre ft. per year and are calculated using an energy cost of \$0.148 per acre foot per ft.of lift. Other surface water and aquifer parameter values and data sources are given in Table 1.

Horizon, initial conditions and solution procedure

The analysis is primarily focused on the life-history of the resource over a finite horizon. Accordingly, initial conditions are generally taken to be a full aquifer $h_1 = \bar{h} - h_z$ where h_z is rootzone depth, and zero net financial assets $k_1 = 0$. The optimization problem is solved using nonlinear programming (NLP) methods over either a 60 or 100 year horizon. While these initial conditions are our primary interest, some attention is also given to alternate initial conditions. For example, a formerly unmanaged aquifer might be at a lower initial level than an optimal steady-state, in which case standard PV-optimal management might involve increasing water table levels and consumption, hence sustainability even though this might not be true under similar conditions for h_1 high.

Sustainability criterion

- **Efficiency**: Pareto-optimality.
- **Equity**: non-declining utility.

Pareto-optimality

Short-run efficiency condition[Mitra].

Maximize $u(c_{t+1})$ subject to

$$\begin{aligned} u(c_t) &= \bar{u}_t \\ c_\tau &= \pi_\tau - \Delta k_\tau \\ h_{\tau+1} &= h_\tau + g(w_\tau) \\ k_{\tau+1} &= (1 + r_m)(k_\tau + \Delta k_\tau) \end{aligned} \tag{9}$$

$\tau \in \{t, t+1\}$, and given $\{h_t, k_t\}$, $\{h_{t+2}, k_{t+2}\}$.

Interior solution.

Sustainability conditions

Hotelling's rule(intertemporal efficiency):

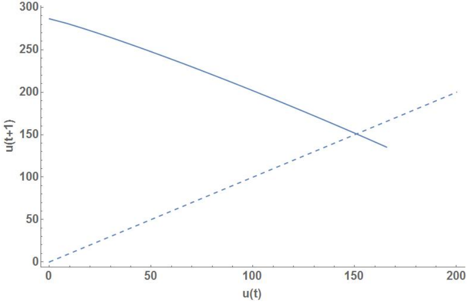
$$\frac{\partial\pi(h_{t+1}, w_{t+1})}{\partial w_t} = (1 + r_m)\frac{\partial\pi(h_t, w_t)}{\partial w_t} - \frac{\partial\pi(h_{t+1}, w_{t+1})}{\partial h_t} \quad (10)$$

Groundwater management is an investment. For efficiency, the economy is run so that rates of return are equalized for different investments in the economy. **Nondeclining utility (intergenerational equity):**

$$u_t \leq u_{t+1} \quad (11)$$

Future generations must be at least as well off as current generations.

Utility-possibilities frontier {t,t+1}



Infinite number of sustainable allocations. Discount rate s.t. PV-opt is sustainable.

Common Property

- Many relatively small users.
- Max ANB in each period [Gisser and Sanchez (1980)].
- Pumping decisions are independent of saving.
- Saving decisions are optimized given the income stream.

Optimal saving

Maximize the present value of utility

$$\sum_{t=1}^{T} \alpha^t u(c_t) \tag{12}$$

subject to the output balance equation (2),

$$c_t + \Delta k_t = \pi_t \tag{13}$$

the capital equation of motion (8)

$$k_{t+1} = (1 + r_m)(k_t + \Delta k_t) \tag{14}$$

and the associated bounds.

Annual income stream π_t is exogenous. Control variable is net savings Δk_t.

Time-series

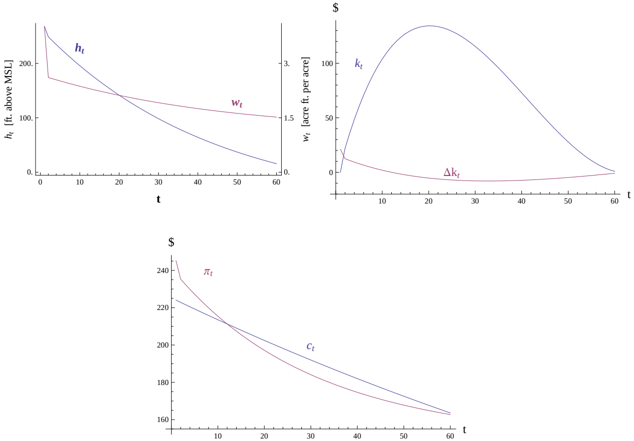


Figure: (i) Water table and extractions. (ii) Capital and net investment. (iii) Income and consumption.

