Intensive development of groundwater: concept, facts and suggestions

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Abstract

Groundwater is increasingly used for water supply and irrigation. For several decades, aquifers have been intensively developed and notable changes have occurred to recharge, groundwater flow, discharge and water quality conditions. These changes have inevitably accompanied technological developments that have allowed individuals, small groups and whole communities to solve their water problems affordably and, in impoverished areas, to diminish poverty and improve health conditions. The measurable benefits from intensive groundwater development may also come with detrimental hydrogeological and environmental consequences, which are additional direct and indirect costs. To ensure a rational and sustainable use of the groundwater resource, there must be an understanding of the physical structure and characteristics of the aquifer system and extraction must be managed in the context of the basin-wide water

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resources. Effective groundwater management necessitates empowerment of the appropriate institution to conduct the management activities and participatory stakeholder involvement in the development and implementation of the groundwater management programme. This includes establishing environmental goals and a monitoring plan tailored to the history of local groundwater abstraction, projected water demands, issues of concern (e.g. water quality protection and preservation of water-dependent wetlands) and the available water supplies within the basin. A series of considerations on technical, economic and social aspects are proposed, in agreement with the far-reaching nature of the issue.

Keywords: Groundwater; Intensive exploitation; Rational use; Aquifer management

1. Introduction

The availability of mechanical means to drill wells, the introduction of the submersible turbine pump and the advent of relatively cheap energy sources has dramatically changed the way of development of groundwater in the last half century all over the world. What was a water resource available mostly from springs and as river base flow, now is affordable by individuals and small groups over extensive areas, thus changing the panorama of freshwater resources and the continental water cycle.

Intensive groundwater development and use occurs when a significant proportion of the inter-annual renewable resource is withdrawn from the aquifer, which in turn noticeably modifies the hydrogeological functioning of the aquifer system or may result in changes to surface water–groundwater relationships. The physical stress imposed on the aquifer system may also cause significant (positive or negative) ecological, socio-economic or political impacts. For the purposes of this paper the intensive groundwater development is considered to be an increased level of

groundwater abstraction that necessitates effective management, including monitoring, to avoid long-term negative consequences. In contrast, the term “overexploitation” and other similar terms are commonly used but may be technically unjustified or inappropriate (Custodio, 2002), particularly when used by the media and laypersons. Consequently, the authors discourage the indiscriminate use of the term “overexploitation”, and other similar terms, and suggest that increased use of and reliance on groundwater resources instead be referred to as intensive groundwater development. The condition of the groundwater system should be appropriately described through the ongoing collection and evaluation of case-specific data. Programmes to manage groundwater resources effectively must account for current and future water needs and also the ecological, economic and social factors.

Intensive groundwater use is becoming common in many areas of the world, especially in semi-arid and arid areas and on small islands and coastal zones. Many different and sometimes opposing views exist on the issues related to intensive groundwater development. The different opinions reflect the diversity of regions, including varied climatic, hydrogeological, economic, social, legal, political and even religious conditions. Additionally, the stakeholders of the region, that is, groundwater developers, water suppliers, farmers, conservationists, water managers, administrators and policy-makers, have wide-ranging positions about groundwater use as a result of their different interests and objectives.

This paper elaborates the main results of the Madrid Workshop on Intensive Groundwater Use (13–15 December 2001) and also of the International Symposium on Intensive Use of Groundwater (Valencia, Spain, 10–14 December 2002). It includes comments and suggestions for improving water management in regions where intensive groundwater use is occurring, with special regard to arid and semi-arid areas and

consideration of the developing regions. The peer-reviewed invited papers contributed to the 2001 Workshop have been published (Llamas & Custodio, 2003) and this book provides the background and supporting data for much of this paper. The results of the 2002 Symposium are published by the International Association of Hydrogeologists (IAH) in their Selected Paper Series (Sahuquillo *et al*., 2004).

2. Facts and consequences of groundwater development

Groundwater is an essential water resource. In most circumstances, aquifers are developed to provide a sufficient water supply of acceptable quality to meet regional development needs and beneficial uses. Aquifers are a reliable water resource for human water supply and for the irrigation of crops. Groundwater development can generally be achieved at reasonable cost using affordable technology. Groundwater is also a very important water resource for alleviating poverty, fighting malnutrition and famine and improving sanitary conditions (Burke & Moench, 2000; Moench, 2003). However, groundwater is not the solution for all water needs. It is a finite and, to some extent, a vulnerable resource that must be managed to ensure that groundwater management goals are achieved and the effects of groundwater development remain within acceptable limits.

