Integrating Science into Groundwater Management Decisions

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Abstract

Groundwater development has seen an unprecedented growth in many parts of the world during the last couple of decades. Especially in populous Asian countries like India and China, exponential growth rates, in terms of number of wells and estimated accumulated pumping volumes, give an impression of an explosion rather than a steady and controlled evolution.

This paper examines the general distinct features of groundwater that poses both the merits for its rapid utilization potential as well as the obstacles for its sustainable management. It looks at the key challenges to groundwater management that reflect and respond to the various stages of development and some misconceptions that tend to hamper an effective approach to groundwater management. The concepts of 'safe' or 'sustainable' yield and 'groundwater overexploitation' are particularly interesting as they have been inscribed in the contemporary groundwater vocabulary, and while they may be valuable in environmental debates they bear no scientific definition, let alone guidelines for thresholds on sustainable groundwater exploitation. The paper investigates the roles of groundwater scientists and managers in an attempt to identify the means to unlocking the gap that is often perceived between these two parts in the collective development of practical management solutions to groundwater degradation. Ways forward are suggested, with particular focus on the linkage between assessment of groundwater potential and decision-making on groundwater development in India.

Introduction

Traditionally, the focus of water managers has been on surface water, except maybe in cases of extreme aridity and/or non-mountainous areas. This can be explained by the fact that surface water is immediately accessible and tangible whereas groundwater is concealed and not directly within reach. On the other hand, distinctive features of groundwater, like its prevalence and reliability in supply and quality (Table1), have over the last quarter century proven to be major drivers for its utilization in widespread small scale irrigation farming in developing countries (Shah, 2004). However, the same inherent characteristics of groundwater, its invisibility and prevalence, also give rise to major challenges faced by groundwater managers. Trying to cope with an excessive number of individual users over vast areas and book keeping their use is almost impossible, even in a developed country setting. Add to this the distinct general features of groundwater of slow flow rates, long residence times and long response times to external impacts, like excessive pumping, chemical spills or non-point sources of pollution, it becomes clear that groundwater management is not a straightforward task.

Table 1. Comparative features of groundwater and surface water resources

Feature	Groundwater resources and aquifers	Surface water resources and reservoirs
Hydrological characteristics		
Storage volume	Very large	Small to moderate
Resource areas	Relatively unrestricted	Restricted to water bodies
Flow velocities	Very low	Moderate to high
Residence times	Decades/centuries	Weeks/months
Drought propensity	Generally low	Generally high
Evaporation losses	Low and localized	High for reservoirs
Resource evaluation	High cost and significant uncertainty	Lower cost and often less uncertainty
Abstraction impacts	Delayed and dispersed	Immediate
Natural quality	Generally (but not always) high	Variable
Pollution vulnerability	Variable natural protection	Largely unprotected
Pollution persistence	Often extreme	Mainly transitory
Socio-economic factors		
Public perception	Mythical, unaware	Aesthetic, aware
Development cost	Generally modest	Often high
Development risk	Less than often perceived	More than often assumed
Style of development	Mixed public and private	Largely public

Source: Tuinhof et al., 2003.

As a general rule, groundwater development in many Asian countries has been left to the private initiative. When groundwater exploitation on a wider scale took off in India in the 1970s it was driven primarily by private, small-scale farmers who saw the possibilities in increased income from farming supported by groundwater irrigation, which was made possible and lucrative by government funds, grants and subsidies on drilling, pumping equipment and energy required to start and sustain the business. Similar developments have been seen in China, Pakistan and other Asian countries, though local differences occur and the case of India is extreme and therefore worth focusing on (Shah et al., 2003).

When groundwater exploitation is approaching levels that appear to have excess negative impacts to society, which is the case in some areas of India, the need for response becomes evident. Also, it becomes clear that a relevant, necessary and adequate response cannot solely be based on, and expected from, the same private initiative that drove it. A reactive, and preferably a pro-active, role from the overall authorities responsible for water development and use is required.

Key Challenges for Groundwater Resources Management

Groundwater resources management deals with balancing the increasing demands of water and land users with the long-term maintenance of a complex natural resource (in terms of quantity, quality and surface water interactions).

