Title

Sustainable groundwater management: The theory of a game

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Sustainable Groundwater Management: the Theory of a Game

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Abstract

Principles of sustainable groundwater exploitation are presented in this article. The renewable and inappropriable nature of groundwater is examined in light of the process of recharge. An example illustrates the interplay among groundwater extraction, recharge, natural recharge, and storage. It demonstrates the aquifer-specific characteristics of overdraft and replenishment, which are driven by climatic variability and the rate of groundwater mining. A second example uses game theoretic methodology to quantify the roles of cooperation and non-cooperation on groundwater extraction. The economic and environmental advantages of cooperative groundwater extraction are demonstrated with data from a coastal aquifer.

What is sustainable?

Is groundwater a renewable resource? Let us put our hydrologic opinions aside for one moment and consider other scientists' perspective on this. The economic viewpoint is of interest, because of the central role of economics in modern affairs. Table 1, adapted from Samuelson and Nordhaus (1995), provides a good starting point to our discussion. In Table 1, natural resources are classified into two dichotomous categories as appropriable or inappropriable, and renewable or nonrenewable. An appropriable resource is one whose full economic value can be captured. It is inappropriable if its use is free to the individual but costly to society. Renewable resources are replenished regularly and, if properly managed, can render useful services indefinitely. Nonrenewable resources are essentially fixed in supply and cannot be regenerated quickly enough or at all. The economists' classification of ground water as a nonrenewable resource in Table 1 is startling. It may be due to a poor understanding of the hydrologic cycle by non-hydrologists. Or, it might have arisen from a perception that groundwater, in terms of its quantity and quality, can be depleted beyond useful regeneration in a relatively short time period. This author prefers the classification shown in Table 2, in which groundwater was reclassified as a renewable resource. It is not our purpose to dwell on the intricacies implied by the

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differences between Tables 1 and 2, but simply to draw attention to the important underlying viewpoints behind each of the tables.

Table 1. Classification of natural resources (adapted from Samuelson and Nordhaus, 1995) and illustrative resources: the economists' view.

Characteristic	Type of resource	
	Renewable	Non-renewable
Appropriable	Solar energy, agricultural land	Oil, copper
Inappropriable	Fisheries, air quality	Groundwater, climate

Table 2. Classification of natural resources, and illustrative resources: the hydrologists' view.

Characteristic	Type of resource	
	Renewable	Non-renewable
Appropriable	Solar energy, agricultural land	Oil, copper
Inappropriable	Ground water, fisheries, air quality	Climate

In this article, groundwater is considered a renewable resource by virtue of its linkage to recharge mechanisms driven by precipitation in the hydrologic cycle. It is classified as inappropriable because its mining for full economic gain by individuals may lead to immitigable resource losses. There are exceptional cases of nonrenewable groundwater. Such is the case of fossil ground water held captive in geologic formations isolated from the hydrologic cycle. Their mining eventually exhausts the resource without possibility of replenishment. A well-known example is the large fossil aquifer in the Algerian Sahara (Damerdji, 1997).

The mining (used interchangeably with exploitation and extraction) of groundwater that meets certain human uses and environmental functions while preserving its natural water quality and avoiding negative geologic and environmental impacts is equated in this article with its sustainable exploitation. This definition is underlain by the notion of an adaptive strategy of groundwater mining, wherein natural changes in groundwater recharge, ecological fluctuations, and associated geologic hazards are taken into consideration in determining when and how much groundwater to extract. Thus, sustainability is understood here as a relative concept. It is relative to the course of natural cycles. This is in contrast to the traditional –and absolutist– concept of safe yield, defined as the average long-term amount of groundwater that can be economically obtained from an aquifer (see e.g. Loáiciga and Leipnik, 2000, 2001a, b).

Sustainable groundwater mining and the role of recharge

Groundwater is extracted to meet human uses: water supply to urban and rural communities, irrigation, and as a factor of industrial production. Its environmental, geologic, and water quality functions, on the other hand, generally do not involve extraction, but, rather, call for keeping sufficient quantities of ground water in storage. Table 3 gives examples of environmental, geologic, and water quality functions of groundwater. The separation of functions into those three main categories serves a pedagogical purpose only. In reality, the functions are all usually interrelated and encompass more than one category at once. For example, groundwater extraction may lower hydraulic head substantially, which may cause, simultaneously, ground subsidence, reduced baseflow in hydraulically connected streams, and seawater intrusion in a coastal aquifer.

