Water and Ethics

USE OF GROUNDWATER

Ramón Llamas

UNESCO International Hydrological Programme

World Commission on the Ethics of Scientific Knowledge and Technology

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Preface

This essay is one of a series on Water and Ethics published under the International Hydrological Programme of UNESCO. A Working Group on the Use of Fresh Water Resources was established under that programme in 1998. Preliminary drafts on fourteen aspects of this topic were prepared under the guidance of this Working Group.

An extended executive summary was prepared by J. Delli Priscoli and M. R. Llamas and was presented to the first session of the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) held in Oslo in April 1999. At the latter meeting, COMEST established a sub-commission on the Ethics of Fresh Water under the Chairmanship of Lord Selborne. The first meeting of this sub-commission was held at Aswan in October 1999. A 50-page survey by Lord Selborne on the Ethics of Fresh Water, based on the above meetings and documents, was published by UNESCO in November 2000.

Since then, the original draft working papers have been revised under the editorship of James Dooge and published on CD ROM as an input to the Third World Water Forum held in Kyoto in March 1993. These are now being published in printed form as the first fourteen titles in a series of Water and Ethics

These essays are written from the point of view of experts on different aspects of the occurrence and use of fresh water who are interested in the ethical aspects of this important subject. They do not purport to be authorative discussions of the basic ethical principles involved. Rather, they aim at providing a context for a wide-ranging dialogue on these issues between experts in diverse disciplines from the natural sciences and the social sciences.

James Dooge
John Selborne

This essay in the series discusses the dangers of a simplistic approach to the issue of the sustainability of groundwater use and the need to treat each case as site-specific. Criteria are presented for the evaluation of proposed schemes of groundwater use and the ethical implications involved

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1. Introduction

Groundwater development significantly increased during the second half of the last century in most semi-arid or arid countries. This development has been mainly undertaken by a large number of small (private or public) developers and often the scientific or technological control of this development by the responsible Water Administration has been scarce. In contrast, the surface water projects developed during the same period are usually of larger dimension and have been designed, financed and constructed by Government Agencies which normally manage or control the operation of such irrigation or urban public water supply systems. This historical situation has often produced two effects: 1) most Water Administrations have limited understanding and poor data on the groundwater situation and value; 2) in some cases the lack of control on groundwater development has caused problems such as depletion of the water level in wells, decrease of well yields, degradation of water quality, land subsidence or collapse, interference with streams or surface water bodies, ecological impact on wetlands or gallery forests.

These problems have been sometimes magnified or exaggerated by groups with lack of hydrogeological know-how, professional bias or vested interests. Because of this in recent decades groundwater over-exploitation has become a kind of 'hydromyth' that has pervaded water resources literature. A usual axiom derived from this pervasive 'hydromyth' is that groundwater is an unreliable and fragile resource that should only be developed if it is not possible to implement the conventional large surface water projects.

Another usual 'hydromyth' is to consider that groundwater mining – i.e. the development of non-renewable groundwater resources – is always an 'overexploitation'. The implication of this word is that groundwater mining goes against basic ecological and ethical principles.

This essay is an updated version of the draft on the same topic presented in the last meeting of the UNESCO Working Group on the Ethics of Freshwater Uses on Almería, Spain, in August 1999 (Llamas and Priscoli, 2000; Priscoli and Llamas, 2001). These ideas were also presented and discussed during a UNESCO meeting on regional aquifers held in Tripoli in November 1999 (Llamas, 2001*a*). Most of the above mentioned draft was also included in the groundwater section of the formal report on Water Ethics of the UNESCO World Commission on the Ethics of Science and Technology (Selborne, 2000). The general topic of Groundwater Intensive Use was the theme of an International Symposium held in Valencia (Spain) in December 2002. This International Symposium was organised by three Spanish institutions and it was sponsored by UNESCO, FAO, the International Association of Hydrogeologists and the International Water Resources Association. The organisers of this International Symposium summarised its main results in the *Valencia Declaration* which is included as an annex to this essay. A closed Workshop on the same theme was held in Madrid in December 2001. The proceedings of this Workshop, with participation of more than thirty authors from more than fifteen countries has been published as a book (Llamas and Custodio, 2003). It seems clear that groundwater development is a topic that is calling the attention of the water experts.

2. Scope and aim

The aim of this essay is to present a summary of: 1) the many and confusing meanings of the term over-exploitation and the main factors of the possible adverse effects of groundwater development; 2) the criteria to diagnose aquifers prone to situations of over-use; 3) the strategies to prevent or correct the unwanted effects of groundwater development in ‘stressed or intensively used aquifers’.

A certain emphasis will be put on the ethical issues in relation to the use of non-renewable groundwater. Nevertheless, groundwater mining is only an end case in the ethics of water resources use. Therefore, the general framework of this paper will be the technical and ethical issues related to the management of ‘stressed aquifers’. The above mentioned proceedings of the International Workshop and Symposium on Intensive Use of Groundwater represent a significant contribution in order to bring more light on this topic.

But what is a stressed aquifer? During the last decade the expression ‘water stressed regions’ has become pervasive in the water resources literature. Usually this expression means that those regions are prone to suffer now or in the near future serious social and economic problems because of water scarcity. Some authors insist in the probable outbreak of violent conflicts, that is, water wars among water stressed regions. The usual threshold to consider a region under water stress is 1,000 m^3/person/year, but some authors almost double this figure. If this ratio is only 500 m^3/person/year the country is considered in a situation of absolute water stress or water scarcity (Seckler et al., 1998).

This simplistic approach of considering only the ratio between water resources and population has little practical application and is misleading. First of all most water problems are related to its quality and not its relative abundance. As a matter of fact, a good number of regions – such as Israel or several watersheds in Spain – with a ratio lower than 500 m^3/year/person are regions with a high economic and social standard of living.

