Environment and Development Economics 7: 625–641 © 2002 Cambridge University Press
DOI:10.1017/S1355770X02000384 Printed in the United Kingdom

Policy issues and institutional impediments in the management of groundwater: lessons from case studies

CHARLES W. HOWE[1]
Professional Staff, Environment and Behavior Program, and Professor Emeritus of Economics, University of Colorado-Boulder, Campus Box 468, University of Colorado, Boulder, CO 80309,USA

ABSTRACT. Many opportunities exist to take advantage of integrated surface water–groundwater management with consequent resource and investment savings. In inappropriate legal and administrative settings, groundwater becomes an open-access resource leading to excessive contemporary and inter-temporal externalities. Several policy instruments have been used to correct these externalities: limits in well spacing and capacities, pumping taxes and tradable pumping permits. Urban–agricultural competition for limited groundwater need not result in crises for either sector if these instruments are used to mediate the competition. In the case of non-renewable stocks of groundwater, rates of economic and demographic development should be planned in keeping with long-term criteria to avoid overly rapid exploitation of the resource, non-sustainable population levels and inappropriate investment in infrastructure. Island states and coastal areas have special problems related to saltwater intrusion and coastal subsidence that can be mitigated if not eliminated through the use of economic and physical measures. Five brief case studies illustrate these points.

1. Background and statement of the issues

It has been recognized for many years that large benefits can be gained from the coordinated management of surface waters and ground water systems. Aquifers provide natural storage reservoirs with little evaporative loss. They provide natural transmission of water from the various sources to points of use. During periods of drought they provide reliable supplies. In some situations, groundwater quality is superior to that of surface supplies. Yet, very few systems of explicit conjunctive management are found, even in advanced countries (Gleick, 1993: various sections under groundwater). Until the 1940s, one reason for this was a lack of understanding of groundwater hydrology and poorly developed models of groundwater–surface water interaction. Since the 1960s, however, groundwater modeling has advanced quite substantially, and combined economic–management–hydrology models have been developed for several river-aquifer systems (for example Young and Bredehoeft, 1972;

---

[1] The author wishes to thank two referees for very careful, constructive and generous comments on earlier versions of the paper.

Bredehoeft and Young, October, 1983; National Research Council (US), 1990). Thus the increased use of conjunctive management now represents great potential for added benefits from water management.

The main impediments to wider use of conjunctive surface–groundwater management are: 1. the geographic fragmentation of decision-making responsibility for hydrologically based systems; 2. issue fragmentation of decision making among multiple agencies, each with different missions, responsibilities, and expertise; and 3. failure to integrate property rights systems applicable to surface and groundwaters (Schenkkan, 1996).

Some groundwater systems involve intimate connection with surface supplies (so-called 'tributary groundwater') while others recharge from rainfall on the surface. Recharge can be expanded through 'artificial recharge' procedures in which water supplies, sometimes using treated waste waters, are pooled over highly permeable aquifers for increased infiltration. In some applications, injection wells can be used to recharge water to deeper levels or into less pervious aquifers (Castro, 1996; Agbanobi, 1996; Longebaugh, 1984).

Some stocks of groundwater are found in largely non-renewable aquifers where water was deposited in ancient times, underlying regions having little river flow or precipitation and thus little recharge. An important example is found in parts of the large, multi-state Ogallala aquifer that underlies parts of five states in the semi-arid High Plains Region of the Western US (Van Slyke, 1990; Bittinger and Green, 1980). This type of groundwater stock should be managed with an eye to the very long-run future, using economic principles for non-renewable resource management (for example Harold Hotelling's famous model, 1931) and should be linked to the policy issue of efficient time patterns of economic and population development (Howe, 1996).

Coastal areas and small islands face unique groundwater problems because of their vulnerability to salt water intrusion. Many coastal areas have experienced salt water intrusion because of excessive pumping, for example the Costa de Hermosillo, Sonora, Mexico; Orange County, California; and many areas of the Middle East (Cummings, 1974; National Research Council (US), 1997: chapter 6; Biswas, 1994). The fresh water lens underlying islands is especially vulnerable to salt contamination through excessive fresh water pumping.

Groundwater quality has become a major issue. Industrial and agricultural contaminants have found their way into the groundwaters of many large regions, leading to increased water treatment costs and residual human health problems. For example, the US Geological Survey has found high levels of nitrates and pesticides in water of the Ogallala aquifer (US Water News, 1999: 7). In some cases, increased salinity or toxic materials (for example arsenic, selenium) from both natural and human sources have rendered the groundwater unusable even for agricultural purposes.

The remainder of this paper will expand on these issues from a conceptual point of view, followed by brief case studies that illustrate important problems and exhibit innovative economic and managerial approaches to the solution of those problems.

2. Economic issues in the management of groundwater

As noted above, large benefits can be gained from the conjunctive management of surface and ground resources, using the excellent storage provided by aquifers at little or no cost and with very little evaporative loss. In contrast, evaporative loss off the surface of reservoirs can amount to two meters or more per year in hot, arid climates. If the aquifers have sufficient storage volume, groundwater can be substituted for surface water in extended droughts. The ability to pump from any point over the aquifer obviates the need for conveyance systems like pipelines or canals with their energy and maintenance costs.