Table 3. Environmental, geologic, and water quality functions with examples.

Functions		
Environmental	Geologic	Water quality
Habitat functionality	Prevention of subsidence	Prevention of seawater intrusion
Base flow to rivers	Ground stability	Prevention of the upwelling of non potable groundwater
Vegetative transpiration	Geomorphic action	Preservation of water temperature

Figure 1 shows an example of long-term annual groundwater extraction (by pumping) in the Edwards Aquifer of Texas (Loáiciga, 2000; Loáiciga et al; 2000). Population growth and economic expansion were accompanied by a steady increase in extracted groundwater. That was the case even during a severe drought from 1949 through 1957, when in fact, groundwater use accelerated.

The regression equation fitted to groundwater extraction in Fig. 1 implies that its average rate of increase was approximately 8×10^6 m^3 yr^{-1} between 1934 and 1995. After 1990, however, groundwater pumping was curtailed by complaints filed by activists to protect threatened and endangered aquifer ecosystems that depend on spring flow. The latter was diminished by lower hydraulic heads caused by steadily rising groundwater extraction. Evidently, groundwater use had become unsustainable in the Edwards Aquifer when performance measures beyond water supply for municipalities and farming were considered.

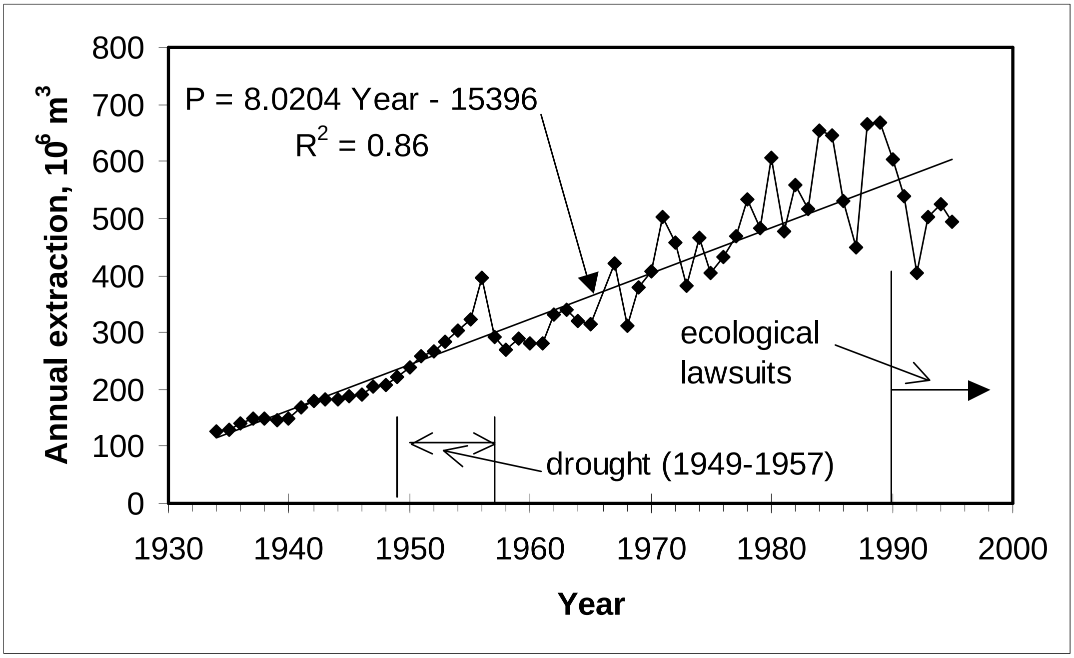

Figure 1. Annual extraction rate in the Edwards Aquifer (1934-1995), with fitted regression equation (P = annual extraction in 10^6 m^3).