In 1997, the United Nations in an Assessment of Global Water Resources has done a more realistic classification of countries according to their water stress. This assessment considers not only the ratio water/population but also the Gross National Product per capita. Other experts are beginning to use other more sophisticated indices in order to diagnose the current of future regions with water problems. The result of these analyses will probably show that a certain 'water-stress' may be an incentive to promote the development of the region. In this case, it could be defined as a 'eu-stress', i.e. a good stress. For example, during the last decades in a good number of semi-arid or arid regions tourist development or cultivation of high value crops have been very intensive. The scarcity of precipitation has been fully compensated by the great amount of sun hours and the high radiation energy. The examples of these developments are the 'sunny belt' in the United States of America and most of the European Mediterranean coast. The necessary water for these activities may have different origins. Groundwater is probably the greater and more frequent resource but also may be imported, recycled or even desalinated brackish or sea water; for example, within the year 2002 in Almería (Southern Spain) a rather large (42 Mm^3/ year) sea water desalting plant has begun to operate. This water will be used mainly to grow high value crops in greenhouses. The real cost of this desalted water will be less than US\$ 0.6/m^3.

3. The manifold concept of over-exploitation

The term over-exploitation has been frequently used during the last three decades. Nevertheless, most authors agree in considering that the concept of aquifer over-exploitation is one that is poorly defined and resists a useful and practical definition (Adams and MacDonald, 1995; Collin and Margat, 1993; Custodio, 1992, 1993, 2000*a*, 2000*b* and 2002; Foster, 1992; Llamas, 1992*a,* 1992*b* and 2001*b*; Sophocleous, 1997 and 2000).

A number of terms related to over-exploitation can be found in the water resources literature. Some examples are: safe yield, sustained yield, perennial yield, overdraft, groundwater mining, exploitation of fossil groundwater, optimal yield and others (Adams and MacDonald, 1995; Fetter, 1994). In general, these terms have in common the idea of avoiding 'undesirable effects' as a result of groundwater development. However, this 'undesirability' depends mainly on the social perception of the issue. This social perception is more related to the legal, cultural and economic background of the region than to hydrogeological facts.

For example, in a recent research study on over-exploitation financed by the European Union, called GRAPES (Acreman, 1999), three pilot catchments were analysed; the Pang in the United Kingdom, the Upper Guadiana in Spain and the

Messara in Greece. The main social value in the Pang has been to preserve the amenity of the river, related to the conservation of its natural low flows. In the Messara the development of irrigation is the main objective and the disappearance of relevant wetlands has not been a social issue. In the Upper Guadiana the degradation of some important wetlands caused by groundwater abstraction for irrigation has caused a serious conflict between farmers and conservationists (Llamas et al., 1996; Cruces et al., 1997).

The Spanish Water Code of 1985 does not mention specifically the concept of sustainability in water resources development but frequently indicates that this development has to be respectful to nature. Nevertheless, it basically considers an aquifer 'overexploited' when the pumpage is close or larger than the 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, already shown by Theiss (1940), has been voiced by other American and Spanish hydrogeologists such as Bredehoeft et al. (1982), Llamas (1986), Sophocleous (1997 and 2000) and Bredehoeft (1997). Bredehoeft et al. (1982) describe the issue in the following way:

> 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.

As an example of the change in the social perception of water values it is interesting to remark that for Theiss (1940) the water 'was gained' by lowering the water table in areas of rejected recharge or where the recharge was 'lost' through transpiration from 'non-beneficial vegetation' (phreatophytes). In Theiss' times 'wetlands were wastelands'.

Bredehoeft et al. (1982) present some theoretical examples to show that the time necessary to reach a new equilibrium or steady state between groundwater extraction and capture may take decades or centuries. Custodio (1992) and Sophocleous (2000) have also presented graphs to show the relationship between the size of the aquifer, its difussivity and the time necessary to reach a new steady state after the beginning of a groundwater withdrawal and obtained similar values to Bredehoeft et al. (*ibid*).

On occasion of the preparation of new Spanish Water Law of 1985 these misconceptions were also discussed before the Law was enacted and afterwards (Pulido et al., 1989). Also two international conferences on 'overexploitation' were organised by Spanish hydrologists (Simmers et al., 1992; Custodio and Dijon, 1991) in order to contribute to dispel these misconceptions. Nevertheless, up till now the success of these activities have been rather limited as it can be seen reading the papers by Postel (1999) or Seckler et al. (1998) or Cosgrove and Reijsberman (2000).

As was previously discussed, certain authors consider that 'groundwater mining' is clearly against sustainable development and that this kind of 'ecological sin' should be socially rejected and/or legally prohibited. Nevertheless, a good number of authors (Freeze and Cherry, 1979; Issar and Nativ, 1988; Llamas, 1992*a*; Collin and Margat, 1993; Margat, 1994; Lloyd, 1997) indicate that, under certain circumstances, groundwater mining may be a reasonable option. As a matter of fact, groundwater mining is today practised in a good number of regions (Bemblidia et al., 1996; Custodio, 1993; Issar and Nativ, 1988; Zwingle, 1993). Fossil groundwater has no intrinsic value if left in the ground except as a potential resource for future generations, but are such future generations going to need it more than present ones? As it was previously told, it is hoped that the recent activities in order to bring more data and transparency on this issue (see *Valencia Declaration* in annex, and Llamas and Custodio, 2003) will mean a clear step forward for a better water policy.

4. Diagnostics of real or apparent over-used aquifers

4.1 Indicators of over-exploitation

Adams and MacDonald (1995) noted that, in general, over-exploitation is only diagnosed 'a posteriori'. They tried in their report and in other subsequent papers to present a method to analyse 'a priori' the susceptibility of an aquifer to become stressed (or over-exploited). They consider three main effects or indicators: a) decline in water levels, b) deterioration of water quality and c) land subsidence. In this essay two other relevant effects are considered: d) the hydrological interference with streams and lakes; e) the ecological impact on aquatic ecosystems fed by groundwater.

