SUSTAINABLE GROUNDWATER USE AND OVEREXPLOITATION

Llamas M.R.
Complutense University, Madrid, Spain

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Summary

Large engineering structures have been constructed since the time of the earliest civilizations to develop irrigation and urban water supplies. These hydraulic structures and their operation contributed significantly to the building of civil societies: cooperation, and not confrontation, was necessary for the common good. Development

of groundwater-using wells and/or infiltration galleries was done on a smaller scale, and usually did not require major societal cooperation.

During the first two-thirds of the twentieth century most large water development projects were focused on surface water structures. Most of them were designed, constructed, and operated by government agencies, and heavily subsidized with public money. However, the period since around 1950 has been characterized by intensive groundwater development, mainly in arid and semiarid regions. Usually this development has seen little government planning and control. This growth in groundwater use has contributed significantly to providing people with food and potable water, particularly in dry regions. Because of a lack of knowledge and planning, however, this groundwater development has caused problems in some places. These problems are often exaggerated or misunderstood.

One common false paradigm, or *hydromyth*, among water resource planners is that groundwater is an unreliable or fragile resource. In their view groundwater development is usually unsustainable, and most aquifers in arid or semiarid regions are overexploited. The concept of "aquifer overexploitation" is very complex. The term has so many meanings that it is practically meaningless and often misleading. Another pervasive hydromyth is that groundwater mining is always unethical because it is unsustainable and damages future generations' prospects. This blanket statement is questionable, since it presents a simplistic view of a rather complicated problem. Each case is site-specific. Long-term groundwater mining may be ethical or unethical, depending on particular circumstances.

1. Introduction

Groundwater development increased significantly during the later twentieth century in most semiarid or arid countries. This development was undertaken mainly by numerous small (private or public) developers, and scientific or technological control by the responsible water administration has often been weak. In contrast, surface water projects developed during the same period are usually on a larger scale and have been designed, financed, and constructed by government agencies that normally manage or control the operation of such irrigation or urban public water supply systems. This historical situation has often led to two effects:

- Most water administrations have limited understanding of, and poor data on, groundwater's status and value.
- In some cases, uncontrolled groundwater development has caused problems such as depletion of water levels in wells, decreasing well yields, degradation of water quality, land subsidence or collapse, interference with streams and/or surface water bodies, and ecological impacts on wetlands or riparian forests.

These problems have frequently been magnified or exaggerated by groups exhibiting professional bias or vested interests, and little hydrogeological expertise. For instance, in the year 2000 the World Water Council stated that: "Aquifers are being mined at an unprecedented rate—10% of world's agricultural production depends on using mineral groundwater." It will be shown that this 10% estimation is not based on any reliable data. In recent decades, groundwater overexploitation has become a hydromyth that has pervaded water resources literature. A common axiom derived from this pervasive hydromyth is that groundwater is an unreliable and fragile resource that should only be developed if conventional large surface water projects are not feasible.

Another common hydromyth is to consider that groundwater mining—that is, the development of nonrenewable groundwater resources—always represents overexploitation. The implication is that groundwater mining runs contrary to basic ecological and ethical principles. In this article, it will be shown that this may not be true under all circumstances. This statement may contribute to support for the opinion of those who consider this author to be a strange optimist working in an environment where gloom and doom predominate.

2. Scope and Aims

This article presents a summary of three topics:

- the many meanings of the terms *groundwater over-exploitation* and *sustainability*;
- the main factors to take into consideration in analyzing the pros and cons of intensive groundwater development; and
- strategies to prevent or correct the unwanted effects of intensive groundwater development.

Emphasis will be placed on the basic ethical issues regarding the use of nonrenewable groundwater resources. Groundwater mining is only one specific area within the ethics of water resources use, and a topic which has recently been dealt with by a number of authors.