Figure 2 shows a time series of annual groundwater recharge in the Edwards Aquifer and a smoothed 10-year moving average of the recharge. Recharge is the volume of water that replenishes aquifer storage. It is seen in Fig. 2 that annual recharge is highly variable. Its coefficient of variation is large (the standard deviation divided by the mean = 595/831 = 0.716) and the range equals about 3000 x 10^6 m^3. The 10-year moving average series suggests a slightly increasing, albeit fluctuating, pattern in annual recharge after the drought of the 1940s and 1950s.

The long-term effect of groundwater extraction is better appreciated in Fig. 3, in which annual extraction and spring flow in the Edwards Aquifer are shown. The base spring flow (= 450 x 10^6 m^3) is required for proper ecosystem functioning. Spring flow exceeded extraction before 1950. That trend was reversed during the drought. Thereafter, groundwater extraction frequently exceeded spring flow. During and after the drought, spring flow fell frequently below the required base level. That pattern of groundwater use exacted a toll on aquifer ecosystems (endemic fish, plants, invertebrates, amphibians), and legal conflict arose (US Fish and Wildlife Service, 1996). The data in Figs. 1-3 illustrate the need to consider the multiple functions of groundwater and the natural fluctuations of recharge in order to devise sustainable extraction strategies. That recipe might seem obvious, yet, there is abundant empirical evidence of so-called groundwater "overdraft" in the USA and elsewhere.

Groundwater overdraft and its causes

Overdraft occurs when the rate of groundwater extraction plus natural aquifer discharge (e.g., spring flow, baseflow, submarine discharge) exceeds the total aquifer recharge (natural plus artificial) during an extended period of time (five or more consecutive years). This produces a decline in groundwater storage that may cause negative impacts: degraded water quality, ground subsidence, impaired habitat functionality, reduce baseflow to streams, etc. Overdraft is the antonym of sustainable extraction. Figure 4 illustrates the phenomenon of overdraft and of storage recovery in the Edwards Aquifer. It graphs a time series of the change of aquifer storage from the initial value in 1934. Between 1936 and 1956, the aquifer was overdrafted to its lowest level in the historical record. This phenomenon was accentuated by the 1949-1957 drought. Storage recovered but remained below the 1934 level between 1957 and 1973. From 1974 through 1989 the storage fluctuated about its 1934 initial value, and after 1990 it was replenished until it reached a historical maximum in 1992. Figure 4 illustrates the large fluctuations that aquifer storage may undergo. Its condition may change from overdrafted to full in a few years: it all depends on the local mechanism of recharge and the human extraction of groundwater. Aquifers vary substantially in their ability to recover lost groundwater storage. This calls for a case-by-case approach to devise sustainable exploitation strategies in aquifers.