Before describing these five indicators, it is relevant to mention that these indicators are sometimes wrongly used. This is either because of lack of hydrogeological knowledge or because certain lobbies may have an interest in expanding the 'hydromyth' of the unreliability (or fragility) of groundwater development in order to promote the construction of large hydraulic works.

4.2 Groundwater-level depletion

It has not been unusual – like in the Spanish 1985 Water Law – to define overexploitation as the situation when the groundwater withdrawal exceeds or is close to the natural recharge of an aquifer. The observation of a trend of continuous significant decline of the levels in water wells during one or two decades is frequently considered as a clear indication of imbalance between abstraction and recharge. This is a simplistic approach that might be a long way from the real situation as it has been shown previously, with reference to the papers of several authors, mainly Bredehoeft et al. (1982) and Custodio (1992).

When a well field is operated, even if the general input is much greater than pumping, a transient state will always occur before the water levels in wells stabilise. The duration of the transient state depends mainly on aquifer characteristics such as size and hydraulic difussivity, degree of stratification and heterogeneity. On the other hand, the natural recharge of an aquifer in semiarid and arid climates does not have a linear relationship with precipitation. In dry years recharge might be negligible or even negative due to evapotranspiration or evaporation from the watertable. Significant recharge may only occur once every one or more decades. Therefore the water table depletion trend during a long dry spell – when the recharge is almost nil and the pumpage is high – might not be representative of a long-term situation.

Groundwater depletion caused by deep wells can cause the drying up of shallow wells or khanats (infiltration galleries) located in the area of influence of the deep wells. This may cause social problems in regions where many farmers can not afford to drill new wells or the Water Authorities are not able to demand the just compensation in teh form of water or money to the poor farmers. Some situations of this type are described in the books by Moench (1999) and Burke and Moench (2000). There is no doubt that here there is an ethical issue of equity but probably in most cases the solution is not to forbid groundwater abstraction but to overcome poverty.

4.3 Degradation of groundwater quality

Groundwater abstraction can cause, directly or indirectly, changes in groundwater quality. The intrusion into a freshwater aquifer of low quality surface or groundwater because of the change in the hydraulic gradient due to groundwater abstraction is a frequent cause of quality degradation. Saline intrusion may be an important concern for the development of aquifers adjacent to saline water bodies. This is a typical problem in many coastal regions of semiarid or arid regions. The relevance of the saline water intrusion not only depends on the amount of the abstraction, in relation to the natural groundwater recharge, but also on the well field location and design, and on the geometry and hydrogeological parameters of the pumped aquifer. In many cases the existing problems are due to uncontrolled and unplanned groundwater development and not to excessive pumpage (Custodio and Bruggeman, 1982).

The degradation of groundwater quality may not be related at all to excessive abstraction of groundwater in relation to average natural recharge. Other causes may be responsible, such as return flow from surface water irrigation, leakage from urban sewers, infiltration ponds for wastewaters, septic tanks, urban solid waste landfills, abandoned wells, mine tailings and many other activities not related to groundwater development (Foster et al., 1998; Barraqué, 1997). Also a temporary situation, such as a serious drought, can contribute to the degradation of groundwater quality (Lambrakis et al., 1997).

According to the European Commission, groundwater pollution is the most serious problem of the European Union water resources policy. The Programme for the Integrated Management and Protection of Groundwater (*Official Journal of the EU*, 25 November 1996) has been designed to deal with this problem, although it is still too early to assess the practical effectiveness of this EU Programme. Its first positive impact is the greater attention paid to groundwater in the new European Union Water Framework Directive enacted in December 2000.

An awareness of the crucial importance of preventing groundwater pollution in order to avoid a future water crisis exists only in a few countries. The old proverb: 'out of sight out of mind' is very apt in this case. A strong educational effort is necessary in order not to bequeath next generations some of our better aquifers almost irreversibly polluted (Custodio, 2000*a*; Llamas, 1991). This is the real problem in most countries, humid, arid and semiarid. The depletion of groundwater storage (classical misconception of over-exploitation) is not generally a problem as serious as groundwater quality degradation and may often be solved without great difficulty, e.g. if water-use efficiency is improved.

One might think that the problem of groundwater quality degradation is mainly an issue in humid and industrialised regions. This does not seem to be the general situation. For instance, Salameh (1996) in his study of Jordan water resources says: 'It is not water quantity, but its worsening quality that will bring us to our knees'. And Jordan is one of the countries with least amount of renewable water resources per capita (about 160 m^3/year and person) (Gleick, 1993; Bemblidia et al., 1996).

It is significant that the book Groundwater Protection published by the Conservation Foundation (1987) shows no significant concern about groundwater overdraft or overexploitation in the United States of America. Its main interest is to mitigate groundwater pollution. This aspect has been also emphasised in the Workshop and Symposium on Intensive Use of Groundwater (see Llamas and Custodio, 2003 and annex with the *Valencia Declaration*).

4.4 Susceptibility to subsidence

Sedimentary formations are deposited at low density and large porosity. As subsequent layers are deposited the overburden compresses the underlying strata. The overburden is in static equilibrium with the intergranular stress and the pore water pressure. This equilibrium is quickly reached in coarse-granular layers, but in fine-grained layers with low permeability, it may take a long time. The effect of this process is the natural progressive consolidation of sediments.

When an aquifer is pumped the water pore pressure is decreased and the aquifer solid matrix undergoes a greater mechanical stress. This greater stress may produce compaction of the existing fine-grained sediments (aquitards) if the stress due to the decrease in water pore pressure is greater than the so-called 'preconsolidation' stress. This situation has occurred in some aquifers formed by young sediments, such as those in Mexico City, Venice, Bangkok and others (Poland, 1985).