What is an "intensively-used" or "stressed" aquifer? During the 1990s the expression *water-stressed region* became pervasive in the water resources literature. Usually it means that those regions are considered to be at risk of suffering serious social and economic problems, now or in the near future, because of water scarcity. Some authors insist on the likelihood of violent conflict: that is, "water wars" between water-stressed nations. The usual volume threshold used when adjudging a region to be under water stress is a maximum availability of 1000 m^3 of water per person per year, but some researchers almost double this figure. If this ratio is only 500 m^3 per person per year the country is considered to be in a situation of absolute water stress or water scarcity. This simplistic approach of considering only the ratio between water resources and population has little practical application, and is misleading. Most water problems are related to quality degradation and not relative abundance. In fact, many regions below the 500 m^3 per person per year threshold—such as Israel or several watersheds in Spain—enjoy high levels of economic and social development.

In its 1997 *Assessment of Global Water Resources*, the United Nations made a more realistic classification of national water stress. This assessment considered not only the ratio of water to population but also gross national product *per capita*. Other experts are also beginning to use more sophisticated indices or concepts in order to identify regions with current or future water problems. The results of these analyses will probably show that a certain level of water stress may actually be an incentive to promote the development of the region. In these cases, it could be defined as a *eu-stress*: that is, a “good stress.” For example, tourism or the production of high-value crops intensified significantly in many semiarid or arid regions during the late 1990s. The scarcity of precipitation may be fully compensated by the great number of sun hours and the high solar energy levels received. Examples of these areas are the “sunny belt” in the United States and most of the European Mediterranean coast. The necessary water for the activities mentioned may have several different origins. Groundwater is probably the most frequently used resource, but water may also be imported, recycled, or desalinated. For instance, in 2002 a desalination plant (40 million m^3 per year) will be completed in southeast Spain to supply water for greenhouse irrigation.

Throughout this article many examples from Spain will be presented. This is for several reasons. The first is that it is the region best known by the author. Another is that Spain is the most arid country in the European Union, and consequently groundwater abstraction for irrigation is more significant there than in other European countries. A third reason is that the Spanish Water Code of 1985 is probably the only body of water law in the world that has defined the concept of an *overexploited aquifer*.

3. What Does Sustainability Mean?

During the 1990s, the concept of sustainability was proposed by many as offering a philosophical approach to most water problems or conflicts. In 1987, the United Nations Commission on Environment and Development defined sustainability as “the ability to meet the needs of the present generations without compromising the ability of future generations to meet their needs.” The European Union Water Framework Directive, enacted in December 2000, states that it is necessary to promote or foster sustainable water use. Most people probably agree with this general principle, but its practical application to natural resources management is challenging. For instance, in terms of water resources management even the concept of minimum basic water needs, estimated as 20–50 liters per person per day, is heavily debated.

The concept of “future generations” represents another terminological problem. Are we talking about the people that will live on this planet in the twenty-second century, or in the whole third millennium, or only about the next two generations (in other words, the next fifty years)? No scientist is able to predict the situation a thousand years from now, and very few dare to offer scenarios for the twenty-second century. Most current predictions refer to the needs of humans in one or two future generations.

It is clear that environmental problems have a natural science foundation but also—and perhaps more significantly—a social science foundation. There is no doubt that the issue is complex. For instance, Gabaldon (this Encyclopedia) analyzes sustainable development in Latin America and the Caribbean and considers four different types of sustainability: ecological, social, economic, and political. One very interesting conclusion is that this region has plenty of water and other natural resources; in terms of practically all ecological indicators the people in the region are *rich*. Nevertheless, because of the economic, social, and political situation their sustainable development prospects are in jeopardy.

For many years, this author has argued that water scarcity is not usually the problem. The real issue is widespread water mismanagement. The main result of this mismanagement is water quality degradation—and every expert knows that groundwater quality degradation or pollution is a more serious problem than surface water pollution. Many authors now consider that the way to begin solving existing water problems—mainly lack of potable water and sanitation—is to desist from unrealistic “gloom and doom” campaigns, trying to create environmental scares, and predicting “water wars” in the near future.

