Sustainable Groundwater Management: Concepts and Tools

Briefing Note 1

Groundwater Resource Management

an introduction to its scope and practice

Authors (GW•MATE Core Group)

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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 amongst the numerous distinctive features of groundwater systems (Table 2).

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

Rainwater that falls to earth starts a long voyage during which its ambient environment and physical condition (liquid, vapor, solid) may change several times. It is instructive to consider the trajectory of two individual droplets.	
Raindrop A infiltrates the soil, reaches the water-table 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.	

Table 2: Comparative features of groundwater and surface water resources

FEATURE	GROUNDWATER RESOURCES & AQUIFERS	SURFACE WATER RESOURCES & RESERVOIRS
Hydrological Characteristics		
• Storage Volumes	very large	small to moderate
• Resource Areas	relatively unrestricted	restricted to water bodies
• Flow Velocities	very low	moderate to high
• Residence Times	generally decades/centuries	mainly 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, unpredictable	aesthetic, predictable
• 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

- 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-

Figure 1: Supply-driven groundwater development—leading to a vicious circle

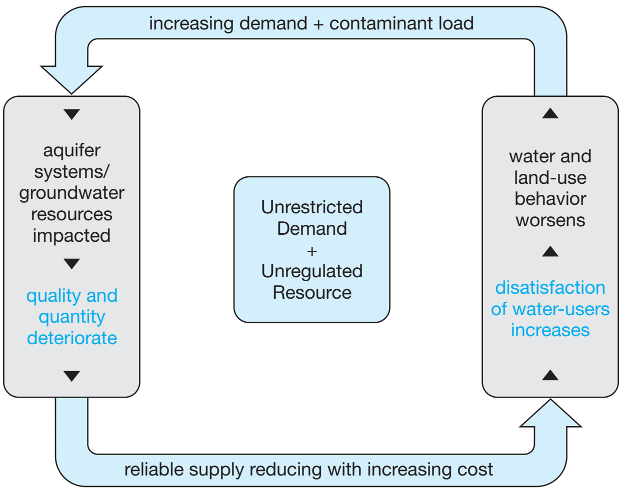
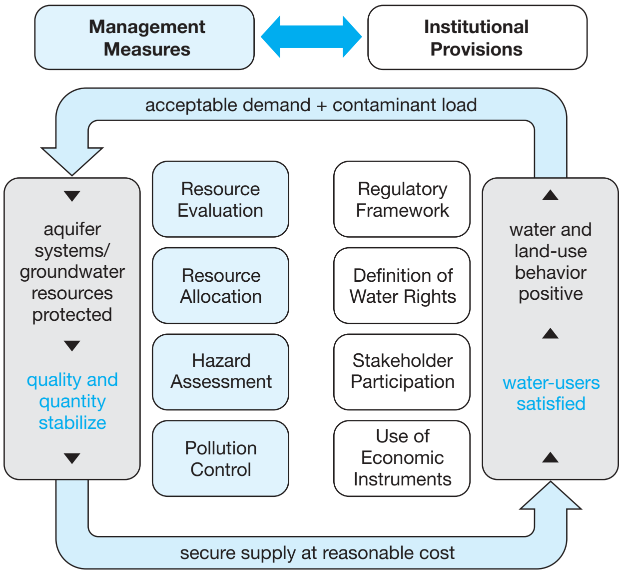


Figure 2: Integrated groundwater resource management—leading to a virtuous circle



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

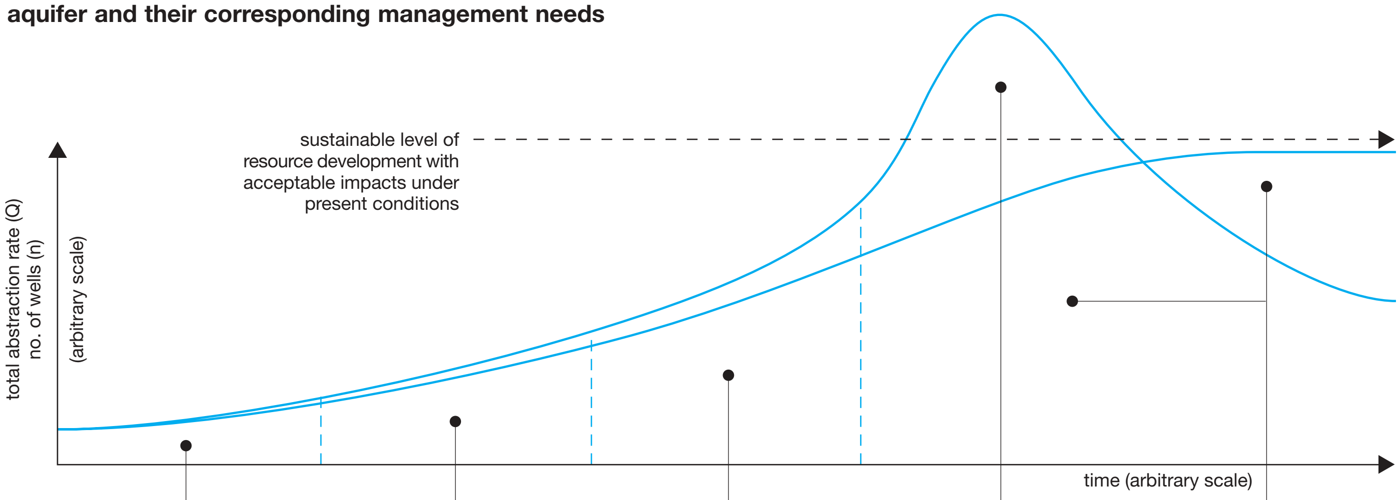
- Key issues for *groundwater supply management* are the need to understand:
  - aquifer systems and their specific susceptibilities to negative impacts under abstraction stress
  - interactions between groundwater and surface water, such as abstraction effects (on river baseflow and some wetlands) and 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 in water-resource authorities and amongst water users.