Caves and other types of empty spaces may exist under the watertable in karstic aquifers. When the watertable is naturally depleted the mechanical stability of the 'roof' of such empty spaces may be lost and the roof of the cave collapses. This is a natural process that gives rise to the classical 'dolines and poljes' in the karstic landscape. When the water table depletion or oscillation is increased by groundwater abstraction the frequency of karstic collapses can be also increased. The accurate prediction of such collapses is not easy (LaMoreaux and Newton, 1992).

In both cases the amount of subsidence or the probability of collapses is related to the decrease in pore water pressure which is related to the amount of groundwater withdrawal. Nevertheless the influence of other geotechnical factors may be more relevant that the amount of water abstracted in relation to the renewable groundwater resources of the aquifer.

4.5 Interference with surface water

Some anthropogenic activities may have a significant impact on the catchment hydrologic cycle, as was already stated by Theiss (1940) and Bredehoeft et al. (1982). For example in the Upper Guadiana catchment in Spain (Cruces et al., 1997), a serious water table depletion (about 30–40 m) has decreased the evapotranspiration from the watertable and wetlands between 100 and 200 Mm^3/year. This depletion has degraded several important wetlands but has increased significantly the renewable water resources that can be used for irrigation, which were estimated between 300 and 400 Mm^3/year under non-disturbed situation.

The artificial depletion of the water table can also change dramatically aquifer-streams relationship. 'Gaining rivers' fed by aquifers may become dry except during storms or humid periods when they may become 'losing rivers', an important source of recharge to the aquifer. Nevertheless, this 'new water budget' may present legal problems if the downstream water users have previous water rights (Sophocleous, 2000).

4.6 Ecological impacts

Ecological, real or pretended impacts are becoming an important new constraint in groundwater development in some countries (Fornés and Llamas, 1999; Llamas, 1992*b*; Custodio 2000*b*; Sophocleous, 2000). These impacts are mainly caused by water table depletion. This can induce different effects such as: 1) decreasing or drying up of springs or low flow of streams; 2) diminution of soil humidity to an extent in which phreatophitic vegetation cannot survive; 3) changes in microclimates because of the decrease in evapotranspiration. In some cases, the ecological impact of such changes is obvious. For instance, if the water table that was previously at land surface and it is lowered by more than 10 meters during more than twenty years it is obvious that the peatland or riparian forests that might exist on that aquifer are not going to survive. But if the water table is depleted only during one or two years and not more than one or two meters probably it cannot be assured that the ecological impact will be irreversible. Quantitative and detailed studies on this type of problems are still rather scarce.

5. Strategies and criteria

5.1 Introduction

In this section seven criteria or strategies are presented in order to assess the potential impacts or problems that groundwater development can induce. One aim of this essay is to analyse the ethics of groundwater mining but such analysis demands a more general framework. Perhaps the main moral of this paper is that an 'stressed aquifer system' can become an 'eu-stressed aquifer system' if the criteria described hereafter are applied; in other words, the groundwater intensive use can be often be beneficial if such development is well designed and controlled.

5.2 Diagnostic method

As previously mentioned, Adams and MacDonald (1995) proposed a method to make an 'a priori' diagnosis of aquifer susceptibility to over-exploitation effects. The method established three levels of susceptibility based on groundwater level decline, saline intrusion and subsidence. The ecological impacts and the influence of groundwater abstraction on surface water bodies or streams are not graded. The technique involves assigning numerical values to the contributing factors and then summing them up to give an overall grade or susceptibility to the particular impact under consideration. Only relative values are used in the final designation (high, medium, low) due to the high parameter variability at individual locations. According to these authors, as only relative values are used in the grading, this diagnostic method should only be used with great caution for inter-regional comparisons. The third proposal of the *Valencia Declaration* (see annex) insists on the need to recognise the great diversity in hydrogeological and socioeconomic situations. This makes almost impossible to apply the same groundwater management tools everywhere.

5.3 Management of uncertainties

A generally accepted principle is that 'prevention is better than cure'. But this version of the precautionary principle should be applied with considerable prudence. In general, groundwater development should not be rejected or seriously constrained if it is well planned and controlled. During recent decades, notable socio-economic benefits have derived from groundwater withdrawal, particularly in developing countries. It has provided affordable potable and irrigation water, thus improving public health and significantly contributing to alleviate malnutrition and famine. Moreover, groundwater development is usually the cheapest and fastest way to achieve some of the UN Millennium Declaration goals of halving by the year 2015 the proportion of people under the poverty threshold (US$ 1 per person per day), without affordable drinking water, and malnourished (UN, 2000*a* and 2000*b*). It is estimated that about one billion human beings are now in this situation. The UN World Summit of Sustainable Development of Johannesburg 2002 endorsed these goals (UN, 2002). The World Conference on Freshwater (Bonn, 2001) also endorsed the some goals (German Federal Government, 2001).

An important first step when trying to manage a resource in the face of uncertainties, is to assess the seriousness and type of the assumed problem. Often the adverse effects of 'over-exploitation' may be misunderstood or exaggerated. This is often the case in relation to the interpretation of a long (e.g. 10 years) water level decline as an indication of a groundwater abstraction higher than the average renewable resources. As previously several times explained, such a decline may be due to: a) a dry spell, 2) a transient situation, or 3) scarce or incorrect data about streamflow, groundwater levels, climatic conditions, groundwater abstractions and natural recharge. The two last factors are usually difficult to determine in arid and semi-arid countries.

Frequently it will be necessary to ask for more funds in order to obtain better data in regard to quantity or quality of information. Nevertheless, the natural recharge in semi-arid regions will only be accurately known after a substantial number of years of good climatic and hydrological data have been collected. One should avoid transferring to the public a sense of accuracy that is really only illusory.