The complexities of groundwater management stem from the physical interconnections among the pumpers and impacted surface water users, as well as those affected by surface subsidence (land surfaces in parts of central Arizona have fallen 9 meters in the last 20 years). Thus individual actions are likely to impact other activities (sometimes in positive ways but most often in negative ways) in ways that escape the decision maker's attention. These external impacts are called 'externalities' in economic terms and can be classified as: *1. contemporary pumping externalities; 2. intertemporal externalities; and 3. groundwater quality externalities.* Since externalities are always created in water systems, the question is whether they are excessive as judged by an economic efficiency criterion.

One contemporary externality takes the form of affecting other groundwater users (especially those in close proximity) by lowering their water tables and increasing their pumping costs. Another contemporary externality, which can be positive or negative, is the effect on surface water users that results from recharge into the aquifer from surface streams or from the additions to streamflow from the aquifer in the late season.

The major intertemporal externality is the change in groundwater stock that affects conditions of water availability in the future—both the stock and costs of recovery. In some geological settings, sustained groundwater pumping results in the compaction of the aquifer with resultant reduction in the storage capacity of the aquifer while affecting occupants of overlying land areas through surface subsidence.

Water quality externalities can be both contemporary and intertemporal and result when water at different depths has different quality or if salt water intrusion is induced by pumping. Groundwater quality externalities are likely to occur when different 'layers' of groundwater are of different quality—usually with quality diminishing with depth, although there are cases where deeper *confined* aquifers contain higher quality waters. Particularly important are those coastal and island situations where salt water intrusion occurs with the drawdown of the fresh water stock underlying the area (or the 'lens' underlying islands). Salt water intrusion, like other forms of groundwater contamination, can be irreversible or reversible only at high cost by injecting fresh water under high pressure. Salt water intrusion then can permanently destroy the useful storage capacity of the aquifer.

As noted above, externalities are the rule rather than the exception in water systems. The real issue is not the elimination of externalities (usually physically impossible) but whether or not the impacts on others are *excessive* relative to some standard. The standard usually used in judging the appropriateness of externalities is that of *economic efficiency* which is achieved when resources are being used over time in patterns that maximize the *present value* of the differences between social benefits and costs. In practice, one asks whether or not the pattern of externalities resulting from individual pumper decisions deviates significantly from the externalities that would result from a solution by an optimization model that takes into account all the externalities. When the deviations are significant, some form of intervention is called for.

Economic efficiency need not imply *sustainability* of the groundwater resource. If the resource is non-recharging, any use will result in drawdown of the aquifer, and economically efficient use consists of a pattern that maximizes the present value of the resource. With a renewable resource, sustainability implies equality of average recharge and average discharge over time. Efficiency would dictate drawing down the aquifer during droughts and allowing recharge during periods of plentiful surface flow.

A major historical barrier to the efficient adjudication of groundwater was lack of understanding of groundwater hydrology, but sufficiently accurate groundwater modeling is now well established. The underlying cause of inefficiencies is now the ‘open access’ nature of many groundwater bodies, that is situations where property rights to the water are not clearly defined, with many users having unrestrained access to the aquifer.

Groundwater–surface water systems have long been modeled by economists or economist–hydrologist teams to investigate optimal schemes of management. Castle and Lindborg (1961) early applied linear programming to these systems, using a very simplistic representation of aquifer behavior. Buras (1963) and Burt (1964) made major contributions. Aron (1969) used dynamic programming and more realistic representations of aquifer behavior to determine optimal management for the aquifer in the Santa Clara Valley of California, a basin that was experiencing serious saltwater intrusion and surface subsidence. Pathbreaking work in combining detailed economic models of agriculture with advanced groundwater hydrology models was carried out by Bredehoeft and Young under the sponsorship of Resources for the Future and the US Geological Survey (Bredehoeft and Young, 1970 and 1983; Young and Bredehoeft, 1972). The results of these optimizing studies have emphasized the importance of aquifer characteristics, energy costs, and the marginal values of water in alternative uses in analyzing water system performance. The strength of negative externalities depends on aquifer characteristics (especially transmissivity), the spacing of wells, and the proximity of connected surface waters.

In cases where aquifer recharge is negligible, the exhaustible nature of the groundwater should raise the issue of the appropriate long-term economic and demographic development of the region. The availability of open access, exhaustible resources often induces ‘gold rush’ patterns of excessively fast exploitation with accompanying maladapted patterns of infrastructure and social development. The ‘boom towns’ of the Rocky Mountain region of the western United States during the uranium boom of the 1950s and 1960s and the coal boom of the 1970s represent such phenomena. The social ills and unwise infrastructure developments of such epochs have been extensively investigated (for example Cummings and Schulze, 1978; Cummings, Schulze, and Mehr, 1978; Gilmore, 1976; Lillydahl and Moen, 1983; Mehr, 1976). In the case of large non-rechargeable aquifer regions, the optimization of population growth and investment in production and social infrastructure warrants study and guidance (Howe, 1996). This issue will be elaborated in the later case study of the Ogallala aquifer in the High Plains region of the United States.

3. Policy instruments for management of groundwater systems

The optimization studies referred to above have modeled systems from the point of view of a centralized planner, determining the quantities of ground and surface waters that should be used over time to maximize the present value of some criterion of social well-being. The studies then move to recommendations regarding specific policy execution, that is how to move toward better solutions under real world conditions. One historical policy has been to ignore externalities, allowing landowners to pump without limit under the 'rule of capture' (Texas groundwater law). Another approach has been to incorporate groundwater into the 'appropriations (priority) doctrine' of water law, a policy that may preclude effective conjunctive management since most wells are quite 'junior' to surface rights.

