Groundwater Resource Management
an introduction to its scope and practice

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Why is groundwater different from surface water?

- Groundwater differs from surface water because of the contrasting physical and chemical environment in which it occurs, although the water itself is essentially part of the same overall cycle (Table 1).
- Surface water flows relatively rapidly in small streams, which feed the main river draining the catchment area concerned. The catchment area of each river basin is determined by land surface topography and generally does not change with time.
- Groundwater moves through aquifers (permeable strata) from areas of recharge to areas of discharge (determined by the geological structure), normally at slow rates ranging from 1-m/year to 100s-m/day. Tens, hundreds or even thousands of years may elapse between initial recharge and eventual discharge, to a spring, stream or the sea. These slow flow rates and long residence times, consequent upon large aquifer storage volumes, are among the numerous distinctive features of groundwater systems (Table 2).

Table 1: Groundwater and surface water—viewed as an integrated resource

| Raindrop A infiltrates the soil, reaches the watertable and becomes groundwater. After 10 years underground it is pumped from a waterwell and used for potable supply. It is then discharged as sewage effluent to a river, becoming surface water perched above the local water-table, which seeps through its bed to recharge the underlying aquifer. The raindrop then joins the groundwater flow in a fissured limestone aquifer and discharges directly to the sea some 2-years later. | Raindrop B falls directly into an upland lake, becoming surface water. After 5 days it evaporates back to the local atmosphere and falls again as rain, but this time on permeable ground where it infiltrates to become groundwater. It flows underground in an unconsolidated sand aquifer for more than 100 years but discharges eventually as a lowland spring. It thus becomes surface water again, part of a stream and river system which some 2 days later reaches the sea. |

From the sea both raindrops will, centuries later, evaporate to commence the cycle anew.
The flow boundaries of groundwater (in space and depth) are generally more difficult to define and may vary with time. The difference is further accentuated because groundwater forms the ‘invisible part’ of the hydrological cycle, which can lead to misconceptions amongst stakeholders. Often water resource decision makers (like many water users) have little background in hydrogeology and thus limited understanding of the processes induced by pumping groundwater from an aquifer. Both irrational underutilization of groundwater resources (compared to surface water) and excessive complacency about the sustainability of intensive groundwater use are thus still commonplace.

What is the key challenge for groundwater resources management?

Groundwater resources management has to deal with balancing the exploitation of a complex resource (in terms of quantity, quality and surface water interactions) with the increasing demands of water and land users (who can pose a threat to resource availability and quality). This note deals mainly with the quantitative, essentially resource-related, issues of groundwater management, and only touches marginally upon groundwater pollution protection (which is dealt with in Briefing Note 8).

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 is allowed, a ‘vicious circle’ may develop (Figure 1) and damage to the resource as a whole may result (with serious groundwater level decline, and in some cases aquifer saline intrusion or even land subsidence).

To transform this ‘vicious circle’ into a ‘virtuous circle’ (Figure 2) 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)
**Figure 1: Supply-driven groundwater development—leading to a vicious circle**

- Increasing demand + contaminant load
- Aquifer systems/groundwater resources impacted
- Quality and quantity deteriorate
- Reliable supply reducing with increasing cost

**Figure 2: Integrated groundwater resource management—leading to a virtuous circle**

- Acceptable demand + contaminant load
- Aquifer systems/groundwater resources protected
- Quality and quantity stabilize
- Secure supply at reasonable cost

is as important as the hydrogeological dimension (supply-side management) and integration of both is always required.

- Key issues for **groundwater supply management** are the need to understand:
  - Aquifer systems and their specific susceptibilities to negative impacts under abstraction stress
  - Interactions between groundwater and surface water, such as abstraction effects (on river baseflow and some wetlands) and recharge reduction effects (due to surface-water modification).

All of these effects can be short-term and reversible or long-term and quasi-irreversible. Operational monitoring is a vital tool to develop the understanding needed for effective resource management.

- On the **groundwater demand management** side it will be essential to bear in mind that:
  - Social development goals greatly influence water use, especially where agricultural irrigation and food production are concerned, thus management can only be fully effective if cross-sector 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.

- Other generic principles that emerge are that:
  - Both hydrogeologic and socio-economic conditions tend to be somewhat location-specific and thus no simple blueprint for integrated groundwater management can be readily provided
  - The development of an effective and sustainable approach to management will always require involvement of the main stakeholders
  - Implementing management measures will often require capacity building, both among water-resource authorities and water users.
How should integrated groundwater management be practiced?

- In most situations, groundwater management will need to maintain reasonable balance between the costs and benefits of management activities and interventions, and thus take account of the susceptibility to degradation of the hydrogeological system involved and the legitimate interests of water users, including ecosystems and those dependent on downstream baseflow.
- In practical terms it will be necessary to set possible management interventions in the context of the normal evolution of groundwater development, and for this purpose it is convenient to distinguish a number of levels (Table 3). However, it must be noted that **preventive management approaches are likely to be more cost-effective than purely reactive ones**.
- The condition of excessive and unsustainable abstraction (3A—Unstable Development), which is occurring all too widely, is also included in Figure 3. For this case the total abstraction rate (and usually the number of production waterwells) will eventually fall markedly as a result of near irreversible degradation of the aquifer system itself.