The use of numerical models to analyse groundwater flow and management might be useful. Such models should employed to perform sensitivity analysis of the plausible variations of the stochastic and deterministic parameters, including those related to social sciences, such as the possible future scenarios of the irrigated agriculture in the next decades.

Uncertainty about water resources is usually no higher when dealing with groundwater than when dealing with surface water or other water policy-related problems. A good example of such uncertainties is related to the general exaggeration that is associated with the prediction of future water demands. Gleick (1998) has analysed the progressive decline in estimates of future water demands, according to different authors. These have decreased from 7,000 km^3/year about 20 years ago, to less than 4,000 km^3/year in one of the latest predictions issued by United Nations (Shiklomanov, 1997). Even this last prediction is probably exaggerated. For example, it estimates a 20% growth in North America´s water demand. However, the US Geological Survey (Solley et al., 1998) has indicated a steady decline in total water uses in the United States of America over the past two decades, while during that same period population and standard of life have continued to grow. Wood (1999) considers that this decline may be due to the pressure of conservation groups that have demanded a more efficient use of water.

In summary, professional hydrogeologists should transfer the awareness of these uncertainties to decision-makers and the general public. This transfer must be done with prudence and honesty in order to avoid loss of credibility of the scientific community either in the short term (by giving the impression of lack of knowledge) or in the medium term (because of the failure of the predictions to be realised). The frequent and widely voiced 'gloom and doom' pessimistic predictions made by certain individuals and institutions about the depletion of natural resources or the population explosion have usually not been realised. For example, Dyson (1996) shows how the predictions made during the last three decades by the 'pessimistic neo-malthusians' have not been realised. On the other hand, quite recently, according to Pearce (1999), it seems that the focus about population explosion is misplaced and next century may have to worry about falling birth rates, not rising ones. Nevertheless, the fashion of 'preaching environmental scares' (*The Economist,* 1998) seems to be so deeply rooted in most media (Lomborg, 2001) that it will not be an easy task to bring objectivity and transparency in this field.

5.4 Abstraction of fossil groundwater

In most countries it is considered that groundwater abstraction should not exceed the renewable resources. In other countries – mainly in the most arid ones – it might be considered that groundwater mining is an acceptable policy, as long as available data assure that the groundwater development can be economically maintained for a long time, for example, more than fifty years and that the potential ecological costs and socio-economic benefits have been adequately evaluated (Llamas et al., 1992). Nevertheless, some authors consider this option as unsustainable development or a unethical attitude with respect to future generations. What Lazarus (1997) proposes for South Africa could also be the policy in many other countries: 'In essence, current thinking in the sector is that strategies need to be developed to ensure that groundwater resources are utilised within their capacity of renewal. It is recognised however that quantification of sustainable use levels requires extensive research'.

In contrast, few authors speak of the frequent unsustainability of most dams in arid regions. Bemblidia et al. (1996) consider that the 'useful life' of most dams in the North African Mediterranean countries use to be between 40 and 200 years because of their silting.

Lloyd (1997) states that the frequently encountered view that the water policy of arid zone countries should be developed in relation to renewable water resources is unrealistic and fallacious. Ethics of long-term water resources sustainability must be considered with ever improving technology. With careful management many arid countries will be able to utilise resources beyond the foreseeable future without major restructuring.

In Saudi Arabia, according to Dabbagh and Abderrahman (1997), the main aquifers (within the first 300 m of depth) contain huge amount of fresh fossil water – a minimum of 2,000 km^3 – that is 10,000 to 30,000 years old. It is considered that these fossil aquifers can supply useful water for a minimum period of 150 years. Current abstraction seems to be around 15–20 km^3/year. During a couple of decades the Saudi government has pumped several cubic kilometres per year of non-renewable groundwater to grow low cost crops (mainly cereals) which were also heavily subsidised. The official aim of such activity was to help to transform nomadic groups into farmers. Apparently such ‘overdraft’ has been a success. Now the amount of groundwater abstraction has been dramatically reduced and the farmer nomads have become high-tech farmers growing cash crops. Another example is the situation of the Nubian sandstone aquifer located below the Western desert of Egypt. According to Idriss and Nour (1990), the fresh groundwater reserves are higher than 200 km^3 and the maximum pumping projected is lower than 1 km^3/year. Probably similar situations do exist in Libya and Algeria. Other examples of mining groundwater can be found in Llamas and Custodio (2003).

It is not easy to achieve a virtuous middle way. As Collin and Margat (1993) state: ‘we move rapidly from one extreme to the other, and the tempting solutions put forward by zealots calling for *Malthusian underexploitation of groundwater* could prove just as damaging to the development of society as certain types of “excessive pumping”’.

5.5 Apportioning available groundwater

The distribution of the estimated renewable resources of available groundwater or fossil groundwater among the potential or actual users may be a source of conflict between persons, institutions or regions. There is no universal solution. Each case may be different according to the cultural, political and legal background of the region. Nevertheless, it may be useful to try to achieve some kind of universal agreement on the ethical principles that should rule water distribution and management. The initiative of the International Association of Hydrologists (IAH) to create a Working Group to analyse the problems in internationally shared aquifers may become a positive step forward.

5.6 Mitigating ecological impacts

The ecological cost of groundwater development should be compared with the socio-economic benefits produced (Barbier et al., 1997; Custodio, 2000*b*; National Research Council, 1997). The evaluation of the ecological impacts is highly dependent on the social perception of ecological values in the corresponding region. This social perception is changing rapidly in most countries. For example, the recent Framework Directive on Water of the European Union pays great attention to monitoring and conservation of aquatic ecosystems and especially to wetlands. In arid and semi-arid regions, wetlands or oases are usually rare and related to groundwater discharge zones. The development of groundwater for irrigation or other uses may often have a significant negative impact on the hydrological functioning of wetlands or oases (Fornés and Llamas, 1999). These impacts should be properly evaluated by decision-makers.