Groundwater development provides benefits to society. At some time, observable changes to the aquifer system are likely to result depending upon the level of development and management approaches employed in that development. Water quality deterioration and other detrimental environmental effects result in additional costs and may ultimately result in reduced long-term beneficial uses. These indirect costs or externalities are generally not adequately accounted for when evaluating the economics of water management and should be considered in the appropriate time frame.

Experience shows that intensive, unmanaged groundwater development can result in negative consequences, which are mostly the result of aquifer properties. They can be anticipated and taken into account by calculation and modelling. Undesirable effects include prolonged groundwater level drawdown, groundwater storage depletion, interference with springs, pumping-induced stream-aquifer effects, subsidence and sometimes water quality deterioration. These are all effects or externalities to be considered (Sophocleous, 2003). Interference with groundwater-dependent wetlands is another important issue (Custodio, 2000).

Environmental issues can be important, particularly if the area becomes more economically and technologically developed. When intensive groundwater development occurs, groundwater should be viewed as one of the components of the entire eco-system. Management goals should be established such that the distribution, rate, magnitude and duration of abstraction are not detrimental to other components of the eco-system, within limits that are technically, socially and politically acceptable.

Some problems and circumstances (e.g. some fractured aquifers in arid lands or naturally occurring dissolved constituents such as arsenic or fluoride at elevated concentrations) may require special consideration or additional evaluation. Such issues can also cause serious concern about the quality or quantity of the water supply available to meet water demands in a local area.

The following comments should be considered:

- The consequences of intensive groundwater development can be reasonably evaluated and considered inside a groundwater management programme. This programme includes: establishing management goals; understanding the aquifer system within a basin-wide context; understanding potential management issues (e.g. water quality concerns, salt-water intrusion and land subsidence); developing and

implementing a comprehensive monitoring programme, including data collection (groundwater levels and quality, surface water flows and quality, pumpage, etc.) and data storage and analysis; understanding short and long-term water demands; and conducting relevant studies.

- Externalities, or potential environmental or economic consequences of intensive groundwater use, should be socially acceptable. With intensive groundwater development, there should be a long-term net benefit to society. Therefore, the management plan should include a component for mitigating externalities. Action to mitigate externalities may seem technically simple. However, implementing the action may become very complex depending on economic, social and political factors.
- Negative effects of groundwater development may not appear for a long time, years or decades. This is one of the most difficult aspects for non-specialists who measure cause–effect relationships in a short-term context or in a political time frame.
- The short or long-term occurrence of externalities and their consequent effects should be evaluated. The assumption of externalities should not deter consideration of groundwater as a reliable and effective source of water. However, evaluation of groundwater as a source of supply should be accompanied by an evaluation of beneficial and detrimental effects of a reasonable range of the possible water supply alternatives. Hence, although cautious and methodical groundwater development is prudent, this development should not be unduly constrained in favour of other water resources and management alternatives, which may seem more immediate but less reliable.
- Groundwater development is progressive and becomes more complex as it intensifies. Increased complexity demands more means and resources devoted to management, in proportion to the benefits derived from this development, particularly if

sustainability is the overall objective. It is important to distinguish between short-term and long-term benefits and possible consequences. A long-term consequence can result in an irreversible impact that may also cause other consequences and may ultimately reduce the benefits (e.g. extended groundwater storage depletion where hydrogeologic conditions result in inelastic land subsidence).

- Evaluation of benefits and consequences should include analyses of the local effects as well as those that are more regional. These analyses should also be considered in light of management goals and long-term benefits established for a larger community, usually the whole watershed.
- Intensive aquifer development can be optimised when considered within the framework of integrated water resources management plans that also include natural resources protection.

3. Economic considerations for intensive use of groundwater

The benefits and costs of groundwater development change with time. For example, what may be an acceptable practice or valuable asset today, may have been different in the past and may differ again in the future. In the early stages of economic and social development of an area, groundwater may play an essential role, particularly since it can allow smooth economic growth without the need for large previous investments. However, present circumstances may be not a good reference for the future. Therefore, cost–benefit analyses should be conducted within dynamic frameworks (Abderrahman, 2003; Custodio, 2002).