**Figure 3: Stages of groundwater resource development in a major aquifer and their corresponding management needs**

- **0: BASELINE SITUATION**
  - availability and accessibility of adequate quality groundwater greatly exceeds small dispersed demand
  - registration of abstraction wells and captured springs required, together with maps of occurrence of usable resources

- **1: INCipient STRESS**
  - growth of aquifer pumping, but only few local conflicts arising between neighboring abstractors
  - simple management tools (for example, appropriate well-spacing according to aquifer properties) should be applied

- **2: SIGNIFICANT STRESS**
  - abstraction expanding rapidly with impacts on natural regime and strong dependence of various stakeholders on resource
  - regulatory framework needed, based upon comprehensive resources assessment with critical appraisal of aquifer linkages

- **3A: UNSTABLE DEVELOPMENT**
  - excessive uncontrolled abstraction with irreversible aquifer deterioration and conflict between stakeholders
  - regulatory framework with demand management and/or artificial recharge urgently needed

- **3B: STABLE HIGHLY DEVELOPED**
  - high-level of abstraction, but with sound balance between competing stakeholder interests and ecosystem needs
  - integrated resource management with high-level of user self-regulation, guided by aquifer modeling and monitoring
Table 3: Levels of groundwater management tools, instruments and interventions necessary for given stage of resource development

<table>
<thead>
<tr>
<th>GROUNDWATER MANAGEMENT TOOLS &amp; INSTRUMENTS</th>
<th>LEVEL OF DEVELOPMENT OF CORRESPONDING TOOL OR INSTRUMENT (according to hydraulic stress stage/see Figure 3)</th>
<th>TECHNICAL TOOLS</th>
<th>INSTITUTIONAL INSTRUMENTS</th>
<th>MANAGEMENT ACTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Assessment</td>
<td>basic knowledge of aquifer</td>
<td>conceptual model based on field data</td>
<td>numerical model(s) operational with simulation of different abstraction scenarios</td>
<td>models linked to decision-support and used for planning and management</td>
</tr>
<tr>
<td>Quality Evaluation</td>
<td>no quality constraints experienced</td>
<td>quality variability is issue in allocation</td>
<td>water quality processes understood</td>
<td>quality integrated in allocation plans</td>
</tr>
<tr>
<td>Aquifer Monitoring</td>
<td>no regular monitoring program</td>
<td>project monitoring, ad-hoc exchange of data</td>
<td>monitoring routines established</td>
<td>monitoring programs used for management decisions</td>
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<tr>
<td>Water Rights</td>
<td>customary water rights</td>
<td>occasional local clarification of water rights (via court cases)</td>
<td>recognition that societal changes override customary water rights</td>
<td>dynamic rights based on management plans</td>
</tr>
<tr>
<td>Regulatory Provisions</td>
<td>only social regulation</td>
<td>restricted regulation (e.g. licensing of new wells, restrictions on drilling)</td>
<td>active regulation and enforcement by dedicated agency</td>
<td>facilitation and control of stakeholder self-regulation</td>
</tr>
<tr>
<td>Water Legislation</td>
<td>no water legislation</td>
<td>preparation of groundwater resource law discussed</td>
<td>legal provision for organization of groundwater users</td>
<td>full legal framework for aquifer management</td>
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<tr>
<td>Stakeholder Participation</td>
<td>little interaction between regulator and water users</td>
<td>reactive participation and development of user organizations</td>
<td>stakeholder organizations co-opted into management structure (e.g. aquifer councils)</td>
<td>stakeholders and regulator share responsibility for aquifer management</td>
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<tr>
<td>Awareness and Education</td>
<td>groundwater is considered an infinite and free resource</td>
<td>finite resource (campaigns for water conservation and protection)</td>
<td>economic good and part of an integrated system</td>
<td>effective interaction and communication between stakeholders</td>
</tr>
<tr>
<td>Economic Instruments</td>
<td>economic externalities hardly recognized (exploitation is widely subsidized)</td>
<td>only symbolic charges for water abstraction</td>
<td>recognition of economic value (reduction and targeting of fuel subsidies)</td>
<td>economic value recognized (adequate charging and increased possibility of reallocation)</td>
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<tr>
<td>Prevention of Side Effects</td>
<td>little concerns for side effects</td>
<td>recognition of (short- and long-term) side effects</td>
<td>preventive measures in recognition of \textit{in-situ} value</td>
<td>mechanism to balance extractive uses and \textit{in-situ} values</td>
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<tr>
<td>Resource Allocation</td>
<td>limited allocation constraints</td>
<td>competition between users</td>
<td>priorities defined for extractive use</td>
<td>equitable allocation of extractive uses and \textit{in-situ} values</td>
</tr>
<tr>
<td>Pollution Control</td>
<td>few controls over land use and waste disposal</td>
<td>land surface zoning but no proactive controls</td>
<td>control over new point source pollution and/or siting of new wells in safe zones</td>
<td>control of all point and diffuse sources of pollution; mitigation of existing contamination</td>
</tr>
</tbody>
</table>
The concept of an increasing need for integrated groundwater management is illustrated in Table 3, which breaks management down into a series of interrelated aspects and indicates levels of response appropriate for each level of resource development. It should be noted that the approach to groundwater resource development and management for minor aquifers (only capable of supplying rural domestic and livestock water supply) would not be expected to pass level 1 in Table 3.

The framework provided in Table 3 can be used as a diagnostic instrument to assess the adequacy of existing groundwater management arrangements for a given level of resource development (both in terms of technical tools and institutional provisions). By working down the levels of development of each groundwater management tool or instrument, a diagnostic profile is generated which can be compared to the actual stage of resource development to indicate priority aspects for urgent attention. Such a diagnostic exercise can also be undertaken by each major group of stakeholders to promote communication and understanding. Through this type of approach necessary management interventions for a given hydrogeological setting and resource development situation can be agreed upon.

Further Reading


Publication Arrangements

The GW•MATE Briefing Notes Series is published by the World Bank, Washington D.C., USA. It is also available in electronic form on the World Bank water resources website (www.worldbank.org/gwmate) and the Global Water Partnership website (www.gwpforum.org).

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