The social relevance of the conflict between nature conservation and groundwater development and its solution will be different from country to country and also changes with time. However, considering the relevance of this issue, the team of a research project on groundwater, funded by the Spanish Foundation Marcelino Botín, submitted through the Spanish Government, a proposal of Resolution to the Eighth Meeting (Valencia, Spain, 18–26 November, 2002) of the Conference of the Contracting Parties (COP8) to the Convention on Wetlands (Ramsar, Iran, 1971). This proposal was approved with some minor changes as Resolution No. 40 'Guidelines for rendering the use of groundwater compartible with the conservation of wetlands'. It is expected that this resolution will contribute to avoid or, at least, mitigate the current conflicts between groundwater development for utilitarian uses and groundwater as a support of ecosystems.

5.7 Socio-economic issues

Groundwater development has produced great economic and social benefits in many respects during the latter half of the last century. For example, the intensive use of groundwater for irrigation has contributed significantly to alleviate the problem of hunger or famine and of potable water supply to cities and rural areas. Although in some cases this groundwater development has induced some of the problems previously described (depletion of water levels, degradation of water quality, subsidence, deterioration of aquatic ecosystems and land subsidence), this author is not aware of any case of a large aquifer (e.g. with a surface greater than 1,000 km^2) in which intensive groundwater development has caused social disturbances (see Villiers, 2001). In contrast, serious social problems are well known because of the construction of dams (e.g. Narmada Valley in India), soil water logging and salinisation caused by excessive surface water irrigation and/or poor drainage (e.g. S. Joaquin Valley in California and Punjab plain in Pakistan) or surface water diversions (e.g. Aral Sea disaster).

Economic studies analysing in detail cases of intensely developed aquifers are still rare. In his economic analysis of over-exploitation, Young (1992) defined it as a 'failure to achieve maximum economic returns of the resource'. Nevertheless, the estimation of the real economic cost of the different factors is a difficult and controversial matter. Therefore the final solution of conflicts related to overexploitation will not be only dictated by economic rules; socio-political motivations may play the leading role.

Different scenarios can be presented in relation to the economy of over-used aquifers. Among them, two extreme theoretically situations are unrestricted (free) development against controlled development (Custodio and Gurgui, 1989; Foster, 1992).

Another issue to be considered is the almost universal policy of public 'perverse subsidies' for water supply, mainly for irrigation. According to Myers and Kent (1998) these subsidies are those which are noxious both for the economy and the environment. In most cases, the water users only pay a small fraction of the real cost of the water supplied. This is especially true in surface water for irrigation. Water policy all over the world has, during the past decades, focussed on the management of the supply and not to the management of the demand. This has induced an almost universal wasteful use of water.

In most groundwater developments the situation may be quite different. The owners of the water wells usually pay for the wells' construction, maintenance and operation. But they do not usually pay the external costs caused by the impacts of the groundwater abstraction.

The great socio-economic benefits produced by groundwater developments are rarely documented. According to Dhawan (1995), research in India indicates that yields in areas irrigated with groundwater are one third to one half higher than those in areas irrigated with surface resources. In a previous report it was estimated that as much as 70–80% of India's agricultural output may be groundwater dependent. More recently, the Indian Water Resources Society (1999) has published, among others, the following significant data:

- Groundwater is contributing at present 50 percent of irrigation surface, 80 percent of water for domestic use in rural areas, and 50 percent of water in urban and industrial areas;
- Groundwater abstraction structures had increased from 4 million in 1951 to nearly 17 million in 1997;
- In the same period groundwater irrigated area has increased from 6 to 26 million hectares;
- It is estimated that this rapid pace of development is likely to continue and will reach 64 million hectares in the year 2007.

By indirect calculation it may be estimated that in India the average amount of water applied in surface water irrigation is around 16,000 cubic metres per hectare per year; in groundwater irrigation this ratio is only 4,000 cubic metres per hectare per year. In other words, it seems that in India (as an average) the economic yield in irrigation and by cubic meter is from 5 or 10 times higher when groundwater is used than when irrigation is made with surface water.

Corominas (1999) and Hernández-Mora et al. (2001) published an assessment of irrigated agriculture in Andalusia (Spain). It is a well documented and transparent analysis. Some significant data from this study are:

a) Out of 800,000 hectares currently under irrigation, 75% use surface water and 25% groundwater;
b) Average water applied per ha is 4,000 cubic metres per year in groundwater irrigation and 7,500 cubic metres per year in surface water;
c) The average economic yield per hectare is more than three times greater in groundwater irrigated areas than in surface water irrigated areas;
d) The economic yield by cubic meter used is five times higher in groundwater than in surface water. And the jobs provided by volume unit of groundwater irrigation were more than three times greater that the similar jobs provided by surface water irrigation.

This analysis of Andalusia has been extended to other regions of Spain (Hernández-Mora and Llamas, 2001) with different climatic and social conditions and the results are similar.

It would be highly desirable that similar studies be done in many other arid and semi-arid countries. Also it would be appropriate to include this type of analysis in the framework suggested in the report of the World Commission on Dams (WCD, 2000) in order to study the economic and social feasibility of new dams. Nevertheless, it seem necessary to state that the ideas on the role of groundwater in water resources policy presented in the WCD's report follow the pervasive hydromyth of groundwater fragility.