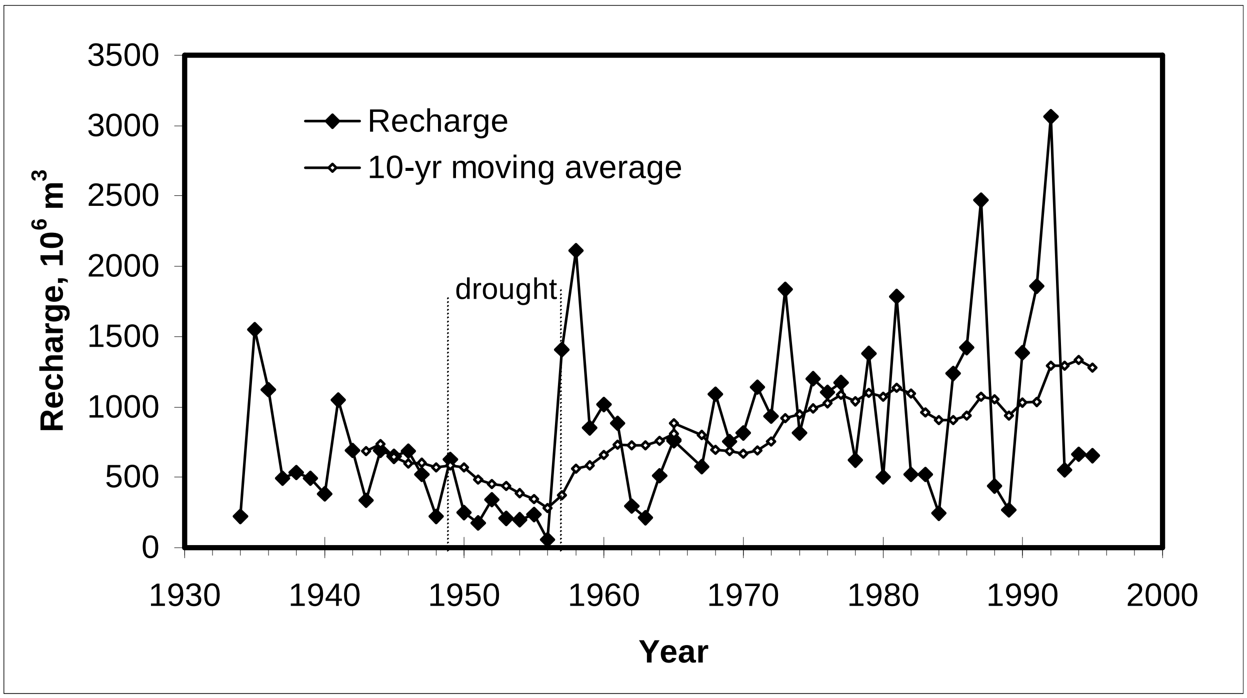

Figure 2. Annual groundwater recharge in the Edwards Aquifer, 1934-1995. Annual data and 10-year moving average are shown.

The causes of groundwater overdraft are multiple. An obvious one is the superposition of hydraulic drawdowns caused by pumping at multiple wells tapping an aquifer. There are, however, more primeval cultural and institutional ones. The zest for individual gain is a prime factor. That human trait –as well as the scarcity of resources– explains the tragedy-of-the-commons syndrome (Hardin, 1968, 1992), whereby the harvesting of a commonly owned resource by users, each driven by the zest of personal gain, results in its eventual demise. This is a classical example of the potential dire consequences caused by the proclivity of micro-economic agents (groundwater users in this case) to exploit a commonly accessed resource with the aim of maximizing their individual returns without regard to sustainability.