In most cases, groundwater development produces clear social benefits. However, management programmes are needed to sustain groundwater resources. Locally, there may be negative effects (e.g. energy costs may increase owing to the desired well distribution or depth of abstraction). However, the benefit of managed

abstraction to the broader community and particularly the long-term sustainability of the groundwater resource, may outweigh the negative effects on a local area. Accordingly, economic impacts to the local area should be adequately compensated.

When the negative effects of groundwater development are emphasised, planners and decision-makers may not recognise the value of groundwater as a reliable water resource. In other words, the benefits available from the use of groundwater may be overlooked, while other less suitable, more expensive and less environmentally friendly alternatives are accepted. Some of these other water supply alternatives can become a serious burden for developing regions since more public funds are needed, external debt is consequently increased and there may be an increased dependency on external technology.

A main cause of unsustainable groundwater management is mis-pricing. Water pricing is contentious and complex and requires careful consideration. In many regions, groundwater developers are applying the “full cost recovery” principle since they pay (without subsidies from public funds) the capital, operation and maintenance costs. Because of these costs, water use efficiency can be higher for these developments than for the often highly subsidised surface water developments in the same area. A study of agricultural water use in Andalucia, Southern Spain, demonstrated such an increase in water use efficiency (Hernández-Mora *et al*., 2001, 2003). However, in most cases, neither surface water nor groundwater users pay the indirect costs (externalities), which are supported by the society.

4. Groundwater sustainability and related social issues

The sustainable use of aquifers should be considered in a broad context of space, time, scientific status, available technology and social development. While groundwater development considerations have traditionally been associated with such terms as safe

or perennial yield or similar designations, the application of sustainable development concepts tends to result in a much broader and longer term perspective of community benefits and costs. The safe yield does not necessarily coincide with sustainability (Sophocleous, 1997; Bredehoeft, 1997; Custodio, 2002; Alley & Leake, 2004). Furthermore, sustainable development is more apt to be successful when groundwater development occurs within the context of integrated water resources management plans (Llamas, 1999; Narasimhan & Kretsinger, 2003). Essentially, concepts involving groundwater resources development are in a state of transition where the evolution from safe yield to sustainability is becoming better understood (Alley & Leake, 2004).

Catastrophic consequences (e.g. large-scale, irreversible environmental damage) from intensive aquifer development are forecasted in some papers and news media, but these predictions generally lack reliable data and comprehensive analyses. Some short- and intermediate-term or local negative consequences can occur from intensive groundwater development; however, these may not remain detrimental in the long term or in a larger area. In many cases, economic and social benefits caused by groundwater development have enabled interim coping with some negative effects and, subsequently, the improved socio-economic situation has also provided for mitigating actions, such as aquifer and environmental restoration. For example, in many regions farmers overcame the poverty threshold because of groundwater irrigation. Farmers have also changed operations from flood to drip irrigation and/or from low-value and high-water consumption crops to high-value and low-water consumption crops; this has allowed reduction of groundwater abstraction with fewer economic and social problems (Moench, 2003; Deb Roy & Shah, 2003).

In many regions of the world, intensive groundwater use has helped to alleviate poverty; it is not known to be a cause of poverty. Conversely, it can be said that the

most serious obstacle to sustainable groundwater development may be poverty and lack of democratic rules. Although some serious problems related to groundwater development (e.g. lack of water for the impoverished, general water quality impairment or local disputes over the water supply) have been reported for extremely poor areas, these are subdued by more serious problems of another nature, including widespread illiteracy, authoritarian rule, social inequality or corruption.

A major threat to sustainable aquifer use is groundwater quality deterioration. However, groundwater quality deterioration is only sometimes directly related to intensive groundwater use. Society's practices relating to the application of chemicals in one form or another (including as a product, as a waste and also in the atmosphere) have directly and also indirectly affected groundwater quality. The long-term environmental and economic consequences of many of society's historical practices are not recognised by the public or fully understood by the scientific community.