Calls for groundwater management do not usually arise until a decline in well yields and/or quality affects one of the stakeholder groups. If further uncontrolled pumping or pollution is allowed, a 'vicious circle' may develop (Fig. 1) and overall damage to the resource may result. All of these effects can be short-term and reversible or long-term and quasi-irreversible (such as aquifer saline intrusion and land subsidence).

To transform this 'vicious circle' into a 'virtuous circle' it is essential to recognize that managing groundwater is as much about managing people (water and land users) as it is about managing water (aquifer resources). Or, in other words, that the socio-economic dimension (demand-side management) is as important as the hydro-geological dimension (supply-side management) and integration of both is required.

Key requirements for groundwater management are the recognition and understanding of:

- The characteristics of aquifer systems and their specific susceptibilities to negative impacts under abstraction and contamination stress.
- The interactions between groundwater and surface water, such as abstraction effects on river base flow and wetlands, and groundwater recharge effects (due to surface-water modifications).
- Operational monitoring as a vital tool to develop the information and understanding needed for effective resource management.

Furthermore, it is essential to bear in mind that:

- Social development goals and policies greatly influence water use, especially where agricultural irrigation and food production are concerned, thus management can only be fully effective if cross-sectoral coordination occurs
- Regulatory interventions (such as water rights or permits) and economic tools (such as abstraction tariffs and tradable water rights) become more effective if they are not only encoded in water law but implemented with a high level of user participation.
- Regulatory provisions should not go beyond government capacity to enforce and user capacity to comply.
- The development of an effective and sustainable approach to management will always require involvement of the main stakeholders.
- Proper groundwater management requires awareness and capacity at various levels of society, from local level users to central decision makers.
- Proper groundwater management requires the integration of science into management decisions.

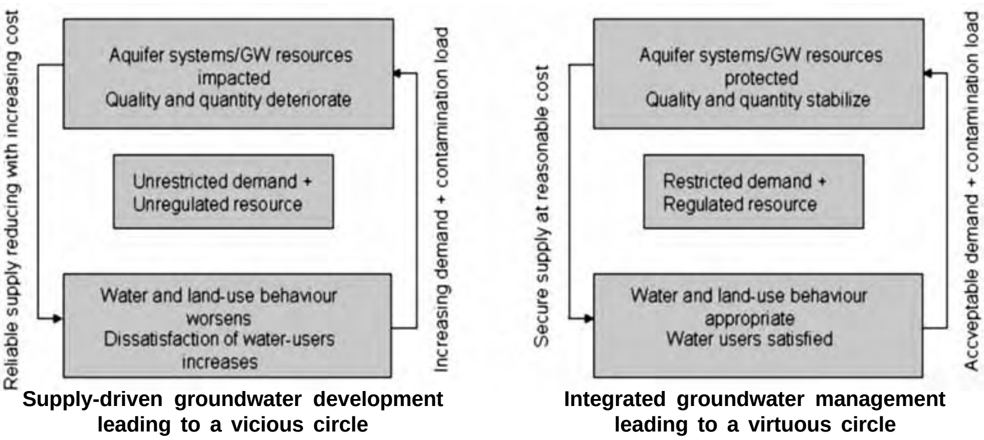


Figure 1. Supply-driven versus integrated groundwater management (Tuinhof et al., 2003)

- Management of groundwater requires integrated approaches that are balancing the needs of the poor and the environment with economic development goals.
- Hydrogeologic and socio-economic conditions tend to be location-specific and thus no simple blueprint for integrated groundwater management can be provided.
- International/inter-state cooperation on cross-boundary groundwater problems is essential for long-term sustainable groundwater management.
- International cooperation and knowledge sharing should play a significant role in facilitating development of sustainable groundwater management.

Stages of Groundwater Development and Management

Not-withstanding the hydrogeologic and socio-economic differences encountered in various countries, a typical evolution of groundwater development (Fig. 2) can be portrayed to illustrate the various levels of development and the phases that follow from a situation where the exploitation of groundwater is minimal to a situation where excessive abstraction and contamination takes place, through to a more balanced and controlled situation based on sound management.