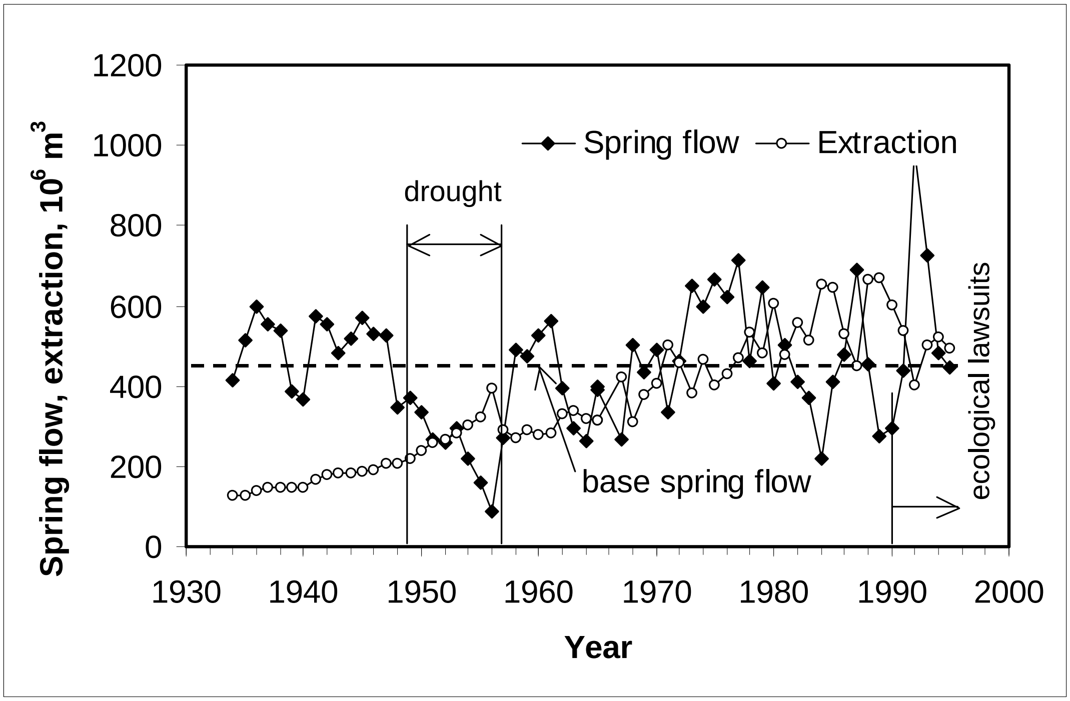

Figure 3. Annual spring flow and extraction in the Edwards Aquifer, 1934-1995.

Some legal doctrines that govern groundwater rights and its use in the western United States may encourage non-sustainable groundwater exploitation as well. The absolute ownership doctrine for example –unless overridden by case law, statutory law, or court adjudications– awards ownership and the unfettered right to use ground water to the owner of the land where the ground water is found (Getches, 1990). If not judiciously applied, such absolute right may lead to non-sustainable groundwater mining and negative impacts. In states with a hybrid groundwater appropriation doctrine, case law has produced some perverse outcomes. One example is the "mutual prescription" of ground-water rights whenever multiple aquifer users overdraft it. Groundwater rights are proportionate to historical use under mutual prescription: the larger the amount of groundwater a user has mined over time, the larger his prescriptive right to the safe yield of the aquifer. Mutual prescription encourages aquifer users to extract large amounts of groundwater for the sake of establishing and minimizing the probable loss of prescriptive rights. If legally challenged, the case to qualify groundwater extraction as a "beneficial use" is strengthened by a high historical water use.

Game theory, cooperation and non-cooperation in aquifer exploitation

Game theory deals with the study of situations in which two or more parties who participate in an activity (a "game", euphemistically) choose individual strategies that affect all the participating parties. Its application arose in the context of competitive business practices, but it has spread to many other fields of inquiry and has found diverse applicability. One of the best-known results of game theory is the Nash or non-cooperative equilibrium (after John Nash, 1951, a mathematician who produced the pioneering theorems): when the parties do not cooperate –as is the case in perfectly competitive markets– no party can do better under its chosen strategy given the other parties' strategies. There can be, on the other hand, collusion among the parties, that is, they may behave in a cooperative manner and act in unison to find strategies that benefit their joint payoffs.