Intensive groundwater use in many areas is a relatively new phenomenon. Therefore, it is not surprising, especially in these areas, that there is prevalence of misinformation, pervasive "hydromyths" and even the conspicuous absence of critical technical evaluation. This is a typical stage occurring along the path that can ultimately achieve the goal of sustainable groundwater resources development. In order to achieve that goal, however, it is necessary to improve the application and transfer of science and technology, and accelerate awareness of sustainable management approaches and benefits.

5. Means of achieving sustainability: management and institutions

Intensive groundwater use requires adequate management as a necessary step to sustainability and long-term beneficial uses of groundwater. This means that:

- The institution in charge of water policy (or through the coordinated efforts of more than one institution) must develop a technically sound groundwater management plan.
- Human, economic and legal means are necessary for the lead institution to carry out its function.
- Stakeholders must be clearly defined.
- Approval, development and implementation of the management plan should include stakeholder participation. Implementation of management activities (e.g. monitoring, permits and plan updating) should include some direct responsibility of stakeholders, as defined in the plan.
- Adequate policies and laws and the means to apply and enforce them, must be adopted.
- The public must recognise and understand water resources and management issues; public education and outreach programmes should be implemented to achieve this objective.
- Comprehensive monitoring and data collection programmes must be implemented; reports summarising the management and monitoring programmes, including data evaluation and results, should be regularly updated and publicly available.
- Specific research and technological activities should be available to address local and regional issues. Addressing issues of sustainability will be important as technologies, understanding of the long-term effects of groundwater use and societal priorities evolve (Alley & Leake, 2004). Specifically, the scientist will have an expanded role in developing new and more comprehensive approaches for defining and

quantifying sustainability, including approaches that incorporate longer-term cost–benefit factors that have socio-economic and environmental significance.

- There should be a mechanism to deter vested interests, abusive privileges, hidden monopolies and illegal actions.

Management plans should encompass not only the technical aspects of sustainability but also economic, social, cultural and environmental concerns. This means that:

- Both quantity and quality aspects should be considered with adequate emphasis.
- Groundwater development and use should be managed to ensure long-term economic and social stability. This may include policies and programmes that provide incentives to promote community understanding of the value of water resources. This includes understanding the potential long-term consequences if short-term local benefits drive decisions that later jeopardise long-term public welfare.
- Management may include rules and controls for transfers of water, rights or land between competing users.
- Knowledge transfer and public education and outreach are major factors for facilitating community interest in and appreciation of groundwater management goals and programmes established to achieve sustainability.

Groundwater management should be carried out within a progressive or phased water plan. The water plan should be:

- Flexible in order to consider uncertainty and readily evolve with changing circumstances;
- Based on clear objectives that will be applied and regularly reviewed to achieve long-term sustained benefits through managed development and use of groundwater resources;

- Transitional to allow time to adapt to major changes;
- Democratically agreed on by water stakeholders;
- Appropriate to local circumstances, i.e. pertinent, the plan should incorporate management actions that consider surface water–groundwater interaction, preserve wetlands or protect groundwater quality in coastal areas (Custodio *et al*., 2001).
- A system of water rights based on incentives to increase groundwater use efficiency, foster investments and promote confidence in its use. The plan should not introduce speculative rights that hinder the goals of the water plan. This is a complex task that generally requires more than just experience with surface water rights. Specifically, occurrence and availability groundwater must be considered, including the relationship between surface water and groundwater resources with land property rights. In many cases, a system of groundwater rights exists prior to the development of a groundwater plan. As necessary to accommodate a changed system of rights, a clear and reasonable plan for the conversion is important and a transition period must be agreed upon by groundwater stakeholders.

Groundwater management should be applied at the “local” level, i.e. development and implementation of the management plan should be carried out at a lower administrative and territorial level rather than at a higher level, as it is the goal of the subsidiarity principle, widely developed in the European Union (Custodio, 1999).

6. Public participation in water management

Public participation in water management is a necessary part of the successful implementation of a groundwater management plan. When public participation is limited to certain interest groups or to certain stages of the management process, as often happens, this type of public participation is not truly effective.

In general, it is possible to distinguish three phases in the evolution of public participation programmes (López-Gunn and Hernández-Mora, 2001):

1 Early stage: public participation is understood, in a very limited framework, as a need to educate and inform the public about management decisions. This is not true participation, but rather a unilateral communication. Therefore, the public has essentially no effect on the decision-making process.