Economists have long advocated the use of pumping taxes to reflect to the individual pumper the negative externalities resulting from his/her actions. An optimal tax will differ by location on the aquifer and will change over time as the water table and demands change. Naturally, taxes will be strongly resisted by those water users who have become used to water as a free resource. Taxes have not proven popular in the United States for either groundwater or water quality management but have been widely used for environmental management in Europe (Howe, 1994).

In the administration of surface water, short-term, and permanent water markets have become an increasingly important mechanism for the efficient and flexible reallocation of water (US National Research Council, 1992; Howe, Schurmeier, and Shaw, 1986). Actual and potential water market opportunities in various countries, including markets for pumped groundwater as practiced in South and Southeast Asia, are described in Easter, Rosegrant, and Dinar (1998) and, for the United States, in Anderson and Hill (1997). In systems where property rights in groundwater have been incorporated into the general water-rights system, groundwater rights can be bought and sold, transferred to other locations, or transformed into surface rights. This is the case in Colorado where tributary groundwater has been efficiently integrated into the 'priority rights system' (to be described in the Platte River case study below). Systems of tradable groundwater permits hold promise as economically efficient and equitable allocative mechanisms and have been initiated in Arizona and on the Edwards Plateau of Texas (as will be detailed in the following sections).

Other steps taken to reduce excessive negative extenalities of groundwater pumping include limits on pump capacities and well spacing requirements. The High Plains Underground Water Conservancy District No. I outside Lubbock, Texas on the lower part of the Ogallala aquifer has used these regulations to reduce overdrafts. The determination of appropriate regulation has been aided by the use of simulation models of the aquifer (The Cross Section, monthly publication of the District: www.hpwd.com). The High Plains District also has an extensive information and education program that stimulates more informed and responsible pumper behavior.

4. Case studies of groundwater management

Conjunctive management of surface and groundwaters in the South Platte River Valley of Colorado

The South Platte River and its tributaries rise on the eastern slopes of the Rocky Mountains, running northeast through the most populous and agriculturally productive regions of Colorado. Intensive use over a period of 140 years has greatly modified the flow patterns of the river. The river valley consists of porous alluvium that constitutes a huge aquifer that is recharged mostly from the river while providing late season flow back into the river. The region's water supply is largely from snow melt, while rainfall is sparce, about 30 cm/year.

Starting in the late nineteenth century, farmers began using groundwater from this extensive aquifer to supplement the highly variable surface supplies. However, pumping technology was limited until the post World War II period when submersible electric pumps became available, along with cheap energy. Of the 1,700 million cubic meters annual average applied to agriculture in the region, roughly 500 million cubic meters is pumped from the aquifers surrounding the river.

The expansion of pumping gradually reduced the return flows from the aquifer to the river, reducing the amount of water available to the surface water users (MacDonnell, 1988). Colorado had long established the 'appropriations doctrine' (or 'priority' system) of water law that gives precedence to uses that were established earliest in time, the so-called 'senior water rights'. Thus senior water rights owners increasingly saw their water availability decreasing. Groundwater remained totally unregulated until 1957 when permits for new high capacity wells were required. However, no restrictions were imposed on the total number of pumps. In 1965, legislation was passed that required the uses of tributary groundwater to be incorporated into the priority system of water rights. Since surface rights had been established in the nineteenth century, the groundwater rights were very 'junior', implying that they were required to be shut off during periods of low stream flow—a perverse result since this was just when the vast underground reservoir's supplies were most sorely needed.

Legislation of 1969 made it clear that, while wells fell under the priority system, they should be constrained only when there was clear damage to senior surface rights. This meant that the effects of pumping on river flows were relevant only during the irrigation season. The same legislation provided for a means of integrating surface and groundwaters: a 'plan for augmentation' of surface flows that would allow pumpers to pump 'out of priority'. What was required of each well (or groups of wells in proximity

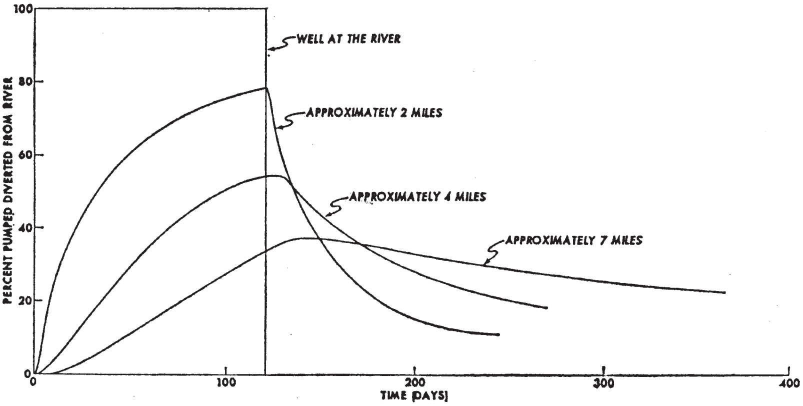

Figure 1. *Computed diversions from the South Platte River due to well pumping as functions of distance and duration*

to one another) was a plan to put into the river at appropriate times during the irrigation season a volume of water that would make up for the pumping-induced reduction in streamflow. This augmentation could be achieved by the purchase of senior surface rights that would simply be left in the stream or by pumping from other wells formerly used for irrigation.