This article will show that groundwater development since about 1950 has contributed significantly to alleviating poverty and improving public health. These improvements should be maintained and increased, but in new ways. The generally uncontrolled and unplanned nature of much groundwater development must be rationalized to take into account the externalities of groundwater extraction, and the various uncertainties inherent in water management. The implementation of this groundwater sustainable use requires, as a *conditio sine qua non*, the participation of educated and informed users and other stakeholders in groundwater management decisions. This demands urgently the development of institutional arrangements for groundwater management where users can work jointly with the corresponding water authorities.

4. The Complex and Varied Concept of Overexploitation

4.1. Overview

The term “overexploitation” has been much used since about 1970. Nevertheless, Custodio and most other current researchers agree that the concept of aquifer overexploitation is one that resists easy and practical definition.

A number of terms related to overexploitation can be found in the water resources literature. These include safe yield, sustained yield, perennial yield, overdraft, groundwater mining, exploitation of fossil groundwater, optimal yield, and others (see Glossary). In general, these terms have the common aim of avoiding *undesirable effects* as a result of groundwater development. However, perceptions of this *undesirability* depend mainly on social factors and viewpoints. These social perceptions may be related more to the legal, cultural, and economic background of the region than to hydrogeological factors.

The Spanish Water Code of 1985 does not mention the concept of sustainability in water resources development specifically, but indicates frequently that development has to be respectful of nature. Nevertheless, it basically considers an aquifer to be *overexploited* when the rate of water extraction is close to, or larger than, that of natural recharge. In other words, the Spanish regulations follow the common misconception of considering that the *safe yield* or *sustainable yield* is practically equal to the natural recharge.

This misconception has been voiced by many other hydrogeologists. In 1982, Bredehoeft and co-authors rightly described the basic concepts as follows:

Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction of the previous discharge from the aquifer, an increases in the recharge, or a combination of these changes. The decrease in the discharge plus the increase in recharge is termed capture. Capture may occur in the form of decreases in the groundwater discharge into streams, lakes, and the ocean, or from decreases in that component of evapotranspiration derived from the saturated zone. After a new artificial withdrawal from the aquifer has begun, the head of the aquifer will continue to decline until the new withdrawal is balanced by capture… In many circumstances the dynamics of the groundwater system are such that long periods of time are necessary before any kind of an equilibrium conditions can develop.
When considering changes in social perceptions of water value it is interesting to note that in 1940, according to the American hydrogeologist Theis, water was *gained* by lowering the water table in areas of rejected recharge, or where recharge was *lost* due to transpiration from "non-beneficial vegetation" (phreatophytes). In Theis' time, *wetlands* were *wastelands*!

Some researchers, like Bredehoeft et al. and Custodio, have presented theoretical examples to show that the time necessary to reach a new equilibrium or steady state between groundwater extraction and capture may be decades or centuries. They have also illustrated the relationship between the size of the aquifer, its diffusivity, and the time needed for it to reach a new steady state after the beginning of groundwater withdrawal.

Several national and international conferences have been organized by Spanish hydrogeologists since the 1980s to discuss and help dispel the misconceptions related to aquifer overexploitation. However success here has been limited to date, in Spain and elsewhere.

In 1992 this author suggested that an aquifer might be considered overexploited when the economic, social, and environmental costs that derive from a certain level of groundwater abstraction are greater than its benefits. Given the multi-faceted character of water as a commodity, this comparative analysis should include hydrologic, ecological, socioeconomic, and institutional variables. While some of these variables may be difficult to measure and compare, they must be explicitly included in the analysis so they can inform decision-making processes. The following sections present the criteria that can be used to evaluate the benefits and costs of groundwater abstraction. In this article the so-called *total economic value* (TEV) of groundwater, as defined in 1997 by the US National Research Council, has not been considered explicitly. Nevertheless, the basic categories of extractive services and *in situ* services are taken into account in the description of costs and benefits of groundwater development. The National Research Council recognizes that ascribing monetary value to groundwater's "*in situ* services" (including avoiding subsidence, promoting conservation of wetlands, and maintaining the base flow of rivers) is a complex and difficult task that requires more research.