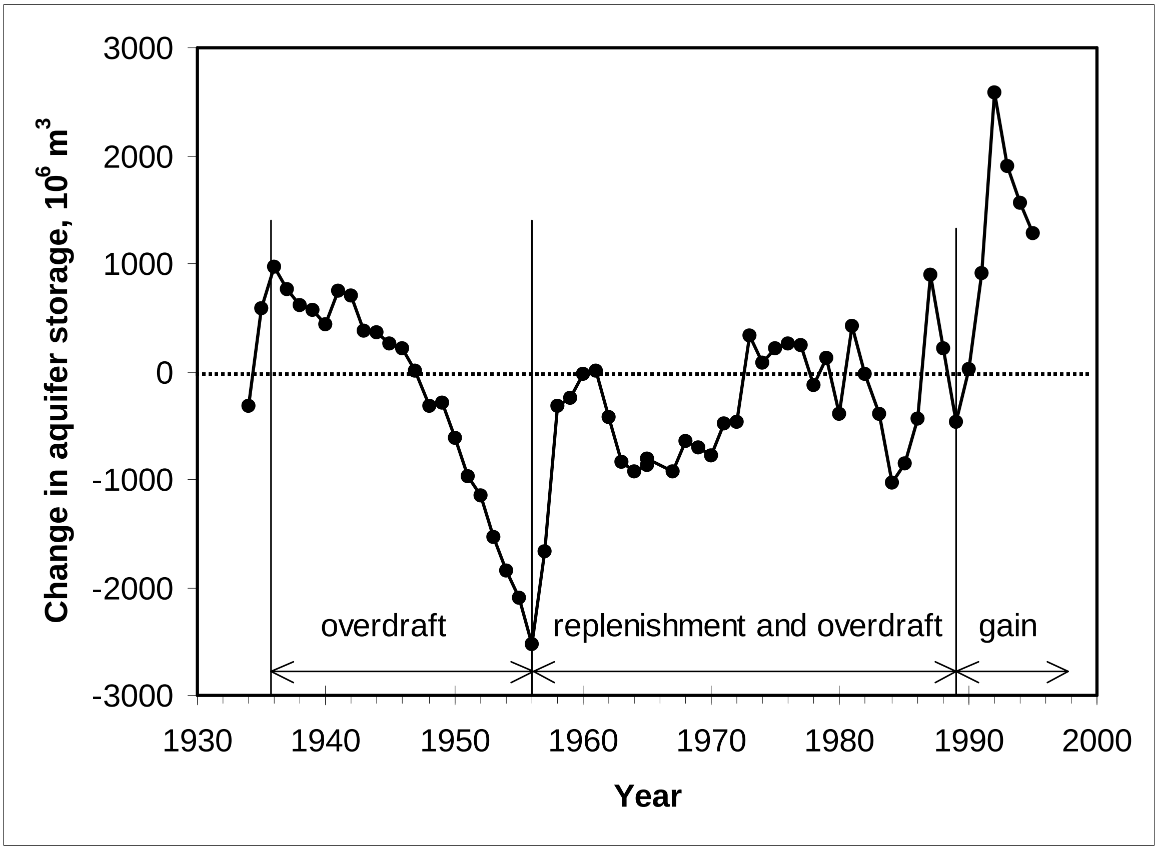

Figure 4. Changes in groundwater storage in the Edwards Aquifer, 1934-1995.

In the context of groundwater exploitation, the parties are all those who extract groundwater from a shared aquifer. Their profits are the revenues from ground-water sales minus the costs of extraction. The author has worked out a mathematical theory for the determination of cooperative and non-cooperative groundwater extraction strategies (Loaiciga, 2002). He showed that groundwater pumping rates (for both cooperative and cooperative strategies) may be obtained by solving a quadratic linearly constrained mathematical optimization problem of the following form:

$$\underset{\text{with respect to } Q}{\text{maximize}} \quad Q^T G Q + b^T Q + c \tag{1}$$

Subject to:

$$A\,Q \le p \qquad (2)$$

in which Q denotes a vector of pumping rates; G, b, and c are a matrix, vector, and scalar, respectively, that depend on aquifer properties, and on economic and climatic parameters; A and p are a matrix and vector, respectively, of constraint factors imposed on the (non-negative) pumping rates to ensure sustainable groundwater extraction. The model of Loáiciga (2002) is illustrated with data from a coastal aquifer in Santa Barbara, California. All the relevant hydrogeologic and economic data are available in Loáiciga and Leipnik (2000). Cooperative strategies were made sustainable by limiting drawdowns so that ground-water intrusion did not occur, even though groundwater extraction proceeded for at least 100 years. Non-cooperative strategies proved to be non-sustainable as we shall see. Without loss of generality, results were obtained for the case of two groundwater extractors tapping a shared aquifer. Their wells were separated a distance of 1000 m. Figure 5 shows the daily pumping rates at each of the two wells when they acted cooperatively or non-cooperatively.