A positive new situation worldwide is that in several international conferences and reports the practical importance of corruption and bribery in the water management has been emphasised. This was an issue that previously was very rarely mentioned in such conferences or in international reports. Perhaps the most important document on this topic is the book by OECD (2000) dealing with the *Convention on Combating Bribery of Foreign Public Officials in International Business Transactions*. This book was specifically quoted in the *Report of the World Commission on Dams* (WCD, 2000). During the Fresh Water Conference of Bonn (December, 2001) the debate on corruption was a frequent topic (German Federal Government, 2001). The present author has also mentioned the practical relevance of corruption as a frequent driving force in water policy in several papers (Llamas and Priscoli, 2000; Llamas, 2001*a* and 2001*b*). Postel (1999) presents an interesting view of the role of consulting firms, construction companies and politicians in promoting large hydraulic projects.

5.8 Stakeholder participation

There exists a general consensus that, in order to avoid conflicts and to move from confrontation to cooperation, water development projects require the participation of the social groups affected by the projects, the stakeholders. The participation should begin in the early stages of the project and should be, as much as possible, bottom-up and not top-down. The first question is to define who the stakeholders are; second is – how, when and where they should intervene in the decision making processes.

The Spanish experience, in trying to implement groundwater management in the public domain, indicates clearly that the active collaboration of Groundwater Users Associations is a key element (Aragonés et al., 1996; Hernández-Mora and Llamas, 2000, 2001). However, the process of implementation demands sometimes a change from the old to the new paradigms (López Gunn and Llamas, 2000).

In July 2001 the Spanish Parliament approved the Law of the National Water Plan. This Plan includes several provisions that if they are really enforced will change the current almost chaotic situation of groundwater development in Spain. Perhaps the most important article of this Law is the one which strictly demands the setting up of Groundwater User Associations in every intensively developed aquifer and a thorough hydrological assessment of every aquifer which may be supposed to receive a surface water transfer from other catchments. The National Water Plan Law also states that a intense and broad Water Education Programme has to be implemented.

Obviously, there is not a universal solution. For example, in some arid and semi-arid developing countries, when dealing with correction of ecological impacts of overexploitation, the influence of conservationists groups will probably be weak compared to the influence of farmers associations or urban water supply companies.

The necessary participation of the stakeholders demands that they are aware of the way the issue at hand will affect them directly or indirectly, and also a basic knowledge of the hydrogeological concepts involved in aquifer development. Probably in most countries there exist a good number of 'hydromyths' or obsolete paradigms about the origin, movement and potential for pollution of groundwater. In any stressed aquifer it is essential to organise different types of educational activities aimed at different groups: from school students and teachers to officials of Water Administrations.

6. Conclusions

6.1 Various factors have made possible the significant increase of groundwater development over the second half of the twentieth century, particularly in arid and semi-arid regions

- Technological: invention of the multistage pump, improvements in drilling methods and in the advance of the scientific knowledge on occurrence, movement and exploration of groundwater.
- Economic: the real cost of groundwater is usually low in relation to the direct economic benefits obtained from its use. The in situ or social value of groundwater is rarely estimated
- Institutional: groundwater development can easily be carried out by individual farmers, industries or small municipalities, without financial or technical assistance from Government Water Authorities. It does not require significant financial investments or public subsidies like surface water projects typically do.

6.2 The socio-economic benefits of groundwater development have been significant

Groundwater is an important source of potable drinking water. World wide, 50 per cent of municipal water supplies come from groundwater. In some regions the proportion is much higher. In general, groundwater is particularly important as a source of drinking water for rural and dispersed population.

Seventy percent of all groundwater withdrawals world-wide are used for irrigation, particularly in arid or semi-arid regions. Irrigation with groundwater has been crucial to increase food production at a greater rate than population growth.

Irrigated agriculture using groundwater is often much more efficient than irrigation using surface water. This is mainly because groundwater irrigation farmers typically assume all abstraction costs (financial, maintenance and operation) and produce high value crops because they have a greater security in their investment, as groundwater usually is not affected by droughts.

6.3 Groundwater administration

In most countries, groundwater development has not been adequately planned, financed, or controlled by existing Water Authorities. Historically, officers of these agencies have been trained to manage surface water systems and lack adequate hydrogeological training. The result use to be a bias toward surface water management and the frequent mismanagement of groundwater sources.

Groundwater management presents particular challenges given the great number of users on a single aquifer system. Co-ordination among the thousands of stakeholders that generally exist on an aquifer of medium or large size is scarce. Various reasons can account for this: 1) the coordination was not really necessary at the beginning of the development; 2) the usual tendency among farmers to individualism; and 3) the lack of willingness to promote such coordination by the Water Authorities.

6.4 Emerging problems in groundwater developments

In certain regions unplanned and uncontrolled development has caused problems, which can be classified in five groups:

1) *Excessive drawdown of the water level in wells,* which increases costs by requiring more pumping energy. Some shallow wells may become dry. Nevertheless, there is no documented case of a medium or large aquifer which has been physically emptied.
2) *Degradation of water quality* because of different factors such as point pollution coming from the surface or from saline groundwater intrusion from adjacent aquifers. Pollution coming from the surface is generally not caused by groundwater use but by inadequate land use planning. In most countries, groundwater pollution or degradation is the main threat to achieve a sustainable water resources management.
3) *Land subsidence or collapse* may be induced by groundwater abstraction but it is more related to the geotechnical properties of the terrain and to the location of the well fields than to the amount of groundwater withdrawal.
4) *Impact on surface water bodies and in the water cycle of the whole basin*
   In some rivers intensive groundwater pumping has caused significant changes in their hydrological regime with the consequent legal problems when the water of such river was previously allocated to other users. Nevertheless, the total renewable water resources in the basin can be significantly increased because of the augmentation of the natural recharge.
5) *Impact on wetlands and other aquatic ecosystems*
   Relatively small (e.g. 2 m) but long-term (e.g. 10 years) depletion of the water table often causes dramatic changes in wetlands, springs and riparian forests. These impacts have only bcome a cause of concern during the last three of four decades and almost exclusively in industrialised countries.