The various stages of development require different types of responses, and by choosing the right level and type of response, corresponding to the actual level of development, the unstable situation, depicted as situation 3 in Fig.2, can be avoided (Tuinhof et al., 2003). Figure 2 illustrates the increasing need for integrated management as groundwater exploitation increases. The development is not only associated with increasing costs as more supply augmentation and management measures are required, but also in increasing complexity as the solutions and assessments become more and more integrated, the potential impacts are more wide-reaching, and the balances in society more precarious. This is exactly why integrated groundwater management calls for the collaboration between the managers and the researchers.

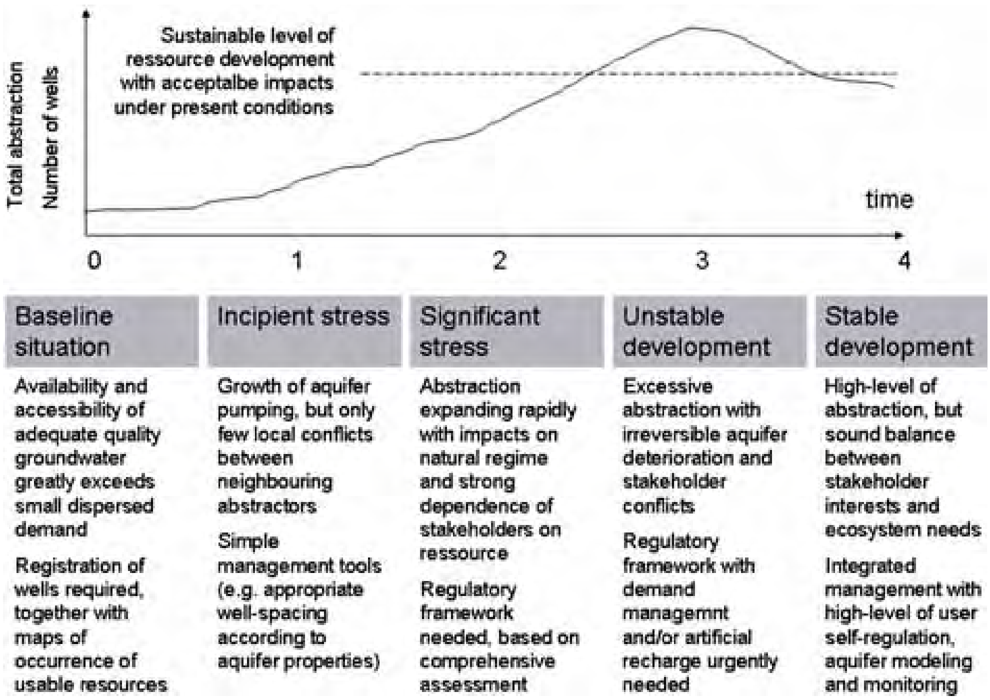


Figure 2. Stages of groundwater resource development in a major aquifer and their corresponding management needs

Some General Misconceptions of Groundwater

'Safe' or 'Sustainable' Yield

Estimation of contemporary aquifer recharge is fundamental in sustainable groundwater resources development. Current long-term average rate of aquifer recharge will indicate the volume of water entering the system and being available for storage and later discharge and use.

When evaluating effects of groundwater abstraction on the resource availability and estimating an acceptable level of abstraction, the fundamental tool is the water balance stating that water that enters groundwater will either be discharged (through a stream, lake or spring) or may be kept in (temporary) storage. Any effective reduction in recharge to the groundwater (from less rainfall or groundwater abstraction) will mean a reduction in discharge and/or storage (Fig. 3).

The average recharge is often, erroneously, considered the 'safe' or 'sustainable' yield, assuming that this is the amount of water that can be pumped from the groundwater without long-term consequences. However, this notion disregards the need to maintain aquifer discharge or water level in downstream freshwater systems or aquatic/terrestrial ecosystems or to suppress coastal salt-water intrusion.

