Beyond Sustainable Yield: Managing Multiple Aquifers, Recycling, and Watershed Conservation in the South Oahu Aquifer System

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Source: Commission on Water Resource Management
Robust Analytical Model (RAM)

Ghyben-Herzberg lens (adapted from Liu, 2006)

What is sustainable yield?

- “allowable net draft for a selected equilibrium head” (Mink, 1980), i.e. that “could be sustained indefinitely” without undesirable results (Lau and Mink, 2006)
- Every point on the (solid) curve can be sustained indefinitely.

“Net recharge” ≡ exogenous recharge – head-dependent-leakage
RAM2: Sustainable yield = maximum sustainable yield (MSY)

- “RAM2 calculates analytically the minimum equilibrium head, which is the hydraulic head of a basal aquifer required to prevent the salinity of water pumped out from becoming higher than the acceptable level” (Liu, 2007)
Approach paths?

Problem

- How to best sustain consumer welfare? (Not yield)
- If MSY is a suitable long range target, how to get there?
Sustainability science

- Sustainable development is about sustaining human welfare in the face of the eco-econ system and declining natural capital
- How we manage (water) resources is a means to that end
- Interacting pieces of a resource system
- Transdisciplinary modeling
- Target paths of water stocks, natural capital, infrastructure
- Implementation strategy (e.g. water prices)

Eco-econ system: it’s the environomy, stupid!

- NATURE
  - Wastes
  - Impacts on biodiversity
- THE ECONOMY
  - Firms (production)
  - Households (consumption)
  - Inputs
  - Outputs
  - Resource inputs
  - Amenity values
  - Global life-support
Extensions

- If there are multiple aquifers, which one to use first and how fast to deplete each to MSY?
- How does water reuse change the optimal management strategy?
- Climate/Invasives: How does declining recharge change optimal management? How to finance watershed conservation? $.05/tg?

Two-aquifer schematic
Total benefit is area under marginal benefit (demand) curve

Demand is a relationship, not a number.

“Demand projections” do not account for the possibility of changing price.

Golden rule of resource extraction

- Objective: choose extraction to maximize present value (PV) net benefits
  \[ \text{Max } \sum_{t=0}^{\infty} \left( \frac{1}{1+r} \right)^t \text{(net benefits)} \]
  subject to \( x_{t+1} - x_t = F(x_t, q_t) - q_t \)

- Nike principle of economics: Just do it until marginal benefit equals marginal cost

- Pearce equation:
  - MB = MOC (marginal extraction cost + marginal user cost)
  - MUC is “…the loss in value when a capital asset is reduced by one marginal unit” (Clark, 2005)
Optimal steady state turns out to be MSY

Managing multiple aquifers

- With two aquifers, the resource manager faces the following problem:

\[
\text{Max } \sum_{q_i', q_i^2, b_i}^{\infty} \left( \frac{1}{1 + r} \right)^t \left[ \text{Benefits}(q_i^1 + q_i^2 + b_i) - \text{Costs}(q_i^1, q_i^2, b_i; h_i^1, h_i^2) \right]
\]

- Subject to:

\[
\begin{align*}
  & h_{i+1}^1 - h_i^1 = \overline{R}_1 - L_1(h_i^1) - q_i^1 \\
  & h_{i+1}^2 - h_i^2 = \overline{R}_2 - L_2(h_i^2) - q_i^2 \\
  & q_i^1 \geq 0, q_i^2 \geq 0, b_i \geq 0 \\
  & h_i^1 \geq h_i^1_{\text{min}}, h_i^2 \geq h_i^2_{\text{min}}
\end{align*}
\]
Optimal order of extraction: the least shall be first

- Optimal extraction requires that the aquifers are used in reverse order of their MOCs (scarcity values):
  \[ MOC_t = \min[MOC_t^1, MOC_t^2, c_b] \]

- Least-cost first (cost includes lost asset value)
- Pearl Harbor aquifer has a higher extraction cost than Honolulu aquifer but a lower scarcity value

**Order of extraction: Honolulu and Pearl Harbor aquifers**

![Diagram showing the order of extraction with time and MOC values](image_url)
Implementation by block pricing

- Price is one instrument that can induce efficient consumption
- Block pricing permits maximum sustainability of consumer welfare without making current consumers worse off

![Graph showing block pricing](Image)
Water reuse to supplement groundwater extraction

- Adding recycled water as an alternative to groundwater for the non-potable sector means the resource manager’s problem is modified as follows:

\[
\begin{align*}
\text{Max} & \quad \frac{1}{1 + r} \sum_{t=0}^{\infty} \left( \text{Benefits}^H + \text{Benefits}^N - \text{Costs} \right) \\
\text{Subject to:} & \quad h_{t+1} - h_t = R - L(h_t) - (q_t^{GH} + q_t^{GN}) \\
& \quad \beta(q_t^{GH} + q_t^{BH}) - q_t^{RN} \geq 0
\end{align*}
\]

