# Sustainability Economics of Groundwater Usage and Management

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# Introduction

Sustainability analysis is widely discussed in natural resource economics and policy settings. However, beyond discussion of Green GDP, there is relatively little formal analysis. This paper analyzes sustainability in the context of groundwater.

## Groundwater economics: general

- Burt; Gardner and Brown: 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: spatial dynamics.
- Olson and Conrad; Zeitouni: quality.
- Khoundrini; Knapp and Baerenklau: quantity and quality.
- Richard; Roumasset; Reinelt: seawater intrusion.

## Groundwater economics: sustainability

- Explicit sustainability definitions are rare!
- *Reverse-engineered definition: declining water tables.*
- OSS: ignores transition period which can be decadal.
- Lower the discount rate: violates asset equilibrium in the general economy.
- Non-declining income in a resource-only model: stepwise-inefficiency [Woodford].

# Research objective

This paper extends the literature to consider groundwater sustainability. Following the **capital-resource literature** [e.g. Mourmouras (1991), Asheim (2001)]

- **Sustainability** = **efficiency** (Pareto-optimality) + **intergenerational equity** (non-declining utility).
- The standard CP and PV-optimal groundwater models cannot be used to assess sustainability since these models report only income streams and the physical variables, while sustainability is measured over consumption.

Standard groundwater economics model is extended to include household utility and saving/dissaving from a **financial asset**.

# Contribution

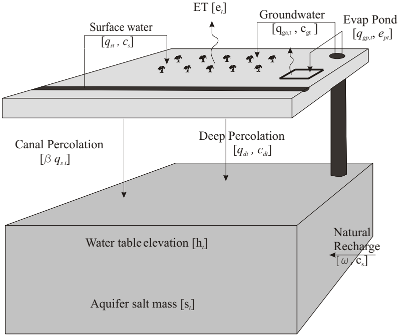
- Formal sustainability analysis for groundwater. (Other studies: lower disount rate, stepwise-inefficiency.)
- Extend capital-resource sustainability literature to CP natural resources.
- CP inefficient, but might be equitable; PVU-opt efficient but might not be equitable.
- Previous theoretical work has discussed sustainability of competitive equilibrium for a renewable resource [Mourmouras], and provided an axiomatic basis for the sustainability criterion utilized here [Asheim]. However, there is relatively little available work applying the concept to evaluate and calculate sustainable allocations.
- Finally this work also motivates the need for resource management studies to consider the role of borrowing/saving and household preferences for natural resource management.

# 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

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

$\Delta k_t =$ net saving, $\pi_t =$ 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**

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

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 ($\sigma$) 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

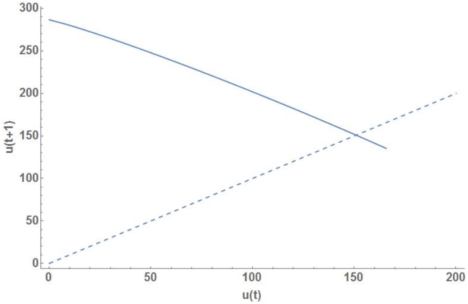
**Hotelling's rule(intertemporal efficiency):**

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

**Nondeclining utility (intergenerational equity):**

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

## 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.

# Time-series

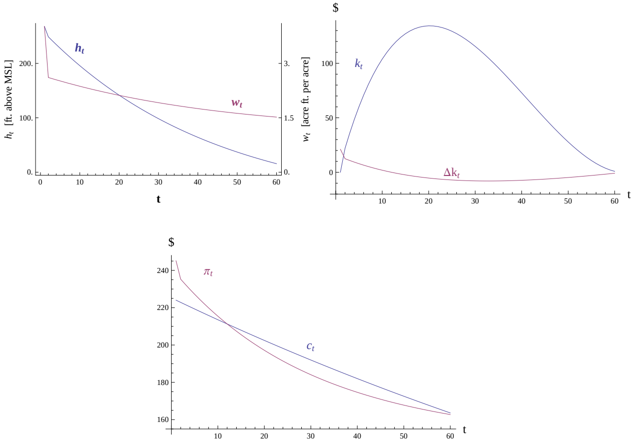


Figure: (i) Water table and extractions. (ii) Capital and net investment. (iii) Income and consumption.