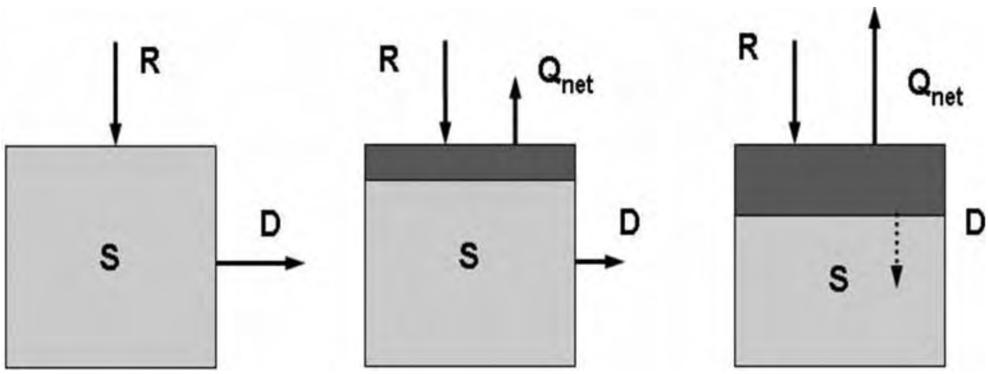


Figure 3. Conceptual effects of abstraction on the groundwater resource balance (from Foster et al., 2003)

'Groundwater Overexploitation' and Continuously Declining Groundwater Levels

The term 'groundwater overexploitation' has become everyday vocabulary in water management as well as the media. However, it fails to bear a rigorous scientific definition. Some regard an aquifer as being overexploited when its groundwater levels show evidence of 'continuous long-term' decline. But this is also a rather ambiguous measure or criteria for identifying problems of excessive pumping. When are the declines statistically significant, how many years to average over, are they due to erratic or systematic changes in rainfall and will they continue?

The fact is that all groundwater abstraction will lead to drawdown, but whether the declines will persist (ref. c in Fig. 3) can often not be assessed over a shorter period because the flow processes in groundwater are slow and it may take years for a new equilibrium to be established (ref. b in Fig. 3). Not-withstanding this, falling groundwater levels in areas where effects are obviously impacting local stakeholders negatively, are probably one of the best indicators of the need to intensify assessment of impacts and devise appropriate guiding limits on abstraction.

Another measure of 'overexploitation' is taken to be that abstraction is greater than the long-term average rate of groundwater recharge. However, due to the uncertainty of groundwater recharge mechanisms and methodological difficulties in estimating it this is usually a rather unworkable approach.

In practice, when speaking of aquifer overexploitation we are invariably much more concerned about the consequences of intensive groundwater abstraction than in its absolute level or recharge rate. Thus the most appropriate definition is probably an economic one: that the **'overall cost of the negative impacts of groundwater exploitation exceeds the net benefits of groundwater use',** but impacts can be equally difficult to assess and to cost.

However, the term groundwater overexploitation should not be dismissed altogether, despite lack of precision because it conveys a clear message to the public and the politicians and may bring about the dialogue necessary to define the acceptable negative costs of society associated with intensive use of groundwater.

Rejected Recharge

Another mis-conception refers to the notion that groundwater recharge will increase if the aquifers are drawn down sufficiently before the onset of the rainy season, in order to allow for higher interception in underground reservoirs during the rainy period for later beneficial use in the dry season. The rejected recharge refers to the perceived loss of water storage due to overtopping of the reservoir in the wet season, a concept that is similar to the one applied to surface water reservoirs.

This is an intriguing concept, but several points make the comparison inappropriate. Firstly, if groundwater tables are lowered excessively during the dry season, it may have major downstream impacts on other water users and/or surface water bodies dependent on the discharge from groundwater or the maintenance of a certain water level (ref. b in Fig. 3). Effectively what is obtained is an abstraction of water that was previously available for downstream uses.

Secondly, groundwater recharged during the wet season will not be retained in enclosed reservoirs with a maximum storage capacity like behind surface water dams. Though a reliable resource will be available for abstraction through the dry season, the total absolute amount of available groundwater from recharge will not be increased in the case where groundwater levels have been suppressed to leave room for incoming monsoon recharge.