- H: household sector; N: industrial sector

Honouliuli Water Recycling Facility

Source: Honolulu Board of Water Supply
Cost of wastewater treatment for reuse

- Variable costs: energy, labor, etc.
- Infrastructure: treatment facility, pipes, etc.
- Possible modeling strategies
  - Constant unit cost: infrastructure costs amortized; may make sense for “satellite” treatment facilities
  - Rising unit cost: continuum of users ordered by distance from treatment facility; may make sense if scale economies are very large

Optimal order of resource use by sector

- Resources should be used in the reverse order of their scarcity value (MOC) within each sector

- The scarcity value of water for each sector is therefore:
  \[
  MOC_i^H = \min\{MOC_i^G, MOC_i^B\}
  \]
  \[
  MOC_i^N = \min\{MOC_i^G, MOC_i^R, MOC_i^B\}
  \]
### Stages of optimal water use

#### Constant unit recycling cost

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Steady state</th>
</tr>
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#### Increasing unit recycling cost

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**Sector-specific backstop**

**Intermediate backstop**

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**Head Level Groundwater Extraction**

![Scarcity value of water in the H-sector](chart1.png)

![Scarcity value of water in the N-sector](chart2.png)

**Groundwater Extraction**

![Groundwater Extraction](chart3.png)

**Key:**
- Optimal
- No recycling
- Premature recycling

PV welfare loss (% loss)

- No recycling: $67 million (0.6%) / BCR=1.3
- Premature recycling: $500 million (4.5%)
Adapting to declining recharge

- Climate change and invasive species threaten the condition of the watershed. If we do nothing, recharge will decline. **Maximum sustainable yield is non-sustainable.**
- An additional water management instrument to investing in infrastructure and technology for other water resources (e.g. desalination, wastewater reclamation) is investing in nature’s infrastructure.

Optimal watershed investment and groundwater extraction

- The resource manager must decide on the rates of investment and extraction simultaneously:

\[
\text{Max}_{q_t, b_t, I_t} \sum_{t=0}^{\infty} \left( \frac{1}{1+r} \right)^t \left[ \text{Benefits}(q_t + b_t) - c_q(h_t)q_t - c_b b_t - c_I I_t \right]
\]

- Subject to: 
  \[
  h_{t+1} - h_t = R(N_t) - L(h_t) - q_t \\
  N_{t+1} - N_t = I_t - \Delta N_t \\
  I_t \in [0, I_{\text{max}}] \\
  R_{n>0}
  \]
Pearce equation

- Condition is the same whether investment is zero or positive, but the actual paths will differ (optimal paths of N and h will differ)

\[ p_t = c_q(h_t) + \frac{\dot{p}_t - c_q'(h_t)[R(N_t) - L(h_t)]}{r + L'(h_t)} \]

- Price at MOC, but MOC (scarcity value) is a function of the state of the watershed

Pearce equations for various conservation scenarios
DLNR: $.05 water surcharge for watershed conservation?

- “By establishing a dedicated source of funds to protect, preserve, and enhance important watershed areas…the State will be better able to ensure that the essential and sustainable sources of fresh water will exist for future generations’ use.”
- Impose a “watershed protection tax of 5 cents per one thousand gallons of water used.”

Source: Hawaii State Legislature Archives, HB2835 through SSCR2919 (2000)

Calculating the optimal fixed surcharge

- Optimize groundwater and watershed → PV cost of (optimal) investment and PV benefit from (optimal) water use
- The proportion of benefits that balances the intergenerational budget is \( \alpha = \frac{PV \text{ costs}}{PV \text{ benefits}} \)
- The period-t benefit from consumption can be calculated with \( (V_t) \) and without \( (W_t) \) optimal investment
- The optimal lump-sum tax for a period-t consumer is then: \( \tau_t = \alpha(V_t - W_t) \)
Conclusions

- MSY (RAM II version of sustainable yield) is the economically correct long run head level. But in the interim head levels should go up and then down.
- In PHA/Honolulu case, use PHA first, i.e. large buildup of HNL.
- Reusing treated wastewater in effect subtracts from demand for potable water, thus stretching out the time before desalination becomes necessary.
- Watershed conservation ameliorates upward pressure on scarcity.
- Fixed, not volumetric, surcharges.
- All require price reform.
What enabling legislation is needed?

- Pricing for historical cost recovery leads to wasted water now, premature desalination, and high prices in future.
- Benefit finance requires debt for price reform and other investments. Same principle as capital improvements budget.
- State water code to move beyond sustainable yield?

  *Sustainable yield means the maximum rate at which water may be withdrawn from a water source without impairing the utility or quality of the water source as determined by the commission.*

  State Water Code (HRS 174C-3)

Extensions

- Increasing costs for recycling
  - Differentiate users across space
  - Better estimates of treatment and distribution costs
- Watershed optimization
  - Key is establishing link between investment dollars and recharge. (Big research challenge.)
- Back to Mink?: reverse osmosis of brackish groundwater as another intermediate backstop
Mahalo!