The functional relationship showing the percentage of pumpage actually coming from the river during the irrigation season (the dependent variable) as a function of the distance of a well from the river and the number of days of continuous pumping is illustrated for a segment of the South Platte River in figure 1 (Young and Bredehoeft, 1972). This relationship is derived from a surface water-groundwater simulation model and is used by the State Engineer to determine how much surface water 'augmentation' will be required of a pumper or group of pumpers. Plans for augmentation have proven useful as a mechanism for resolving other surface water–groundwater conflicts. In the conflict between the States of Kansas and Colorado over division of the waters of the Arkansas River, Colorado pumpers located near the river have been required to cease pumping or to provide the State Engineer with an acceptable plan of augmentation to augment the streamflow to Kansas.

Severe agricultural–urban–ecosystem competition for a limited groundwater supply: the Edwards aquifer of Texas

The Edwards aquifer of south-central Texas is a large carstic formation that historically has provided large volumes of irrigation and urban water. It also feeds six large springs that provide important recreational and ecosystem services and constitute the main source for the downstream Guadalupe-Blanco River (Keplinger and McCarl, 1996). Pumping for agricultural and urban purposes has constituted 45 to 50 per cent of total discharge over the 1934–1999 period (Edwards Aquifer Authority, 1999).

Total average annual discharges (wells and springs) of about 821 million cubic meters have been quite close to the average recharge from streams and precipitition of 836 million cubic meters over the 1934–1999 period, as one would expect in a highly permeable carstic aquifer (Edwards Aquifer Authority, 1999). Spring flow is the residual, so is highly variable with precipitation. In 1956 as a result of a seven-year drought, some of the springs stopped flowing with total flow reduced to 13 million cubic meters. Spring flow over the 1934–1999 period averaged 451 million cubic meters, while the average over 1990–1999 was 523 million cubic meters. Drought in the year 2000 resulted in a drastic drop in the water table, triggering restrictions on urban water use. The ecosystem supported by the springs supports several endangered species of fish and amphibians, giving the federal Fish and Wildlife Service the right to intervene to protect these species if the State fails to act. The federal agency has determined that a flow of 150 cubic feet per second must be maintained at the most sensitive of the springs (Comal Spring).

Control over pumping has been made difficult by the State's legal doctrine of 'the rule of capture' under which the right to pump without limit lies with the land owner as long as the water is being put to 'beneficial use'. The highly permiable nature of the carstic aquifer means that the effects of pumping are quickly transmitted over large areas, thus creating, in combination with the 'rule of capture', a real 'open access' system with excessive externalities. The need for carefully planned conjunctive management of this system was widely acknowledged and has resulted in extensive hydrogeologic, biological, agricultural and economic modeling and research that has contributed to policy formulation (for example McCarl, Dillon, and Keplinger, 1999; Schaible, McCarl and Lacewell, 1999; Kaiser and Phillips, 1998).

Attempts to control pumping have been one of the most litigated and contentious water issues in Texas for many years. In 1993, the Edwards Aquifer Authority was authorized and, after extended litigation, was established in 1996. The Authority has chosen to use a system of marketable groundwater permits which were issued to all pumpers in proportion to historical use, subject to a total pumping cap. The cap is currently 450,000 acre-feet (540 million cubic meters) per year which appears to be accepted by the urban and agricultural pumpers on the one hand and the spring–downstream flow interests on the other. In 1998, the Authority established the Groundwater Trust to facilitate the trading of permits. In the period 8/1997 through 8/2001, there have been 403 trades of permits, 335 to M&I users with an average size of 191 acre-feet (235,000 cubic meters.[2] At present, there is a list of about 85 offers to lease or sell permits.

Management of a non-renewable aquifer: the Ogallala aquifer of the US High Plains region

The Ogallala aquifer underlies a large land area from the State of Nebraska on the north to western Texas on the south. The total volume of water is vast, differing in depth from area to area, from nearly zero to 600 feet (185 meters). Much of the aquifer is essentially non-rechargable because of the

---

[2] E-mail from Greg Ellise, 13 September, 2001.

semi-aridity of the region and the small size of rivers and streams in the region, although it is hydraulically connected to the overlying alluvium along several rivers like the Arkansas and the Cimmeron. Irrigation started during the 'dust bowl' days of the 1930s, but pumping expanded greatly in the post-World War II period when advanced pumping technologies became available, accompanied by low energy prices. Over 6.5 million hectares were under irrigation in 1990. Groundwater irrigation changed agriculture in the High Plains from a risky, low return activity to a much more viable economic activity (Opie, 1993).

However, there remains the issue of the socially optimal time pattern of use of this largely non-renewable resource—a typical 'Hotelling' type of problem (Hotelling, 1931; Howe, 1979). An early study (Mapp, 1972) simulated agricultural operations on both the shallow and deep parts of the aquifer to determine whether or not actual rates of water use were 'efficient' in the usual economic sense. Mapp found that actual time paths of agricultural water application on the thick parts of the aquifer (where lots of water was stored) were quite close to those derived from the dynamic optimizing model, while the water-use path on the thin parts of the aquifer were in excess of the optimal amounts, warranting some form of policy intervention. For this situation, the optimizing model found that a pumping tax that tracked the shadow price of water over time induced a more efficient path of water use than did uniform quantitative restrictions that reduced water applications by the same percentages everywhere.

Water tables have been falling steadily over all parts of the aquifer since the initiation of intensive pumping around 1950. In a small number of areas, the aquifer has been physically exhausted, while in all areas pumping costs have been increasing (Kromm and White, 1992). A large multi-state study carried out by the US Army Corps of Engineers, state government participants, and private consultants in the early 1980s predicted that over 1 million hectares would have to revert to dryland farming by the year 2000, and the total would grow to more than 2 million hectares by 2020 (Arthur D. Little, 1982; High Plains Associates, 1982). In fact, the reduction in irrigated acreage has proven to be considerably smaller than the 1 million acre prediction (Great Plains Symposium, 1998), largely because of technological and biological advances and adaptations to the growing cost of pumping.