# 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 $\pi_t$ is exogenous. Control variable is net savings $\Delta k_t$.

# Subjective discount rate sensitivity

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

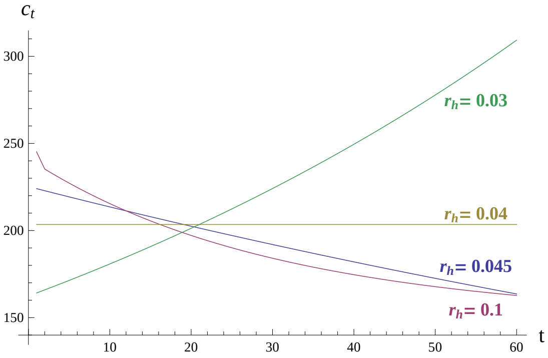


Figure: Consumption as dependent on household discount rate ($r_h$).

# 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[$\pi$]-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

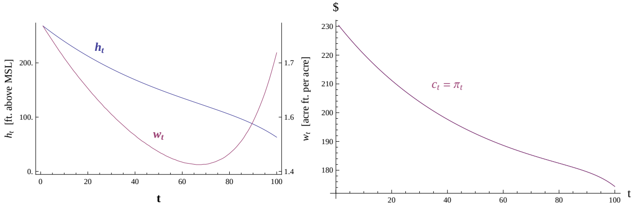


Figure: (i) Aquifer height and extractions. (ii) Income and consumption.

# Subjective discount rate sensitivity analysis

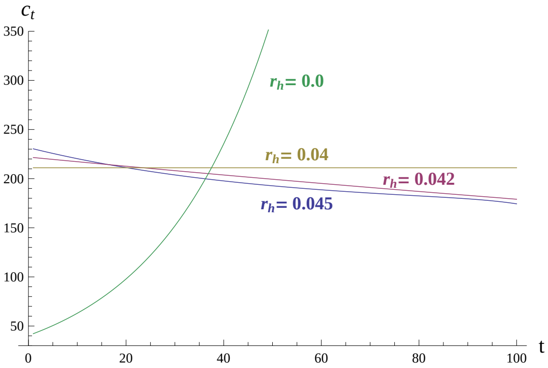


Figure: consumption as dependent on subjective discount rate ($r_h$).

# 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 $\infty$-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[$\pi$]-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

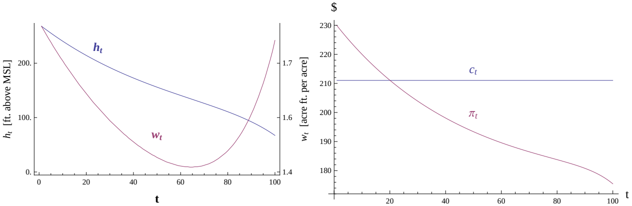


Figure: Sustainability: Income and Consumption

# Sustainability constraint

**Sustainable:**

- Efficiency = YES.
- Intergenerational equity = YES.

**Sustainability is 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.

**Contrast with previous work**

- Previous GW Econ literature is resource-only.
- Previous analysis/discussion not necessarily efficient or considering transition paths.

**Can't evaluate sustainability by resource-only analysis!**

## Aquifer management

**Initially high water table** means that the aquifer is managed according to standard PV[$\pi$]-opt model.

This is **not general**:

- Low initial water table plus borrowing constraint.
- Endogenous market interest rates.

## 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**.

**Sustainability constraint:**

- Efficient.
- Constant utility under baseline conditions,

**Sustainability is consistent with falling water tables; in fact, may require them.**

# Borrowing/saving

**Standard separation theorems** ⇒ separate household and production decisions, so PV optimization at the market interest rate is the appropriate criterion. Most natural resource economics literature utilizes this criterion.

Presupposes **perfect capital markets** where borrowing and saving at a constant rate are possible.

- Limited capital markets in low-income countries.
- Borrowing constraints even in high-income countries (Ponzi game).
- Endogenous interest rates
  (e.g. transaction costs, household debt burden, capital accumulation in growth models).

# Future work

**Limitations, extensions, modifications, applications ...**

… **Infinite!**