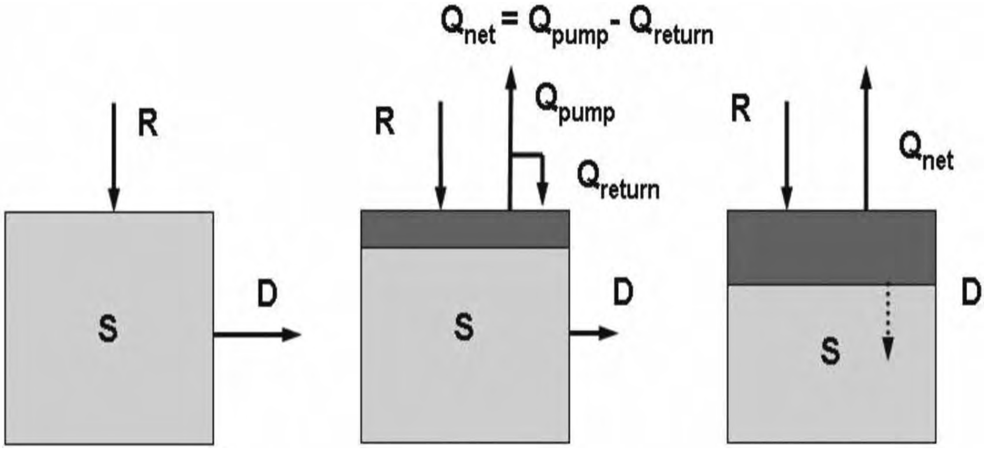
The only situation where increased pumping in the dry season could be justified is if the water taken out is not consumed (i.e. lost by evapo-transpiration) and it can be brought back into the system without harming the environment and hence allowing it to be reused further downstream.

The last argument for not drawing down the aquifers prior to the wet season is that the system becomes much more vulnerable to drought. If the monsoon rainfall fails the groundwater 'reservoir' will not be replenished to the same extent as without prior drawdown leaving much less buffer in the system to counteract a drought situation.

Pumping is Equal to Loss in Recharge

Often, groundwater abstraction rates and volumes are equated with the loss in groundwater recharge (Q_{pump} equal to decrease in S in Fig.4) and hence held directly responsible for groundwater depletion. However, in groundwater irrigated areas, a significant fraction of irrigation water drawn from groundwater is not utilized for plant growth and returns to the groundwater as recharge, often called return flow. Hence, it is only the fraction of applied water that is actually depleted/consumed through evapo-transpiration that is contributing to the decrease in net recharge and potentially contributing to groundwater level declines (if this amount exceeds the net incoming rainfall and other irrigation sources). A failure to realize this may misinterpret a decrease in pumping as a decrease in groundwater depletion when, in reality, declines persist because the overall evapo-transpiration increases and the return flows are reduced due to water saving technologies.

The critical parameter to focus on is the actual evapo-transpiration (Q_{net}) in comparison to the incoming water, in terms of rain water and imported surface water. If this balance comes out negative depletion is occurring (S in Fig. 4 decreases).



Natural conditions
Averaged over long-term R=D and S is constant

Stable groundwater punping
Qnet is equivalent to reduction in D and S

Unsustainable condition
Qnet is greater than R, D reduces to O and S decreases continuosly

Figure 4. Conceptual effects of abstraction on the groundwater resource balance, considering return flows (from Foster et al., 2003)

Water Savings Free Water for the Environment

An often perceived notion is that with the introduction of water saving technologies (e.g. drip or sprinkler irrigation, green houses), water will be freed for the environment, i.e. if less water is abstracted from groundwater for irrigation, more water will be left in the system to benefit other users, including ecosystems and the environment in general. This perception is directly linked to the previous stated misconception. Applying the same overall rule that only savings in actual evapo-transpiration will improve the overall water balance, drip and sprinkler irrigation will only improve the situation if the overall loss to evapo-transpiration is decreased. This can be the case, without harming crop yields, for these technologies, if the fraction of evapo-transpiration that is attributable to non-plant related evaporation (i.e. direct evaporation from the soil surface) is decreased. So far so good. However, what is often overlooked is the fact that the water savings may encourage the farmers to increase the cropped area with an ensuing increase in evapo-transpiration, which may offset the otherwise obtained water savings.