The multi-state study (Arthur D. Little, 1982) found that importation of water from other regions was prohibitively costly as an input for agriculture. Attention was then turned to stimulating technological, biological, and management advances in agriculture to extend the economic life of the aquifer and the communities dependent on it. Irrigation technology has been improved with better 'center pivot' irrigation systems using drop lines which greatly reduce evaporation. Investment in these systems has become widespread. They permit not only water savings but the refined application of fertilizers and pesticides. Some center pivot systems measure the nitrogen content of the water being pumped so that it can substitute for new fertilizer (Kromm and White, 1992).

Biological advances in dryland crops have increased dryland yields more rapidly (percentage-wise) than the yields of irrigated crops. Farm consolidation has been taking place to take advantage of the scale economies inherent in modern farm machinery, especially in wheat production. Some communities that have been hurt by increased water costs have been actively recruiting alternative activities to diversify their economies—a strategy enhanced by the telecommunications revolution and the increase in 'footloose' professional activities (Supalla, Lamphear, and Schnaible, 1984).

In sum, the economic and social impacts of the falling water tables in the Ogallala have been less severe than had been forecast in 1980 with the exception of some small areas. The increasing cost of pumped water, even in the absense of any program to impose the intertemporal opportunity costs of water use on the farmers, has successfully induced technological, biological, and managerial innovations that have largely offset increased pumping costs and have extended the life of most parts of the aquifer beyond the predictions of 20 years ago.

Management of coastal aquifers: the Costa de Hermosillo, Mexico

The management of coastal aquifers raises difficult and unique problems of controlling salt water intrusion (Whipple, 1988; National Research Council, 1997). The Costa de Hermosillo on the coast of the Mexican State of Sonora has been one of the richest agricultural and horticultural regions of Mexico with 120,000 hectares of irrigated private land. Major crops grown include sesame, safflower, soybeans, sorghum, garbanzo, cotton, wheat, and various fruits. The District's only substantial source of water has been groundwater. Annual withdrawals vary between 800 million and 1.2 billion cubic meters, while estimated recharge is only 350 million cubic meters. These overdrafts resulted in a decline in the water table of 30 meters or more by 1972 with a resultant intrusion of saltwater into the aquifer, moving inland about 1 km per year. As a result, many wells have had to be abandoned, in some cases water pumped from further inland substituting for that of the abandoned wells (Comision Nacional del Agua, 1994). The City of Hermosillo is an important agricultural and financial center heavily dependent on continued agricultural productivity. The region has been actively lobbying the Mexican government for the construction of a large water importation project known as PHLINO (Plan Hidraulico del Noroeste) that would bring water some 480 km from the heavily watered southern state of Sinaloa through a sequence of water exchanges. The cost was estimated to be very high (Cummings, 1974).

Cummings, under the sponsorship of Resources for the Future, of Washington DC modelled this complex agricultural–hydrologic system to gain insight into the economic desirability of the project. The major questions were: What is the optimum (present value maximizing) pattern of exploitation of the aquifer in the light of the salt water intrusion? What is the implied need for the importation project? If the project is desirable, what timing is called for, and what alternatives to importation exist? While this study is dated, it very nicely illustrates the issues arising in the use of coastal aquifers.The results of the model calculations are given in table 1 which is taken from Cumming's study.

The first column shows the estimated optimal rate of annual pumping over a 36 year horizon, with the initial conditions as they were at the time

Table 1. *Optimum solution to groundwater pumping, Costa de Hermosillo, Mexico*

Year	*Annual rate of pumping (million* m^3*)*	*Groundwater storage at the beginning of year (million* m^3*)*	*Increase in storage attributable to pump relocation (million* m^3*)*	*Shadow value of water (not discounted) (dollars/*m^3*)*	*Increase in saltwater intrusion (km)*
1	1,219.1	22,253.0	1,989.6	0.0008	0.96
2	1,219.1	23,023.6	795.3	0.0035	0.96
3	1,219.1	22,234.0	828.1	0.0038	0.96
4	1,219.1	21,412.0	829.4	0.0042	0.96
5	1,219.1	20,588.7	829.5	0.0046	0.96
6	1,219.1	19,765.3	829.5	0.0051	0.96
7	1,219.1	18,941.9	829.5	0.0054	0.96
8	1,219.1	18,118.5	829.5	0.0060	0.96
9	1,206.3	17,295.1	143.3	0.0067	0.95
10	1,206.3	17,834.8		0.0074	0.95
11	1,206.3	16,941.7		0.0080	0.95
12	1,206.3	16,048.6		0.0089	1.7
13	1,206.3	15,091.2		0.0096	1.7
14	1,218.6	13,976.3		0.0109	1.7
15	1,202.2	12,806.5		0.0118	1.7
16	1,126.5	11,638.3		0.0122	1.4
17	1,048.7	10,546.3		0.0124	1.4
18	978.5	9.552.7		0.0134	1.3
19	915.3	8,656.0		0.0138	1.3
20	865.1	7,848.5		0.0141	1.0
21	796.5	7,115.5		0.0156	0.9
22	756.7	6,471.1		0.0173	0.9
23	603.5	5,890.4		0.0175	0.5
24	555.3	5,480.2		0.0178	0.4
25	552.5	5,164.1		0.0184	0.4
26	527.0	4,876.2		0.0188	0.4
27	524.6	4,621.5		0.0192	0.4
28	512.5	4,378.2		0.0203	0.3
29	510.3	4,150.0		0.0224	0.3
30	508.1	3,928.0		0.0246	0.3
31	506.0	3,709.9		0.0272	0.3
32	503.9	3,495.1		0.0296	0.3
33	501.8	3,283.1		0.0320	0.3
34	500.0	3,074.1		0.0360	0.3
35	497.7	2,868.0		0.0360	0.3
36	350.0	2,644.5		0.0400	0.3