2 Development stage: communication between management agencies and the public is bi-directional. Public opinion can, to a certain extent, influence management decisions. While the process is more participatory, it is still the management agency that controls the decision-making process.

3 Mature stage: true participation occurs when management agencies move from informing the public and receiving their opinions to actually making decisions with the public. The effort required from management agencies is significant, as are the possible risks. It is at this stage that it becomes necessary to design conflict resolution mechanisms with the goal of reaching solutions that are acceptable to all. This process requires more effort and is time consuming, but implementation of the mutually agreed-upon plans will be significantly easier.

Stakeholder participation and involvement cannot be effectively improved from the top down; it must grow from the roots. This means that:

- Water stakeholders should be convinced that there is an individual (as well as community) benefit to participating in the management of a common groundwater resource.
- Information must be shared.
- Management should be transparent.

- Stakeholders must develop an appreciation of the value of groundwater sustainability.
- Local institutions, in cooperation with stakeholders, will need to evaluate the potential long-term environmental and economic costs to society caused by actions planned to meet near-term water demands.

7. Water regulations for management

Water regulations have been the primary tool used for surface water allocation and policy in most countries and often their paradigms have been extended to groundwater without considering the differences between surface and groundwater management. It is stressed that:

- Some legislation is needed to ensure a smooth transition from unregulated groundwater abstraction rights based on land ownership, or other forms of private appropriation of groundwater (as generally happens in the early stages of development) to regulated abstraction rights based on formal government permits, if it is determined that formal abstraction permission [IS PERMISSION BETTER THAN PERMITTING?] is necessary to accomplish the objectives of the groundwater management plan.
- Legislation is needed to provide tools to resolve conflicts over real or assumed groundwater water rights and rights on other water resources that are (or presumably could be) affected by groundwater development, in order not to hamper the effective implementation of groundwater management plans.

There are some limitations to a purely regulatory approach to groundwater management:

1 A rigid licensing system, where groundwater abstraction permits are granted for specific uses in specific locations, does not provide the necessary flexibility to address

situations of stress or social change adequately. A more flexible regulatory framework would allow for temporary or permanent transfers of water rights between users, so that efficiency and equity criteria could be met.

2 Effective regulatory approaches require the existence of adequate enforcement tools and institutions to ensure compliance.

3 A groundwater management system based primarily on regulatory means also requires the existence of a complete and continuously updated inventory of water licenses or rights and reliable and generally accepted information on available resources and existing rights. When adequate information is not available, participatory management tools are required to guarantee social acceptance and the effective implementation of management programmes.

4 Existing water legislation may no longer serve current social demands for water resources, particularly in areas where water supplies are scarce or intensive groundwater development already exists. A comprehensive water management plan is particularly necessary to address these conditions.

Dominantly punitive regulations, which are common in many situations, may not be enough. They may hinder rather than help achieve the goals of a groundwater management plan. For example, local regulations that constrain conjunctive water management activities may be counter to management objectives established for the groundwater basin.

8. Information and education to achieve sustainability

Groundwater-related information and basic concepts about water resources management must be presented in a form that is easily understood and accessible to the public. This can be accomplished through information dissemination with printed documents, posters, brochures, videos, seminars, conferences, interpretative centres and

any other means that help laypersons understand the importance of sustaining water resources. Information dissemination should also include the use of the Internet and also conventional educational methods.

Development of public education and outreach programmes should also incorporate:

- Assistance from experts on effective methods for communicating water information on the water management programme;
- Specialists should assist with the development of accurate technical content, but it is necessary to condense and convey the information so that laypersons understand the materials
- Adequate teaching materials should be prepared and made accessible to facilitate groundwater education at a wide breadth of levels (school age, teachers, public, water managers, politicians and others);
- Persons associated with the media must be provided with an understanding of the science and techniques, as well as other factors that play a significant role in groundwater resources issues.

To communicate groundwater information effectively:

- Groundwater hydrologists and hydrogeologists should make an effort to convey essential hydrogeological concepts and facts to the public in an easily understandable way.
- Information dissemination and educating the public are mainly the responsibility of water management agencies; these agencies must support the means and resources to accomplish these objectives.
- Non-governmental organisations have an important role in information dissemination.