6.5 Five ethical issues in groundwater use

Five ethical issues are considered relevant in trying to achieve sustainable or reasonable groundwater use.

1) *Perverse subsidies to surface water projects*

The hidden or open subsidies that have traditionally been a part of large hydraulic works projects for surface water irrigation, are probably the main cause of the pervasive neglect of groundwater problems among water managers and decision-makers. Surface water for irrigation is usually given almost free to the farmers; and its wasteful use is the general rule.

Progressive application of the 'user pays' or 'full cost recovery' principle would probably make most of the large hydraulic projects economically unsound. As a result a more comprehensive look at water planning and management would be necessary and adequate attention to groundwater planning, control and management would probably follow.

2) *Public, private or common groundwater ownership*

Some authors consider that the legal declaration of groundwater as a public domain is a 'conditio sine qua non' to perform a sustainable or acceptable groundwater management. This assumption is far from evident. For many decades groundwater has been a public domain in a good number of countries. Nevertheless, sustainable groundwater management continues to be a significant challenge in many of those countries. Highly centralised management of groundwater resources is not the solution but to promote solidarity in the use of groundwater as a 'common good'. Groundwater management should be in the hands of the stakeholders of the aquifer, under the supervision of the corresponding Water Authority. The stakeholders' participation has to be promoted bottom-up and not top-down.

3) *Lack of hydrogeological knowledge and/or education*

Adequate information is a prerequisite to succeed in groundwater management. It has to be a continuous process in which technology and education improve solidarity and participation to the stakeholders and a more efficient use of the resource.

4) Transparency in groundwater related data

Good and reliable information is crucial to facilitate cooperation among aquifer stakeholders. All stakeholders should have easy access to good, reliable data on abstractions, water quality, aquifer water levels. Current information technology allows information to be made available to an unlimited number of users easily and economically. Nevertheless, in a good number of countries it will be necessary to change the traditional attitude of water agencies of not facilitating the easy access to water data to the general public.

5) The ethics of pumping non-renewable groundwater resources (groundwater mining)

Some arid regions have very small amounts of renewable water resources but huge amounts of fresh groundwater reserves, like for example the existing reserves under most of the Sahara desert. In such situations, groundwater mining may be a reasonable action if various conditions are met: 1) the amount of groundwater reserves can be estimated with acceptable accuracy; 2) the rate of reserves depletion can be guaranteed for a long period, e.g. from fifty to one hundred years; 3) the environmental impacts of such groundwater withdrawals are properly assessed and considered clearly less significant that the socio-economic benefits from groundwater mining; and 4) solutions are envisaged for the time when the groundwater is fully depleted.

7. ANNEX: Valencia Declaration

The organisers of the Symposium on Intensive Use of Groundwater, held in Valencia, Spain, on December 10–14, 2002, after consulting with the participants declare:

1. There is intensive development of groundwater when a significant proportion of the interannual renewable resource is withdrawn from the aquifers, which in turn noticeably modifies their hydrogeological functioning, causes significant ecological, political or socio-economic impacts, or important changes are produced to river-aquifer relationships.

2. The intensive use of groundwater, mostly but not exclusively developed in the last few decades in arid and semi-arid countries, has been a driving force to produce a large number of benefits to society. These include the affordable supply of drinking water and the development of irrigated land, which have contributed to health improvement and famine alleviation of hundreds of millions people in developing countries.

3. The large water storage capacity of aquifers allows facing interannual precipitation variability. Aquifers become an efficient solution to overcome or mitigate drought impacts.

4. The guarantee in supply, coupled with the low cost of extraction of groundwater facilitated by the scientific and technological advances, have led to a spectacular increase in groundwater use, especially for irrigation, in numerous arid and semiarid regions and in many coastal areas.

5. Groundwater being usually extracted close to the place of final utilisation of the water and users having to support directly the largest amount of the total cost, have generally led to a responsible and efficient use of this valuable resource. This has indirectly contributed to a better general use of water resources.

6. Due to the previous socio-economical factors, a large amount of the irrigation developments in which groundwater is involved have been carried out by the final users, with almost no planning or control by public or governmental agencies that often have not the necessary human and the economic means, and the know-how to cope with this new situation.

7. Numerous problems have arisen due to intensive use of groundwater and lack of public control. These include excessive lowering of water level in the aquifer, important aquifer water reserves depletion, land subsidence, affects on other users (e.g. drying up shallow wells, increased cost of abstraction), decrease in the flow to rivers and springs, potential mobilisation of contaminants, and impacts on aquatic ecosystems. Most of these problems can be avoided, corrected, or at least mitigated with an adequate planning and control.

8. The above problems are usually from a short to medium-term. Efforts to overcome them should not deviate the attention of the water policy decision-makers from the most serious medium to long-term problem: groundwater contamination. However, this problem is more linked to land use planning than to the intensive use of groundwater.

In order to maintain the benefits and to avoid the already mentioned negative aspects of groundwater exploitation, we present the following proposals.

First:

Public Administrations must play a key role in the planning and the integrated management of water resources. Among other things, this implies understanding and coordinating surface and groundwater and their relationship with land use planning. To achieve these goals, water administrations of most countries need to improve their hydrogeological capabilities much beyond what has been the case in recent years.

Second:

In parallel with the above large scale planning, immediate groundwater decision-making has to be performed at the local scale by institutions for groundwater management, establishing a framework for the effective users' participation in this management through the appropriate institutions. These institutions require the active and democratic participation of all the users or stakeholders, who should be provided with an adequate training and knowledge on the hydrogeological principles.

Third:

International organisations should recognise the great diversity in hydrogeological and socio–economic situations that make almost impossible to apply the same groundwater management tools everywhere.

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