Source: Cummings (1974), table 29.

of the study. Obviously because of the increased pumping depth and because of the increasing need to shut down pumps as the salt front continues to advance (see last column), the optimum rate of pumping falls. Groundwater storage continues to fall, resulting in a rising shadow (marginal) value for groundwater (column 4). This shadow value is the key to the optimum timing of the import project: the year in which the shadow value rises to equality with the average cost per cubic meter of bringing in new water via the project ($0.022 per cubic meter at the time of the study) is the appropriate year for bringing the project into operation—year 29 in the table when the shadow value rises to $0.0224 per cubic meter.

This solution is similar to findings of other studies that have shown that water projects are often built prematurely, for example the Central Arizona Project in the US that was built much too early in the attempt to reduce groundwater overdraft. Young and Martins' (1967) analysis of that project has become a classic of water project analysis (also Kelso, Martin, and Mack, 1973). The concept of optimal timing is not well understood in the water planning and engineering communities but is of great importance to intertemporily efficient water development and related economic development.

Some will disagree with the appropriateness of this solution, especially since it calls for continued salt water intrusion over a long period of time. Principles of sustainability would probably call for a much quicker approach to a steady state, after which the remaining storage capacity of the aquifer would be maintained. However, since PHLINO would deliver only 400 million cubic meters per year, such a steady state would be achieved only in year 35 or 36 in the absence of restrictions on pumping. Environmental effects on the surface were not included in the evaluation, while issues like preservation value were not involved. The opportunity cost of the imported water to the basin of origin was included but the social and ecological effects were not given weight. A solution that would be acceptible today would probably lie between the extremes of immediate construction and the long-term continuation of aquifer drawdown.

Water management in an island setting: the 1987 Hawaii water code

The question of surface and groundwater rights has long been an important issue in Hawaii (Hawaii, State of, 1979). The rise of sugar cultivation in the nineteenth century greatly increased the demand for water in contrast to levels established under the older, traditional modes of cultivation and traditional surface water practices. The ensuing controversies were partially settled by the traditional ruler in 1848 and subsequent court decisions, so that by 1920 surface water rights seemed to be well defined and clearly transferable among uses (Moncur, 1989). However, continued fighting by powerful sugar companies over water supposedly allocated according to riparian doctrine led the 1978 Hawaii Constitutional Convention to establish an agency to set water policies and practices and to regulate water use. A decade of studies of alternative methods of water administration followed, with field trips to different parts of the world including the western continental United States to assess the appropriation (priority) systems found there.

The final recommendation was to establish a Commission on Water Resource Management that requires all surface and groundwater users to obtain permits of limited duration. The Commission has the power to deny renewal and to disapprove any transfers. The Advisory Commission even denounced the idea of market institutions by saying, 'Indeed, the Commission strongly feels that water and the right to use it should not be the subject of purchase and sale on the open market.'

Moncur's analysis (1989) of the alternatives that were open to the State of Hawaii makes it clear that a system of marketable permits could have worked very well in that setting. The Islands are undergoing very rapid economic change with consequent need to reallocate water supplies. Native Hawaiian claims to water taken from them much earlier are mounting. There is a clear need for a mechanism that could establish the marginal values of water in different applications.

Islands are typically underlain by a 'lens' of fresh water that is recharged from surface flows and rainfall. The volume of this stock is frequently large enough that fluctuations caused by variable recharge and changing withdrawals still results in relative stability of this lens. Thus the 'average safe yield' can be accurately estimated, leading to the possibility of the issuance of withdrawal permits summing to the safe yield.This would allow the market to determine efficient changing patterns of water use while satisfying the sustainability criterion. The topography of islands with short distances from points of water use to the sea assures that externalities caused by one party's water use will be small, so that permits could be treated as homogenious and interchangeable. Thus, the prospects for efficient market operation were excellent, while the need for 'market price discovery' was great.

The Water Commission must now continue to make endless decisions concerning the continuation of existing permits, the re-issuance of permits to new parties and proposed transfers. The Commission must decide (for example) whether the continuation of sugar plantations is to be given precedence over new resort hotels. There is no room for the market to do what it does best—generating information on values. Again we find that institutional barriers stand in the way of more rational, better-informed water allocation.

Lessons from the case studies

World-wide opportunities exist for utilizing conjunctive management of surface and groundwater resources. The natural economies that exist in using the costless storage of permeable aquifers in conjunction with surface flows are frequently overlooked or ignored because of historical divisions of responsibilities among agencies. The case study of the South Platte River system with its unique developmental and technological history and the invention of 'plans of augmentation' that allow pumpers to optimize their use of water without interfering with surface water users exhibited this potential.