4.2. Benefits of Groundwater Use

The concept of overexploitation must necessarily take into account the numerous socioeconomic—and even ecological—benefits that can derive from groundwater use. Socioeconomic benefits range from improved water supply and sanitation provision to economic development as a result of agricultural growth in a region. With regard to potential ecological benefits, the use of groundwater resources can often eliminate the need for surface reservoirs and other large and expensive hydraulic structures that might seriously damage the natural regime of a river or stream, and/or create serious social problems like those described in the report of the World Commission on Dams.

4.2.1. Water Supply

Groundwater is a key source of drinking water, particularly in rural areas and in island environments. In Spain, for example, medium-sized and small municipalities (of less than 20 000 inhabitants) obtain 70% of their supply from groundwater sources. In some coastal areas and islands, dependence on groundwater as a source of drinking water is even higher. Table 1 shows the importance of groundwater for municipal water supply in Southern European countries.

	Groundwater use by sector (percentage of total abstractions)			**Demand covered by groundwater (Percentage by sector)**		
Country	Municipal Water Supply	Agriculture	Industrial uses	Municipal Water Supply	Agriculture	Industrial uses
Spain	17	80	3	26	21	–[(1)]
France	63	6	31	71	4	55
Italy	39	57,5	3,5	91	25	7
Greece	37	58	5	–	20,5	–
Israel	20	75	5	45	60	20
Turkey	64	36	–[(1)]	64	36	–[(1)]

[1] Included in municipal water supply statistics

Table 1. Current groundwater uses in some Mediterranean countries (from Margat, 1999, as cited in Llamas et al., 2001)

4.2.2. Irrigation

In many arid and semiarid countries, groundwater's main use is for agriculture (Table 1). Although few studies have looked at the role that groundwater plays in irrigation, those that do exist point to the higher socioeconomic productivity of irrigated agriculture using groundwater than that using surface water. A study in Andalusia, southern Spain, in 1999 shows that irrigated agriculture using groundwater is several times more effective in terms both of productivity and of generating employment than agriculture using surface water.

The upper part of Table 2 shows the results of this Andalusian study. It is important to note that these results are based on the average water volumes *applied* in each irrigation agricultural unit (or group of fields): water losses occurring between the source and the fields were not estimated. Nevertheless, these losses are significant in surface water irrigation. Other studies have calculated the volumes used in surface water irrigation in terms of the water actually taken from the reservoirs. For example, the White Paper on Water in Spain, published in the year 2000, estimated average consumption of

6700 m^3 ha^{-1} per year and 6500 m^3 ha^{-1} per year for the two catchments that were the subject of the Andalusían study, without differentiating between surface and groundwater irrigation. Using these new figures and the volumes given for irrigation with groundwater in the Andalusían study, more realistic average volumes used for irrigation including a surface water volume of 7400 m^3 ha^{-1} per year can be estimated. The lower part of Table 2 shows—in the light of these new, more realistic, data—that the productivity of groundwater irrigation is five times greater than that using surface water, and generates over three times more employment per cubic meter used.

Indicator for irrigation	**Origin of irrigation water**			**Relation groundwater surface water**
	Groundwater	**Surface water**	**Combined**	
Irrigated surface (10^3 ha)	210	600	810	0.35
Average volume applied in field (m^3/ha)	4000	5000	4700	0.8
Specific production (10^3 pta/ha) [1]	1500	550	800	2.7
Total production (10^9 pta)	300	325	625	0.9
Water productivity (pta/m^3) [1]	360	110	160	3.3
Employment generated (UTA/100 ha)[2]	23	13	15	1.8
Total employment (10^3 UTA)[2]	50	75	125	0.67
Average consumption at origin (m^3/ha)	*4000*	*7400*	*6500*	*0.54*
Water productivity (pta/m^3) [1]	*360*	*70*	*120*	*5.1*
Employment generated (UTA/10^6 m^3) [2]	*58*	*17*	*25*	*3.4*

[1] US$1 ≅ 170 pta
[2] UTA = Working Units/Year (Unidades de Trabajo-Año), or the work of one person working full-time for one year.