Secondly, water savings through improved irrigation and cropping technologies may, due to the investment required, lead to the switch to more profitable higher-valued crops (e.g. vegetables, flowers), which require (higher) inputs of agrochemicals (fertilizers and pesticides). In this case, the groundwater balance may be improved quantitatively. However, if the water quality is negatively impacted, the availability of groundwater, with a minimum good quality, is still decreased.

'Excess Runoff' is Available for Artificial Recharge

With groundwater coming under increasing pressure, measures to augment the resource, such as rainwater harvesting and artificial recharge, are often considered the way forward. It is a well-received proposition as it increases existing available and attainable resources without interfering with the demand and use, which has more controversial implications.

The idea is to harness and make utilizable the part of the totally available water resources that is in excess; that is: the fraction that today is not captured and is discharged as 'excess runoff', in rivers. Some overall conditions may, however, make this concept less straightforward, feasible and efficient in addressing the groundwater, and in general the overall water shortage problems.

Firstly, problems of groundwater depletion are directly correlated with the overall water availability in a particular area. Intensive groundwater utilization and concomitant problems are generally much more prevalent in arid and semi-arid climates where the water availability naturally is low. This indicates that only in those areas where rainfall is highly seasonal and leading to 'excess runoff' during part of the year, will there be a potential for harvesting additional groundwater during the rainy season. If river basins are already closing, i.e. rivers discharging only minimal amounts at their outlets, which are not uncommon phenomena today, even for larger rivers (e.g. the Yellow River in China) this overall excess may not be available, at least not on a reliable basis.

Secondly, when evaluating the potential for artificial recharge it is essential to assess the overall impacts in a basin context. Harvesting water for groundwater use in upstream reaches, though on a smaller scale, may appear feasible because of 'excess runoff' in these regions. However, downstream effects, of a multitude of such schemes, in terms of decreased water availability, and quality degradation, such as salinity intrusion, will have to be considered.

As water scarcity and disparity between water-rich and less water-rich regions become more apparent, an inevitable solution seems to be the transfer of water from water-abundant to water-deficient areas. Such solutions are not new, and will most likely occur on a wider scale (both in terms of prevalence, and in size of schemes and distances over which water is transferred). As the potential, and limitations, of rain water harvesting and artificial recharge are explored and realized the further potential for water transfer will most likely be developed.

The Role of Groundwater Scientists and Managers

As groundwater resources come under increasing pressure, allocation between various users, including the environment, becomes increasingly complex and the need for sound approaches based on science becomes progressively more evident (Acreman, 2005). As stated earlier, groundwater resources with its complex and distinct features call for proper technical and scientific knowledge. Adding to this the complexity of the human and socio-economic factors, and the need for integration at many levels (with surface water considerations, sectoral interests, etc.), the challenges are numerous.

Traditionally, and especially in the developing part of the world, a gap is perceived between groundwater managers and scientists. This is explained by differences in traditional roles, driving forces, perspectives and probably also reciprocal misconceptions (Table 3).

Table 3. Traditional differences between scientists and managers

	Scientist	Manager
Perspective	Long-term results	Short-term decisions
Driving force, outer	Peers, theory, funding, data	Public, media, donors legislation
Driving force, inner	Curiosity, explanation	Political influence
Evaluation criteria	Scientific publications	Political support
Working focus	Detail, quantity, facts, comprehensiveness	Integration, quality, opinion, simplicity

While a scientist has the long-term perspective and is driven by his own curiosity and subjected to limitations of data and funding availability and looks at facts and details, the manager is concerned with short-term decisions, the reconciliation of views and the general political scene surrounding management at various levels.

Clearly, there is a need to close the gap, to soften up the traditional roles and to improve the appreciation of the significance of mutual understanding of roles and of communication.

The overall goal is to form a partnership that ensures that decisions are made based on the best available multidisciplinary (technical as well as socio-economic) scientific knowledge. Each partner must be prepared to adopt non-traditional practices to enhance the collaboration. Scientists need to:

- Give direct answers to specific questions.
- Give their opinion concerning questions where no firm scientific facts are available, based on their accumulated knowledge.
- Train themselves in associated disciplines that enable them to contribute to more integrated analysis.
- Present results in a form that can be understood by non-specialists.