The geological conditions and institutional evolution surrounding groundwater use often result in 'open access' conditions under which pumpers are motivated to ignore contemporary externalities imposed on other water users. This 'open access' characteristic must be offset either by centralized control, by the issuance of tradable permits with a cap on total extraction, or the imposition of pumping taxes that reflect the externalities to the pumper. The definition of property rights that are operationalized through a system of tradable pumping permits has great appeal and has been utilized on the Edwards aquifer of Texas.

Some groundwater stocks are essentially non-renewable, suggesting consideration of appropriate development paths for population and infrastructure investment so that adjustments to falling water tables can be taken in a timely manner and excessive population growth avoided. The Ogallala is a case in point. Development should not be allowed to proceed on the mistaken belief that the water will last forever. However, some conservation can be accomplished through the substitution of capital for water which, along with technological and biological innovations induced by the increasing pumping costs, can smooth the transition from water intensive forms of agriculture to less water intensive uses, and finally to dryland operations. The Ogallala case illustrates the realities of these possibilities.

Coastal areas face particularly difficult problems in reconciling the objectives of efficient use of their water resources with sustainability. In the Costa de Hermosillo case, economic efficiency was seen to dictate continued overdrafting of the aquifer with continued salt water intrusion into the aquifer for many years. This case illustrates the potential conflict between economic efficiency and common interpretations of sustainability, as well as the frequent tendency of water agencies to build projects far in advance of their justifiable need.

The Hawaiian water allocation study illustrates the potential for a system of tradable permits to solve the problem of efficient allocation in the face of rapid-change while protecting (through the limited number of permits) the quality of the underlying water lens.

Looking across the case studies, we find the pervasiveness of the 'open-access' problem in groundwater systems that requires some type of regulatory intervention to limit pumping to levels that reflect the contemporary and intertemporal externalities. Economic efficiency suggests tradable permit systems that can both cap total pumping and allow flexibility in use patterns over time. Lack of coordination between groundwater management and surface water management is a worldwide problem that occurs because of the division of regulatory power among different agencies. This lack of institutional coordination inhibits efficient conjunctive management.

References

Agbanobi, R.O. (1996), 'Groundwater recharge through permeable barrier of granulated charcoal', in *Proceedings: Integrated Management of Surface and Ground Water*, Universities' Council on Water Resources, Southern Illinois University, Carbondale, IL.

Anderson, T. and P.J. Hill (1997), *Water Marketing—the Next Generation*, New York and London: Rowman & Littlefield Publishers.

Aron, G. (1969), 'Optimization of conjunctively managed surface and ground water resources by dynamic programming', Contribution 129, Water Resources Center, Univ. of California, Los Angeles, 158pp.

Arthur D. Little, Inc. (1982), 'Six State High Plains Ogallala Aquifer Regional Resources Study: Study Element B–11: Regional Economic Model Description', Cambridge MA.

Biswas, A.K. (ed.) (1994), *International Waters of the Middle East: From Euphrates-Tigris to Nile,* Bombay: Oxford University Press.

Bittinger, M.W. and E.B. Green (1980), *You Never Miss the Water Till . . . (The Ogallala Story*, Littleton, CO: Water Resources Publications.

Bredehoeft, J.D. and R.A. Young (1970), 'The temporal allocation of groundwater—A simulation approach', *Water Resources Research*, **6**: 3–21.

Bredehoeft, J.D. and R.A. Young (1983), 'Conjunctive use of groundwater and surface water for irrigated agriculture: risk aversion', *Water Resources Research*, **19**: 1111–1121.

Buras, N. (1963), 'Conjunctive operation of dams and aquifers', *Journal Hydraulics Division, American Society of Civil Engineers*, **89**, HY6: 111–131.

Burt, O.R. (1964), 'The economics of conjunctive use of ground and surface water', *Hilgardia*, **35**: 31–111.

Castle, E.N. and K.H. Lindeborg (1961), 'Economics of ground water allocation', *Misc. Paper 108,* Agr. Exp. Station, Oregon State University, Corvallis (1–33).

Castro, J.E. (1996), 'Aquifer Storage and Recovery: A Water Resource Management Alternative for Horry County, South Carolina', in *Procceedings: Integrated Management of Surface and Ground Water*, Universities' Council on Water Resources, Southern Illinois University, Carbondale, IL.

Comision Nacional del Agua (1994), *Informes 1989–1994*, Mexico City.

Cummings, R.G. (1974), *Interbasin Water Transfers: A Case Study in Mexico*, Washington DC: Resources for the Future.

Cummings, R.G. and W.D. Schulze (1978), 'Optimal investment strategies for boomtowns', *American Economic Review*, **68**: 374–385.

Cummings, R.G., W.D, Schulze and A.F. Mehr (1978), 'Optimal municipal investment in boomtowns', *Journal of Environmental Economics and Management*, **5**: 252–267.

Easter, K.W., M.W. Rosegrant, and A. Dinar (1998), *Markets for Water: Potential and Performance*, Dordrecht: Kluwer Academic Publishers.

Edwards Aquifer Authority (1999), 'Hydrologic Data Report for 1999', Report 00–02, San Antonio, Texas.

Gilmore, J.S. (1976), 'Boomtowns may hinder energy resource development', *Science*, February **13**: 535–540.

Gleick, P.H. (1993), *Water in Crisis: A Guide to the World's Fresh Water Resources*, New York: Oxford University Press.

Hawaii, State of, Department of Budget and Finance (1979), *Land and Water Resources Management in Hawaii*, Honolulu: Hawaii Institute for Management and Analysis in Government.

High Plains Associates (1982), 'Six-State High Plains Ogallala Aquifer Regional Resources Study', Camp Dresser and McKee, Inc., Austin, Texas, March.