Special attention should be given to educating managers, policy makers and stakeholders in the special characteristics of groundwater. This includes providing an understanding of the relatively slow response of groundwater systems to physical stresses. It is also important that these groups understand the even slower response that occurs when remedial measures are implemented to mitigate groundwater contamination and the generally high cost of these measures. Educational information on these and other topics is best communicated by supplementing a verbal description of the issue with illustrations that include a depiction of the time scale over which management or remedial activities are planned to occur and the anticipated effectiveness of those activities. Such educational outreach programmes also provide good opportunities to convey to stakeholders the necessity for long-term planning and the importance of monitoring, including the development of and the need to evaluate regularly the monitoring data gathered in order to respond in a timely manner to undesirable conditions imposed on the aquifer system.

For expedient and effective transfer of groundwater information, especially for information relating to intensively developed aquifers, the following actions are recommended:

- Concerted efforts should be undertaken to inform and educate stakeholders and the public about the need for a groundwater management plan.
- The media should receive (and be encouraged to convey) balanced, scientifically sound information on the benefits and problems associated with the intensive use of aquifers.
- Periodic reports should be prepared (for instance, every three years) to document advances in knowledge and applied technology and their application to groundwater management approaches (e.g. case studies) for the purpose of achieving sustainability.

- Information should be exchanged among a network of interested academic and other institutions to facilitate knowledge and technology transfer.

Intensively developed aquifers are characterised by a unique collection of physical, chemical, economic, social, legal and political circumstances. Accordingly, management programmes have generally been tailored to address specific objectives. However, the overall guiding principles of management programmes are broadly applicable. Developing a means of conveying general management approaches with the additionally employed regional or circumstance-specific approaches will be useful to others.

Specifically, a compilation of documented case histories, covering the most common intensive groundwater development scenarios, will help to increase knowledge about intensively developed aquifers and address existing information gaps. The compilation would describe the situations, management approaches employed, what was useful about those approaches or what might have been improved upon. In addition to conventional hydrogeological descriptions, the compilation should also include analyses of the ecological, economic, institutional, social, legal and political factors related to groundwater development. Further, an assessment of public awareness of groundwater-related issues could be used to evaluate to what extent public knowledge has facilitated the implementation of programmes that have sustainability as an overarching objective. Such an assessment could also identify to what extent educational outreach programmes are needed to provide an improved understanding of the long-term public benefit that results from groundwater management and monitoring programmes.

The above case history can be complemented by a worldwide inventory of intensively used/exploited aquifers that includes a summary of socio-economic impact,

an economic analysis and an evaluation of sustainability. This comprehensive task may be difficult to achieve, but perhaps it can be initiated by a search of existing literature. If the information is drawn from currently available published documents, it is important that, among other considerations, there is a clear understanding of the sources of information (including technical data) and whether the information is up-to-date. Additionally, discussion of groundwater development and management examples should convey technical, social and other factors in a balanced light. The task of performing the suggested compilation is something best conducted and/or organised by an international organisation.

9. Conclusions

Groundwater is a finite but renewable resource that is intrinsically linked to surface water and other natural resources. It is generally a more reliable freshwater resource than surface water that can be readily developed to meet human needs and agricultural demands. Intensive use of groundwater resources has solved and will continue to solve water problems. However, with intensive development, there is an increased likelihood of physical, chemical, ecological, economic and/or social impacts. Groundwater management is necessary to sustain the resource, especially when intensive development occurs. Stakeholder participation is an important aspect of groundwater management plan development and implementation, as stakeholders need to appreciate the individual as well as community benefits of groundwater management. Institutions empowered to develop and conduct groundwater management programmes need support from adequate legislation and social and economic means. Scientists also have an important role in developing new and comprehensive approaches for defining and quantifying sustainability. Specifically, it will be important for future methods, developed to forecast whether long-term groundwater management goals will be

achieved, to consider not only technical analyses that assess integrated water resources relationships but also to optimise long-term, region-specific sustainability factors such as cost–benefit factors that have socio-economic and environmental significance. Ultimately, information dissemination to all stakeholders, including public education and outreach will be key to the implementation of successful management programmes and achieving groundwater sustainability.