Water managers, on the other hand, need to:

- Formulate the questions in a way that lends itself to scientific investigation.
- Accept that some questions cannot be answered by current scientific knowledge and are thus a matter of political judgment.
- Accept that uncertainty exists with respect to the answers obtained through science and that the risks associated with the uncertainty should be reflected in the resources put into reducing the uncertainities.

Assessment of Groundwater Potential and Decision Making on Groundwater Development in India

In the last section of this paper, the specific case of groundwater management in India is explored briefly to exemplify some of the requirements needed and the ways forward. It focuses on the technical assessment of available groundwater resources and its application for political decisions on further groundwater development.

Groundwater recharge and development potential assessment in India is based on the two methods (G.E.C., 1984, 1997):

- Water Level Fluctuation Method
- Rainfall Infiltration Method based on ad-hoc-norms

Basically, the current level, or stage, of groundwater development is determined based on a comparison of the estimated actual recharge with the current groundwater draft. If groundwater draft is higher than the utilizable resource (taken as 85% of the actual recharge), development level is considered higher than 100% and a restriction on further groundwater development is implemented.

Though the method is applied rather systematically and broadly over most parts of India (see Fig. 5), some critical issues need further consideration in order to enhance its accuracy and efficiency:

- The method is based on relatively sparse, uncertain data, crude generalizations, simple empirical classifications and norms, making the method at most relative and indicative, rather than absolute and fully quantitative. The method has been improved by including assessment of temporal trends in groundwater levels.
- Groundwater abstraction rates are still used as the parameter indicating groundwater use though this is associated with significant flaws (see Section 'Pumping is equal to loss in recharge').
- Updating of assessment is infrequent and delayed, making an updated, real-time assessment impossible[1]. This is critical when development of groundwater is occurring at present rates.
- The assessment is not implemented in a management and consultation process, linking scientists, managers and groundwater users, in order to enhance the chance of adoption of control measures against excessive abstraction.

Suggestions for improving the accuracy and management application of the method include:

- Testing the method against rigorous scientific methods in a well-defined pilot area, where additional and more accurate field data can be collected. It is suggested to incorporate remote sensing methods to improve the spatial determination of actual evapo-transpiration and hence the water depletion and the upper limit to groundwater depletion. Biggs (2005) have used this approach in the Krishna basin for overall water balance assessments, and it should be modified for use in focused groundwater assessment studies.
- Extending the existing groundwater monitoring network, especially for monitoring groundwater levels, and intensifying monitoring in areas of suspected groundwater depletion.

[1] Central Groundwater Board has informed that a revised assessment will be published soon (Rana Chatterjee, 2005).