How should integrated groundwater management be practised?

- In most situations, groundwater management will need to keep in reasonable balance 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 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 to 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	1: INCIPIENT STRESS	2: SIGNIFICANT STRESS	3A: UNSTABLE DEVELOPMENT	3B: STABLE HIGHLY DEVELOPED
availability and accessibility of adequate quality groundwater greatly exceeds small dispersed demand	growth of aquifer pumping, but only few local conflicts arising between neighboring abstractors	abstraction expanding rapidly with impacts on natural regime and strong dependence of various stakeholders on resource	excessive uncontrolled abstraction with irreversible aquifer deterioration and conflict between stakeholders	high-level of abstraction, but with sound balance between competing stakeholder interests and ecosystem needs
registration of abstraction wells and captured springs required, together with maps of occurrence of usable resources	simple management tools (for example, appropriate well-spacing according to aquifer properties) should be applied	regulatory framework needed, based upon comprehensive resources assessment with critical appraisal of aquifer linkages	regulatory framework with demand management and/or artificial recharge urgently needed	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

GROUNDWATER MANAGEMENT TOOLS & INSTRUMENTS	LEVEL OF DEVELOPMENT OF CORRESPONDING TOOL OR INSTRUMENT (according to hydraulic stress stage/see Figure 3)			
	0	1	2	3
TECHNICAL TOOLS				
Resource Assessment	basic knowledge of aquifer	conceptual model based on field data	numerical model(s) operational with simulation of different abstraction scenarios	models linked to decision-support and used for planning and management
Quality Evaluation	no quality constraints experienced	quality variability is issue in allocation	water quality processes understood	quality integrated in allocation plans
Aquifer Monitoring	no regular monitoring program	project monitoring, ad-hoc exchange of data	monitoring routines established	monitoring programs used for management decisions
INSTITUTIONAL INSTRUMENTS				
Water Rights	customary water rights	occasional local clarification of water rights (via court cases)	recognition that societal changes override customary water rights	dynamic rights based on management plans
Regulatory Provisions	only social regulation	restricted regulation (e.g. licensing of new wells, restrictions on drilling)	active regulation and enforcement by dedicated agency	facilitation and control of stakeholder self-regulation
Water Legislation	no water legislation	preparation of groundwater resource law discussed	legal provision for organization of groundwater users	full legal framework for aquifer management
Stakeholder Participation	little interaction between regulator and water users	reactive participation and development of user organizations	stakeholder organizations co-opted into management structure (e.g. aquifer councils)	stakeholders and regulator share responsibility for aquifer management
Awareness and Education	groundwater is considered an infinite and free resource	finite resource (campaigns for water conservation and protection)	economic good and part of an integrated system	effective interaction and communication between stakeholders
Economic Instruments	economic externalities hardly recognized (exploitation is widely subsidized)	only symbolic charges for water abstraction	recognition of economic value (reduction and targeting of fuel subsidies)	economic value recognized (adequate charging and increased possibility of reallocation)
MANAGEMENT ACTIONS				
Prevention of Side Effects	little concerns for side effects	recognition of (short- and long-term) side effects	preventive measures in recognition of *in-situ* value	mechanism to balance extractive uses and *in-situ* values
Resource Allocation	limited allocation constraints	competition between users	priorities defined for extractive use	equitable allocation of extractive uses and *in-situ* values
Pollution Control	few controls over land use and waste disposal	land surface zoning but no proactive controls	control over new point source pollution and/or siting of new wells in safe zones	control of all point and diffuse sources of pollution; mitigation of existing contamination

- 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.

Further Reading

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