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References

Abderrahman, W.A. (2003). Should intensive use of non-renewable water resources always be rejected? In *Intensive Use of Groundwater* (M.R. Llamas & E. Custodio, eds.). Balkema Publishers: Lisse, 191–203.

Alley, W.M. & Leake, S.A. (2004). The journey from safe yield to sustainability. *Ground Water*, *42* (1), 12–16.

Bredehoeft, J.D. (1997). Safe yield and the water budget myth. *Ground Water*, *35* (6), 929.

Burke, J.J. & Moench, M.H. (2000). *Groundwater and Society: Resources, Tensions and Opportunities.* ST/ESA/265, United Nations: New York, 1–170.

Custodio, E. (1999). The European Geological Surveys and EuroGeoSurveys: roles and tasks in a supranational structure. *Episodes*, *22* (2), 107–112.

Custodio, E. (2000). Groundwater-dependent wetlands. *Acta Geologica Hungarica*, *43* (2), 173–202.

Custodio, E. (2002). Overexploitation, what does it mean? *Hydrogeology Journal, 10* (2), 254–277.

Custodio. E.; Edmunds, W.M. & Travi, Y (2001). Management of coastal palaeowaters. In *Palaeowaters in Coastal Europe: Evolution of Groundwater since the Late Pleistocene.* (W.M. Edmunds & C.J. Milne, eds.). Geological Society of London, Special Publication 189, London, 313–327.

Deb Roy, A. & Shah, T. (2003). Socio-ecology of groundwater irrigation in India. In *Intensive Use of Groundwater*. (M.R. Llamas & E. Custodio, eds.). Balkema Publishers: Lisse, 307–335.

Hernádez-Mora, N., Llamas, M.R. & Martínez Cortina, L. (2001). Misconceptions in aquifer overexploitation: implications in water-policy in Southern Europe. In *Agricultural Use of Groundwater*. (C. Dosi, ed.). Kluwer Academic: Dordrecht, 107–125.

Hernández-Mora, N., Martínez Cortina, L. & Fornés, J.M (2003). Intensive groundwater use in Spain. In *Intensive Use of Groundwater*. (M.R. Llamas & E. Custodio, eds.). Balkema Publishers: Lisse, 387–414.

Kretsinger, V. (2002). Sustaining groundwater resources: the critical vision. *Groundwater Resources Association of California Newsletter "HydroVisions"*, *11* (4).

Llamas, M.R. (1999). *La inserción de las aguas subterráneas en los sistemas de gestión integrada (Introducing Groundwater into Integrated Water Management Systems).* Bol. Geológico y Minero: Madrid, *110* (4), 5–25.

Llamas, M.R. & Custodio, E. (eds.) (2003). *Intensive Use of Groundwater: Challenges and Opportunities.* Balkema Publishers, Lisse, 1–471.

López-Gunn, E. & Hernández-Mora, N. (2001). La gestión colectiva de las aguas subterráneas en La Mancha: análisis comparativo (Groundwater collective management in La Mancha: comparative analysis). *En La Economía del Agua Subterránea y su Gestión Colectiva*. (N. Hernández-Mora & M.R. Llamas, eds.). Edic. Mundi-Prensa: Madrid, 405–474.

Moench, M. (2003). Groundwater and poverty: exploring the connection. In *Intensive Use of Groundwater*. (M.R. Llamas & E. Custodio, eds.). Balkema Publishers: Lisse, 441–455.

Narasimhan, T.N. & Kretsinger, V. (2003). *Developing, Managing and Sustaining California's Groundwater Resources*. A White Paper of the Groundwater Resources Association of California (condensed version in *Groundwater Resources Association Newsletter "HydroVisions"*, *12*, 1).

Sahuquillo, A., Martínez-Cortina, L., Sánchez-Vila, X. & Capilla, J. (eds.) (2004). Selected Papers on intensive groundwater use. *Selected Papers of the International Association of Hydrogeologists*. Balkema: Lisse (in press).

Sophocleous, M. (1997). Managing water resources systems: why "safe yield" is not sustainable. *Ground Water*, *35* (4), 561.

Sophocleous, M. (2003). Environmental implications of intensive groundwater use with special regard to streams and wetlands. In *Intensive Use of Groundwater*. (M.R. Llamas & E. Custodio, eds.). Balkema Publishers: Lisse, 93–112.

Vitae

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