Subjective discount rate sensitivity

Theoretical analysis:
consumption $\{\downarrow\uparrow\leftrightarrow\}$ as $\{r_h > r_m,\ r_h = r_m,\ r_h < r_m\}$.

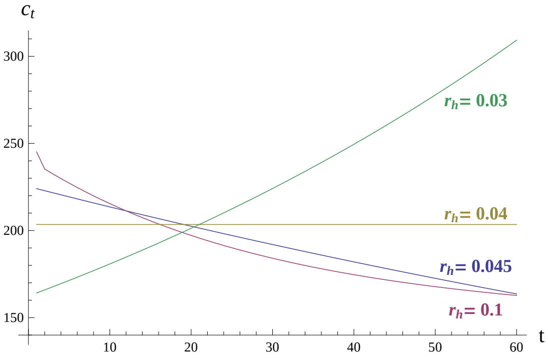


Figure: Consumption as dependent on household discount rate (r_h).

CP sustainability?

CP is not sustainable:

- Inefficient due to well-known pumping cost externality. *However, inefficiency is not necessarily large.*
- Declining consumption. *However, consumption smoothing implies consumption declines* $<$ *agricultural income decline.*

Is CP the fundamental cause of lack of sustainability?

PV[u] optimization

Maximize the PV of instantaneous utility.

- *Interpretation 1*: Competitive equilibrium with externality correction. Limitation is that generations here are 1-period, really need OLG model. However, if generations live 70-80 years, then this might not be a bad approximation given household discounting.
- *Interpretation 2*: PV optimality as a criterion to (possibly) achieve sustainability if CE is not sustainable.

Here we mainly follow *Interpretation 1*.

Optimization problem

$$Maximize \quad \sum_{t=1}^{T} \alpha^t u(c_t) \tag{15}$$

$$subject\ to \quad c_t + \Delta k_t = \pi_t \tag{16}$$

$$\pi_t = b(q_t) - p_{sw} q_{st} - \gamma_e(\bar{h} - h_t) w_t \tag{17}$$

$$q_t = q_{st} + w_t \quad q_{dt} = \beta_q q_t \tag{18}$$

$$h_{t+1} = h_t + \frac{\beta_s \bar{q}_s + \beta_q[(1-\beta_s)\bar{q}_s + w_t] - w_t}{As^y} \tag{19}$$

$$k_{t+1} = (1 + r_m)(k_t + \Delta k_t) \tag{20}$$

and the associated definitions and bounds.

Theory

Initially high water table
$\Rightarrow$ non-binding borrowing constraint:

Aquifer management according to PV[π]-opt.

Efficient:

- P-O essentially immediate.
- Hotelling's rule is satisfied.

Intergenerational equity:

Consumption $\{\downarrow \leftrightarrow \uparrow\}$ as $\{r_h > r_m,\ r_h = r_m,\ r_h < r_m\ \}$.

Time-series

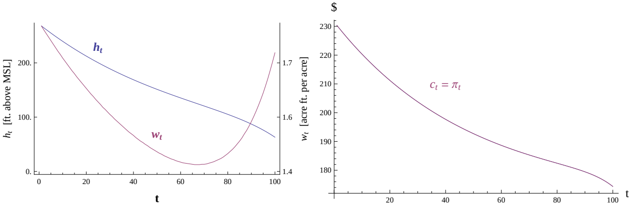


Figure: (i) Aquifer height and extractions. (ii) Income and consumption.

Subjective discount rate sensitivity analysis

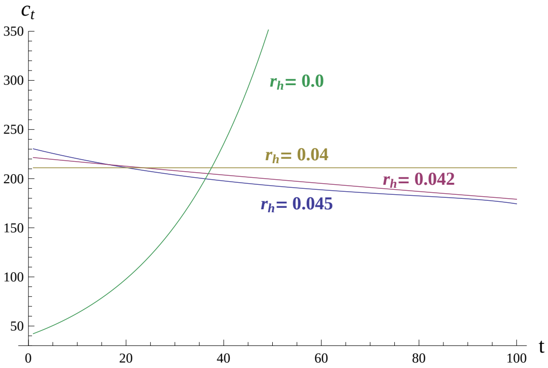


Figure: consumption as dependent on subjective discount rate (r_h).

PV[u]-opt sustainability?

PV[u]-opt is not necessarily sustainable:

- Efficiency = YES.
- Intergenerational equity = NOT NECESSARILY.