Table 2. Comparison of irrigation using surface and groundwater in Andalusian study (from Llamas et al., 2001)

It can be argued that the greater socioeconomic productivity of groundwater irrigation in Andalusia is due to the excellent climatic conditions that occur in the coastal areas. While good climatic conditions may influence the results, the situation is similar to that in other continental regions of Spain. This was demonstrated at a seminar on groundwater economics held in Spain in 2000.

Although no comparable research from elsewhere in Europe is known, studies in India point to similar results. For example, some researchers estimate that groundwater constitutes 30% of all water used for irrigated agriculture in India but is responsible for 70–80% of all agricultural production. In 1995, according to another author, research in India indicated that yields in groundwater-irrigated areas were higher by a third to a half than in areas irrigated using surface waters. Several researchers, and the World Water Council, consider that intensive groundwater use in India has been decisive in helping feed that country's current population of one billion. Nevertheless, this "miracle" has not been considered to be sustainable by a good number of authors because they considered that it has been achieved by pumping about 100 cubic kilometers of nonrenewable groundwater. This figure, frequently quoted, was given by an author based on an undated and unpublished report, and does not match the data provided in the year 2000 by the Indian Water Resources Society. India seems to be the country that has developed groundwater irrigation most intensively during the last three or four decades (more than 20 million hectares—200 000 km^2—developed). A thorough analysis of the benefits and costs of this phenomenon would be of global value.

When analyzing the data considered in this section it is important to remember the deep uncertainties associated with hydrologic data. However, the results obtained are indicative of the greater productivity of irrigation using groundwater. This should not be attributed to any intrinsic quality of groundwater in itself. Instead, explanations may be found in the greater control over, and security of, supply that groundwater provides, especially during droughts, and the greater dynamism that has characterized farmers who have sought their own sources of water and borne the full (direct) costs of drilling, pumping, and distribution.

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Biographical Sketch

Prof. M. Ramon Llamas is currently Professor of Hydrogeology at the Complutense University of Madrid. Since 1986 he has been a Fellow of Spain’s Royal Academy of Sciences.

Dr. Llamas has a Ph.D. in Civil Engineering and another in Geology. He spent fifteen years as a hydraulic engineer in the Directorate General of Hydraulic Works and two years in the Center for Land Use Planning and Environment, both departments in the Ministry of Public Works of Spain. In 1972 he became the first tenured Professor of Hydrogeology in Spain. Since 1972 his main duties have been university teaching and research on water resources. He is author or co-author of more than 50 books or monographs, and almost 200 scientific papers. He was President of the International Association of Hydrogeologists from 1984 to 1989. In 1992 he was appointed Honorary Fellow of the Geological Society of the United Kingdom He is a Vice-President of the International Association of Water Resources (2000–2003).

Over the last 10 years Dr. Llamas has devoted special effort to analyzing the relations between groundwater development and nature conservation, and the positive (and neglected) role that groundwater development may have in national water policies. Between 1986 and 1998 he was a member of the Executive Committee of the Spanish nongovernmental organization CODESPA. This is a charity with a current annual budget of about US$8 million promoting sustainable development in developing countries. In 1999 he was appointed as a member of the Scientific Advisory Committee of the International NGO Action against Hunger.

Dr. Llamas is the designer and director of a four-year research program launched in 1998 by the Spanish Foundation Marcelino Botín on the role of groundwater resources in water policy.