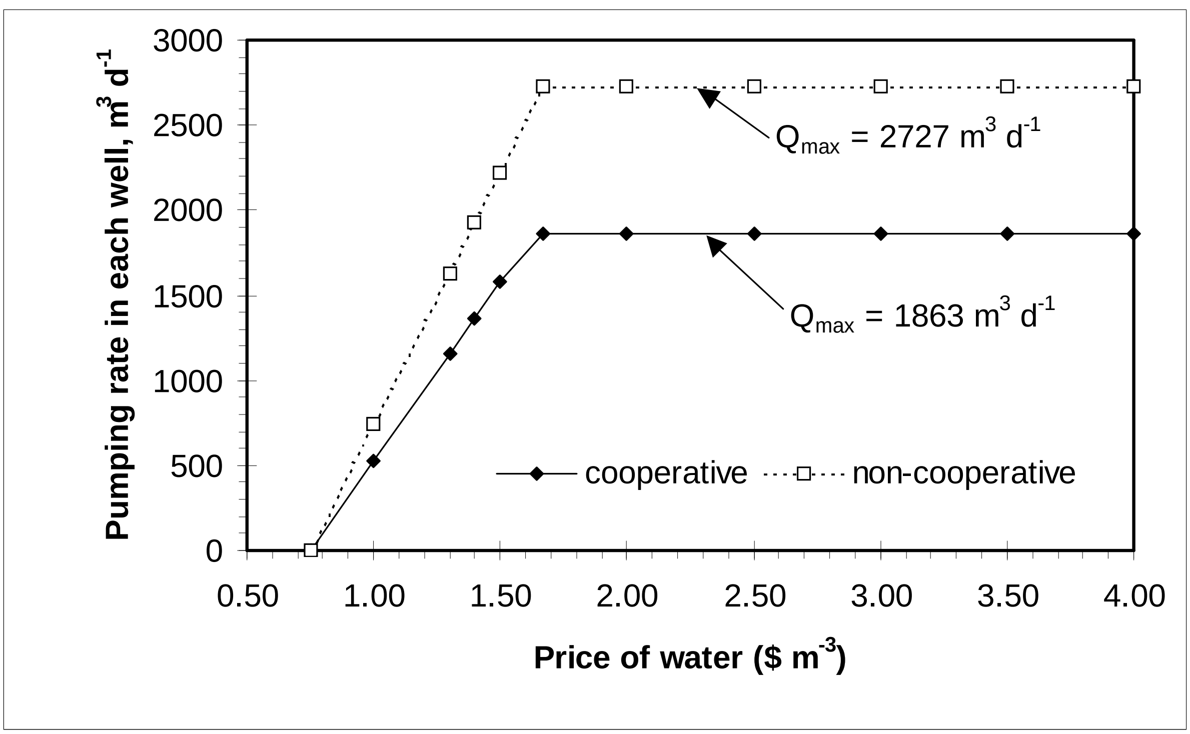

Figure 5. Pumping rates at each well for cooperative and non-cooperative strategies.

It is seen in Fig. 5 that the pumping rates increased with increasing water price up to about \$ 1.67 m^{-3}. For higher prices, the pumping rates remained constant because the allowable drawdowns at the wells (or elsewhere in the aquifer) were achieved with the maximum pumping rates. Notice that the non-cooperative pumping rate exceeded the cooperative pumping rate in all instances. Based on Fig. 5, one may be tempted to conclude that non-cooperative extraction strategies (i.e., expressed in terms of a pumping rate) are superior than the cooperative ones. That is not the case, however, because the latter ones allow continued pumping during the entire planning horizon of 100 years (36500 days) and beyond. The former, on the other hand, produced maximum allowable drawdowns after only a relatively short time of elapsed pumping, at which point the wells had to be turned off to avoid seawater intrusion. For example, for a water price of \$ 1.5 m^{-3}, the wells had to be turned off after 1710 days of elapsed pumping. In short, cooperative withdrawal was sustainable: groundwater can be mined indefinitely while preserving its quality. When non-cooperative strategies were implemented, the exploitation period was short-lived.

Figure 6 shows the present value of the total net revenues (i.e., the sum of net revenues of the two extractors) from sales of groundwater produced with cooperative and non-cooperative strategies. Once the price exceeded \$ 1.40 m^{-3}, the total revenue from cooperative (and sustainable) strategies were substantially larger than those generated by the non-cooperative strategies. In fact, the non-cooperative strategies plunge once the \$ 1.40 m^{-3} threshold is exceeded because, in that instance, the associated non-cooperative pumping rates (see Fig. 5) lead to a short operational time during which revenues are generated. The operational time in that case is stopped by drawdown constraints (seawater intrusion). When the water price exceeds \$ 1.67 m^{-3}, the non-cooperative revenue rebounds and increases monotonically thereafter, simply due to the higher price of ground water.