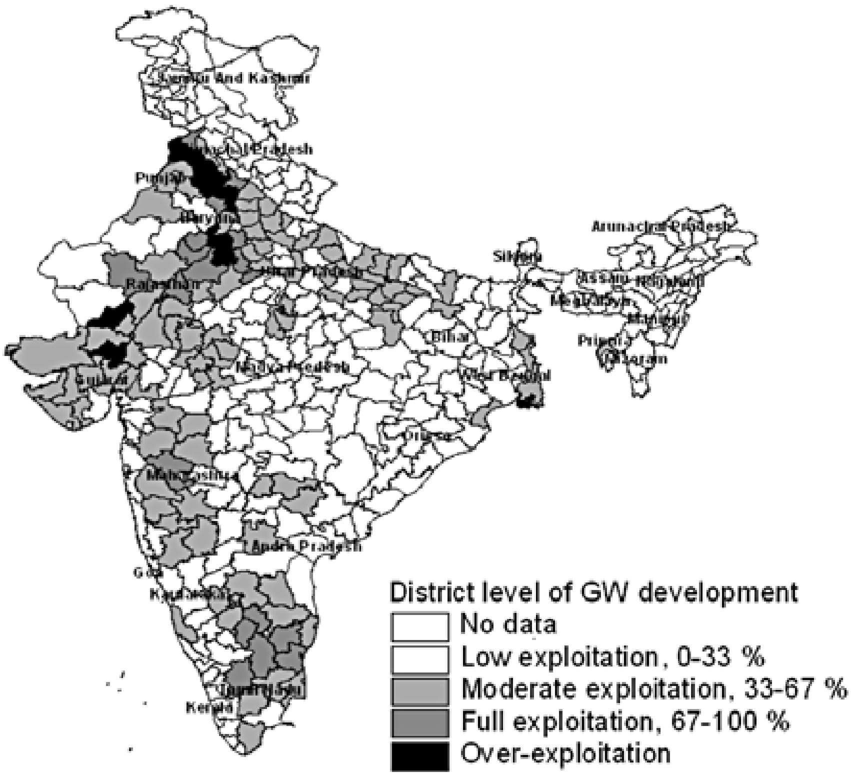


Figure 5. Level of groundwater development in India, district-wise (Data from Central Groundwater Board, 1995)

3. Make knowledge of groundwater and risk of over-abstraction easily understandable to the lay person and general groundwater user and other affected segments of society and establish communication links between users, scientists and managers.

Conclusions

Appropriate management options will depend on the specific hydrogeological context, the socioeconomic conditions and the level of groundwater development. Taking the outset in the Asian context, it needs to be realized that:

- Groundwater managers and researchers need a forum for exchange of experiences, views and approaches.
- This international workshop provides an opportunity to establish such forum.
- Groundwater management is about management of people and their impetus for exploiting the groundwater resource.
- Groundwater assessment and understanding of the physics and properties of aquifers is a prerequisite but not a means in itself. It should be incorporated into a wider process of data collection, information sharing and development of alternative management options.

- Mutual respect, appreciation, and understanding of roles, experiences and constraints and a common vision between groundwater managers and researchers are needed.

The Challenge Program on Water and Food[2] is funding a project on capacity building and multidisciplinary learning on groundwater governance in Asia[3]. This provides a further chance to build partnerships and networks across Asia to address general and specific, often shared, groundwater problems.

References

Acreman, M. 2005. Linking science and decision-making: features and experience from environmental river flow setting. Env. Modelling & Software, 20: 99-109.

Biggs, T. 2005. Groundwater irrigation and urban reservoir depletion – A case study from central India. In preparation., International Water Management Institute, South Asia Regional Office, Patancheru, Hyderabad, India.

Central Groundwater Board. 1995. Groundwater Resources of India. CGWB, Ministry of Water Resources of India, Faridabad.

Chatterjee, Rana. 2005. *Personal communication*.

Foster, S., Tuinhof, A., Kemper, K., Garduno, H., and Nanni, M. 2003. Characterization of Groundwater Systems. Briefing Note 2, GW MATE Briefing Note Series. (http://lnweb18.worldbank.org/ESSD/ardext.nsf/18ByDocName/BriefingNoteNo2CharacterizationofGroundwaterSystems—keyconceptsandfrequentmisconceptions/$FILE/BN2.pdf)

G.E.C. (Groundwater Resources Estimation Committee). 1984. Groundwater Estimation Methodology, Report, Ministry of Irrigation, Govt.of India, New Delhi, India.

G.E.C. (Groundwater Resources Estimation Committee). 1997. Groundwater Estimation Methodology, Report, Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

Shah, T., Roy, A.D., Qureshi, A.S. and Wang, J. 2003. Sustaining Asia´s groundwater boom: An overview of issues and evidence. Natural Resources Forum 27: 130-141.

Shah, T. 2004. Groundwater and Human Development: Challenges and Opportunities in Livelihoods and Environment. Presentation, made at the 2004 Stockholm World Water Week. Water Science and Technology (Forthcoming).

Tuinhof, A., Dumars, C., Foster, S., Kemper, K., Garduno, H. and Nanni, M. 2003. Groundwater Resource Management - An Introduction to its Scope and Practice. Briefing Note 1, GW-MATE Briefing Note Series. (http://lnweb18.worldbank.org/ESSD/ardext.nsf/18ByDocName/Briefing Note No1 Groundwater Resource Management — An Introduction to its Scopeand Practice/$FILE/BN1.pdf)

[2]http://www.waterforfood.org/

[3]http://www.iwmi.cgiar.org/iwmi-tata/index.asp?nc=293&id=1002&msid=100