Integrated hydro-economic management of seawater intrusion

Peter Reinelt

Dept. of Economics, State University of New York, Fredonia, USA

ABSTRACT

Comprehensive management of seawater intrusion (SWI) must integrate economics and hydrology. Hydro-economic analysis can inform SWI management in four ways.

First, failure to understand economic incentives of groundwater extractors can lead to excessive spending on technical solutions that overlying landowners will not support. For example, SWI has been documented advancing inland through the multi-layer confined aquifers of the Salinas Valley in California for more than 75 years, threatening existing agricultural and municipal water supplies. The components of a comprehensive structural solution have been known, recommended, and widely accepted for 65 years (Reinelt 2005). Yet, despite a multitude of water agency studies and proposed projects, overlying landowners have failed to fund the construction of the water conveyance component of the structural solution. To the landowners, the present value cost of funding the structural solution has been more than the present value benefits of slowing SWI. Understanding when the cost of continued SWI will become greater than the cost of the structural solution can improve planning and the spending of resources designing structural solutions.

Second, hydro-economic analysis reveals that the common property rate of SWI, where extractors make decentralized pumping decisions, is greater than the optimal rate of SWI and is thus economically inefficient. The divergence between the optimal and common property rates can be used to design spatial pumping fees to manage private incentives, which may be less expensive than structural solutions. Since individual extractors make pumping decisions based on private incentives (benefits and costs), the spatial pumping fees must be designed to internalize the costs that individual extractors impose on other extractors, common property externalities in the terminology of economics. If extractors are charged a pumping fee equal to the marginal pumping cost externality (cost imposed on other extractors through lowering groundwater levels) and the marginal SWI cost externality (cost imposed on landowners whose property is intruded), then decentralized pumping decisions will lead to the optimal rate of SWI.

Third, the hydro-economic analysis of the spatial profile of the full marginal opportunity cost of water equal to the marginal cost of extraction plus the marginal pumping cost externality plus the marginal SWI cost externality can inform the design of economically efficient structural solutions, in particular the location within the aquifer system that is the least-cost water source for transfer to intruded areas.

Fourth, SWI is economically efficient in some circumstances. In other words, banning or stopping SWI is more costly to the economy than allowing SWI to continue. The economic analysis of SWI examines the tradeoff between building a structural solution now or allowing SWI to occur and building a structural solution later. Since there is a time value of money characterized by an interest or discount rate, it is often less expensive in present value terms to delay the construction of smaller capacity physical solution, as occurred in the Salinas Valley, allow SWI to occur, and build a somewhat larger capacity physical solution later.

ECONOMIC MODEL

Economic models of groundwater management expressed as optimal control problems typically compare extraction under two institutional arrangements: 1) common property where each groundwater extractor maximizes their individual present value of net benefits (benefits minus cost), and 2) optimal extraction where a watermaster maximizes the present value of the net benefits for the whole aquifer. Comparison of these two cases reveals the potential gains from optimal management. To simplify, consider a farming region where extractors are individual farms. In this case, benefits are revenues.[1]

Common Property Extraction

Under the common property institutional arrangement, each firm maximizes the present value of its private revenues minus costs

$$\max_{u(x,t)} \int_0^\infty e^{-rt}\left[R(u(x,t)) - C(u(x,t), g(x) - h(x,t))\right]dt \qquad (1)$$

subject to differential state equation constraints which describe both the water table or piezometric surface and the extent of SWI (rendering parts of the aquifer unsuitable for pumping) and where

R(pumping rate) = revenue function
C(pumping rate, lift) = cost function
u(x,t) = *pumping rate per unit area*
h(x,t) = *water table or piezometric surface elevation*
g(x) = *ground surface elevation*

Therefore, each firm pumps until its marginal revenue product of water equals its full marginal opportunity cost of pumping another unit of water. In dynamic aquifer models, the marginal opportunity cost of pumping water has two components: the marginal cost of extraction and the private marginal user cost, which accounts for the firm's foregone future value of a unit reduction in groundwater stock. The common property calculations in this study impose the additional assumption of a very large number of small firms, which renders a single firm's private marginal user cost negligible. In this case, each firm's intertemporal profit maximization condition for all time *t* and all locations *x* reduces to

$$\frac{\partial R}{\partial u} = \frac{\partial C}{\partial u}$$ i.e. marginal revenue product = marginal pumping cost *(2)*

Optimal Extraction

Under optimal extraction, a watermaster would maximize the present value of benefits minus cost (or revenue minus cost in this case) for the whole aquifer of width *w* and inland length *L*.

$$\max_{u(x,t)} \int_0^\infty e^{-rt}\left[w\int_0^L \left[R(u(x,t)) - C(u(x,t), g(x) - h(x,t))\right]dx\right]dt \qquad (3)$$

subject to differential state equation constraints which describe both the water table or piezometric surface and the extent of SWI rendering parts of the aquifer unsuitable for pumping. The first order condition for this maximization has the form

[1] For municipal water use, a benefit function can be derived from the demand function for water.

$$\frac{\partial R}{\partial u} = \frac{\partial C}{\partial u} + MPCE + MSWICE \qquad (4)$$

In Eq. (4) two additional terms appear compared to the common property case in Eq. (2). MPCE is the marginal pumping cost externality; this is the cost imposed by extractors on other extractors through the lowering of groundwater levels. MSWICE is the marginal SWI cost externality; this is the cost imposed by extractors on other extractors whose lands become intruded. Optimal extraction from society's perspective requires that these additional costs, ignored under common property, be taken into account in pumping quantity decisions.