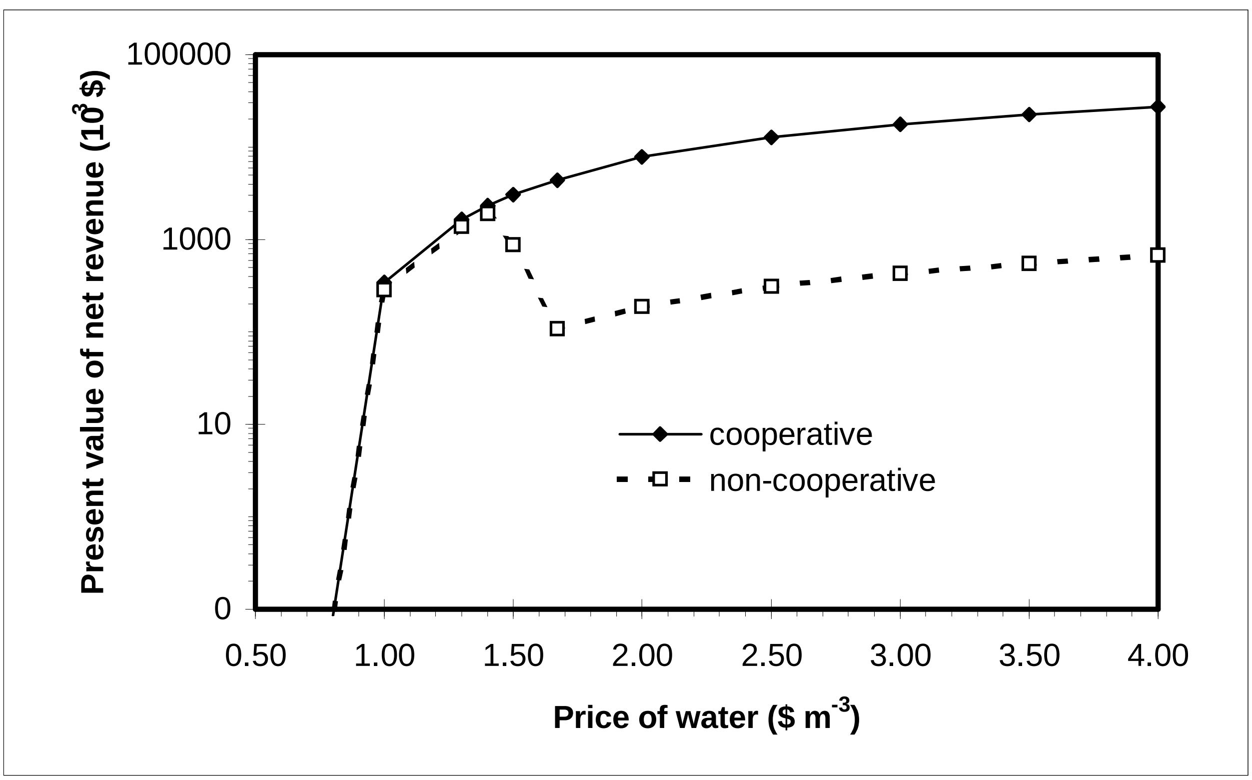

Figure 6. The net present value of the total revenues from groundwater sales.

Conclusions

The principles of sustainable groundwater exploitation have been laid down in this article. Various examples illustrate those principles and their application to real-world aquifer management.

The Edwards Aquifer exemplifies a highly variable system, in which ecological constraints are in direct conflict with old patterns of groundwater extraction for human use. On the other hand, the aquifer shows a remarkable capacity to replenish itself after severe overdraft. In the Edwards, the issue is not exclusively one aquifer storage capacity. The frequency of violations of the base spring flow to meet ecological requirements is important as well, and that requires that groundwater extraction be tuned to climatic and ecological fluctuations.

An example involving a coastal aquifer in Santa Barbara, California, exemplifies the role of environmental constraints on cooperative (sustainable) and non-cooperative (non-sustainable) groundwater extraction strategies. It was demonstrated that cooperation, that is, sustainable exploitation, pays better, both in economic terms and in terms of water-quality preservation.

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