Hotelling, H. (1931), 'The economics of exhaustible resources', *Journal of Political Economy*, **39**: 137–175.

Howe, C.W. (1979), *Natural Resource Economics: Issues, Analysis and Policy*, New York: John Wiley & Sons.

Howe, C.W. (1994), 'Taxes *versus* tradable discharge permits: a review in the light of the US and European experience', *Environmental and Resource Economics*, **4**: 151–169.

Howe, C.W. (1996), 'On the theory of optimal regional development based on an exhaustible resource', in *Regional Dynamics: Volume* II, K.E. Haynes, K.J. Button, P. Nijkamp, and L. Qiangsheng (eds.), UK: Edward Elgar Publishing.

Howe, C.W., D.R. Schurmeier, and W.D. Shaw, Jr. (1986), 'Innovative approaches to water allocation: the potential for water markets', *Water Resources Research*, **22**: 439–445.

Kaiser, R.A. and L.M. Phillips (1998), 'Dividing the waters: water marketing as a conflict resolution strategy in the Edwards Aquifer System', *Natural Resources Journal*, **38**: 411–444.

Kelso, M.M., W.E. Martin and L.E. Mack (1973), *Water Supplies and Economic Growth in an Arid Environment: An Arizona Case Study*, Tucson, AZ: University of Arizona Press.

Keplinger, K.O. and B.A. McCarl (1996), 'Conjunctive management implications for the Edwards Aquifer: an integrated aquifer/river basins economic optimization approach', in *Proceedings: Integrated Management of Surface and Ground Water*, Universities' Council on Water Resources, Southern Illinois University, Carbondale, IL.

Kromm, D.E. and S.E. White (eds.) (1992), *Groundwater Exploitation in the High Plains*, Lawrence, KS: University Press of Kansas.

Lillydahl, J.H. and E. Moen (1983), 'Planning, managing, and financing growth and decline in energy resource communities: a case study of Western Colorado', *Journal of Energy and Development*, **8**: 211–230.

Longebaugh, R.A. (1984), 'Artificial aquifer recharge in the Colorado portion of the Ogallala Aquifer', Information Series No. 54, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, USA.

MacDonnell, L.J. (1988), 'Colorado's law of "Underground Water": a look at the South Platte Basin and beyond', *University of Colorado Law Review*, **59**: 579–625.

Mapp, H.P., Jr. (1972), 'An economic analysis of water-use regulation in the Central Ogallala Formation', Ph.D. Dissertation, Agricultural Economics, Oklahoma State University, University Microfilms, Ann Arbor, Michigan.

McCarl, B.A., C.R. Dillon, and K.O. Keplinger (1999), 'Limiting pumping from the Edwards Aquifer: an economic investigation of proposals, water markets and spring flow guarantees', *Water Resources Research*, **35**: 1257–1268.

Mehr, A.F. (1976), 'Measuring social benefits attributable to social infrastructure in boom towns", Los Alamos Scientific Laboratory, LA-6559-T.

Moncur, J.E.T. (1989), 'Economic efficiency and institutional change in water allocation: the 1987 Hawaii Water Code', *Water Resources Bulletin*, September (5B 23-5B-30).

National Research Council (US) (1986), *Ground Water Quality Protection: State and Local Strategies*, Washington DC: National Academy Press.

National Research Council (US) (1990), *Ground Water Models: Scientific and Regulatory Applications*, Washington DC: National Academy Press.

National Research Council (US) (1992), *Water Transfers in the West: Efficiency, Equity, and the Environment*, Washington DC: National Academy Press.

National Research Council (US) (1997), *Valuing Groundwater: Economic Concepts and Approaches*, Washington DC: National Academy Press, chapter 6.

Opie, J. (1993), *Ogallala: Water for A Dry Land*, Lincoln, Nebraska: University of Nebraska Press.

Schenkkan, P. (1996), 'Legal impediments to integrated water resource management', in *Proceedings: Integrated Management of Surface and Ground Water*, Universities' Council on Water Resources, Southern Illinois University, Carbondale, IL.

Schnaible, G.D., B.A. McCarl, and R.D. Lacewell (1999), 'The Edwards Aquifer Water Resources Conflict: USDA Farm Program Resource Uses Incentives?', *Water Resources Research*, **35**: 3171–3183.

Southwest Kansas Groundwater Management District (2000), <website www.state.ks.us/public/ksgm/hpaquifr.html>

Supalla, R.J., F.C. Lamphear, and G.D. Schnaible (1984), 'Economic implications of diminishing groundwater supplies in the High Plains Region', Paper given at the Regional Science Association meetings, Denver, Colorado, November.

US Water News (2000), 'USGS Discovers Pesticides in the Ogallala Aquifer', November, p. 7.

Van Slyke, G.D. (1990), 'Depletion to the Ogallala Aquifer, Northern High Plains Designated Groundwater Basin', Colorado Division of Water Resources, Office of the State Engineer, Denver, CO.

Whipple, W. (1988), 'Management of depleted coastal zone aquifers', *Coastal Water*

Resources: Symposium Proceedings, American Water Resources Association, Behtesda, MD.

Young, R.A. and W.E. Martin (1967), 'The economics of Arizona's water problem', *Arizona Review*, **16**: 9–18.

Young, R.A. and J.D. Bredehoeft (1972), 'Digital computer simulation for solving management problems of conjunctive groundwater and surface water systems', *Water Resources Research*, **8**: 533–556.