MODEL RESULTS

Reinelt (2005) applies these principles to the confined aquifers of the Salinas Valley with a numerical optimization model, a freshwater fundamental flow equation, the rate of SWI determined by the negative gradient at the coastal interface, and a fixed water level inland boundary condition since the unconfined recharge region in the Salinas Valley regularly fills and spills excess potential recharge river water to the sea. Reinelt (2010)develops analytical results with salt and freshwater regions governed by the fundamental flow equations with continuity of flow and pressure at a sharp interface. Since it is not possible to incorporate analytical models of the mixed water region, the shape of the interface is not estimated, but the average distance of the interface is estimated with a model assumes saltwater to the average distance of the interface and freshwater beyond. The rate of SWI is determined by the negative gradient at the coast, which coupled with porosity determines the average extent of SWI. A simple model of an unconfined recharge region with appropriate continuity conditions with the confined aquifer is also included. Selected results from Reinelt (2010) follow:

Proposition 5: *In the confined aquifer*:

a) *The marginal pumping cost is concave with distance x from the coast*.

b) The marginal pumping cost externality is concave with distance x from the coast.

c) *The marginal SWI cost externality decreases linearly with distance x from the coast.*

Proposition 6: *For any decreasing marginal revenue product function for water, the optimal spatial profile of pumping in the confined aquifer is convex (and will generally be increasing with distance x from the coast if SWI is a significant problem).*

CONCLUSION

The spatial dimension of SWI requires both expansion of the institutional dimensions of the typical economic analysis and re-interpretation of Provencher and Burt's (1993) taxonomy of the common property externality into a pumping cost externality and a stock externality. As seawater progressively intrudes under coastal lands, landowners in intruded areas can no longer exercise their water rights. Thus, the institutional analysis must be extended beyond the typical decision-making dimension—common property vs. watermaster—to consider the relaxation of the appurtenancy dimension of groundwater rights, restricting water pumping only for beneficial use on overlying lands, to consideration of intra-basin water transfers.

The characterization of the spatial-dynamic structure of both the pumping cost externality and the SWI cost externality can be used to develop optimal management policy under either institutional structure. Under enforced appurtenancy, this structure implies the optimal spatial-dynamic tax/water charge policy. If water transfers are permitted, the spatial shape of the full opportunity cost of water, combined with transfer costs as a function of distance and volume, can be used to deduce the efficient structural design to transfer water to intruded areas, in particular identifying the least-cost source of transfer water within the aquifer system

Finally, some confusion has arisen in the literature about the spatial form of the SWI externality through comparison of results between confined and unconfined SWI without recognizing the very different mechanisms by which SWI occurs in each type of aquifer. Moreaux and Reynaud (2006) report a spatially uniform MSWICE (and thus pumping tax) for an unconfined aquifer and contrast with the linearly increasing tax of Green and Sunding (2000) based on the spatial contribution to SWI derived from a purely hydrological engineering simulation model. Unfortunately, Moreaux and Reynaud fail to mention that Green and Sunding analyze a confined aquifer. While Moreaux and Reynaud recognize that their uniform tax result depends on their simplified form for the hydrological model, examination of a more accurate model suggests that the steady-state divergence from spatially uniform causation of SWI is likely to be small for unconfined aquifers. Further research is needed to clarify this matter. Finally, future hydro-economic analysis that combines the foregoing economic optimization models with more realistic finite element or other numerical simulation hydrological models is needed.

REFERENCES

Green, G. and D. Sunding (2000). "Designing Environmental Regulations: The Case of Seawater Intrusion." *Resource and Energy Economics* 22(January): 63-78.

Moreaux, M. and A. Reynaud (2006). "Urban freshwater needs and spatial cost externalities for coastal aquifers: A theoretical approach." *Regional Science and Urban Economics* 36(2): 163-186.

Provencher, B. and O. Burt (1993). "The Externalities Associated with the Common Property Exploitation of Groundwater." *Journal of Environmental Economics and Management* 24: 139-158.

Reinelt, P. (2005). "Seawater intrusion policy analysis with a numerical spatially heterogenous dynamic optimization model." *Water Resources Research* 41: W05006.

Reinelt, P. (2010). *Spatial-dynamic seawater intrusion and pumping cost externalities in a confined aquifer*, SUNY Fredonia.

Contact Information: Peter Reinelt, Dept. of Economics, SUNY Fredonia, Fredonia NY 14063, USA , Phone: 716-673-3291, Email: reinelt@fredonia.edu