CP is not the only - or even fundamental - cause of lack of sustainability

Sustainability constraint

Sustainability constraint $u(c_t) \leq u(c_{t+1})$. *Limitations*:

- Incomplete ranking. Can't distinguish between a generation 100 years from now 1 penny worse off and survivability of all future generations.
- Doesn't easily extend to uncertainty.
- Author's experience, didn't work with ∞-horizon DP.
- What is the objective function being optimized?

Main difficulty is implicit assumption of infinite MC of constraint violation. Reasonable approach for finite-horizon models and policy analysis. Limitations may be more applicable to theory and infinite horizon.

Optimization problem

$$Maximize \quad \sum_{t=1}^{T} \alpha^t u(c_t) \tag{21}$$

$$subject\ to \quad u(c_t) \leq u(c_{t+1}) \quad c_t + \Delta k_t = \pi_t \tag{22}$$

$$\pi_t = b(q_t) - p_{sw} q_{st} - \gamma_e(\bar{h} - h_t) w_t \tag{23}$$

$$q_t = q_{st} + w_t \quad q_{dt} = \beta_q q_t \tag{24}$$

$$h_{t+1} = h_t + \frac{\beta_s \bar{q}_s + \beta_q[(1-\beta_s)\bar{q}_s + w_t] - w_t}{As^y} \tag{25}$$

$$k_{t+1} = (1 + r_m)(k_t + \Delta k_t) \tag{26}$$

and the associated definitions and bounds.

Theory

Initially high water table
$\Rightarrow$ borrowing constraint non-binding:

Aquifer management according to PV[π]-opt. Sustainability constraint met by saving.

Efficiency: satisfies Hotelling's rule (necessary condition).
Intergenerational equity: guaranteed by constraint. Could get increasing consumption if r_h low enough.

Baseline time-series

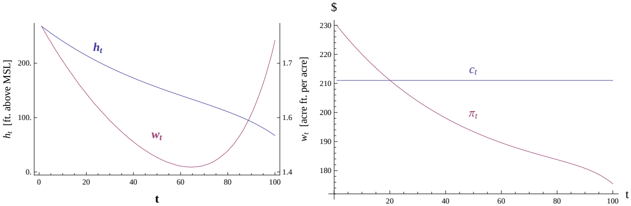


Figure: Sustainability: Income and Consumption

Sustainability constraint

Sustainable:

- Efficiency = YES.
- Intergenerational equity = YES.

Sustainability can be consistent with falling water tables; in fact, may require them.

Conclusions

Analytical framework

- Extend the standard groundwater economics model to include household saving.
- Apply a formal sustainability criterion.

Can't evaluate sustainability by resource-only analysis!
Sustainability can be consistent with falling water tables; in fact, may require them.

CP and PV[U]-opt sustainability

CP is not sustainable:

- Not efficient (pumping cost externality, might be small).
- Baseline not equitable; alternate r_h can $\Rightarrow \leftrightarrow\uparrow u_t$.

PV[u]-opt is not necessarily sustainable:

- Efficient.
- Baseline not equitable; alternate r_h can $\Rightarrow \leftrightarrow\uparrow u_t$.

CP and externalities are not the only - or even fundamental - cause of non-sustainability.

Saving might imply smaller non-sustainability than inferred from physical variables or income.

An unnerving conclusion

In this particular problem (not all resource problems), sustainability is less about resource management and more about what happens with the rents.

Unnerving conclusion for market economies and democracies.

Property rights in the resource: do they belong to the users or to the regional population?

Skeptics guide to SGMA (2016)

There have always been provisions in the law for groundwater users to self-organize (witness Southern California).

- Why didn't this happen?
- Perhaps because gains from management not that large?

Economy and society have been left out?

- Might be very inefficient.
- Imposes costs and possibly even damages on the local economy.
- What about farmworkers and the broader community?

Skeptics guide to SGMA (2016) continued.

Regulation is not free.

- Imposes time and money costs on growers, district managers, and others.
- State must divert scarce resources from schools, roads, hospitals, ...
- Even with net gains from management, regulatory costs could outweigh them.
- State as a whole could lose.

Skeptics guide to SGMA (2016) continued.

Could be stagnating to economic growth.

- With cutbacks, growers and farmworkers might have to save less for college funds and retirement.
- Less investment in industry, service sector, ...
- Less funding for infrastructure.
- California can withstand *ad hoc* management.
- Could be very damaging in low-income/developing countries.

If we want this law to be about people rather than just the aquifer, then we need considerably more - and better founded - formal analysis. Can't just assume a quantitative groundwater management strategy.