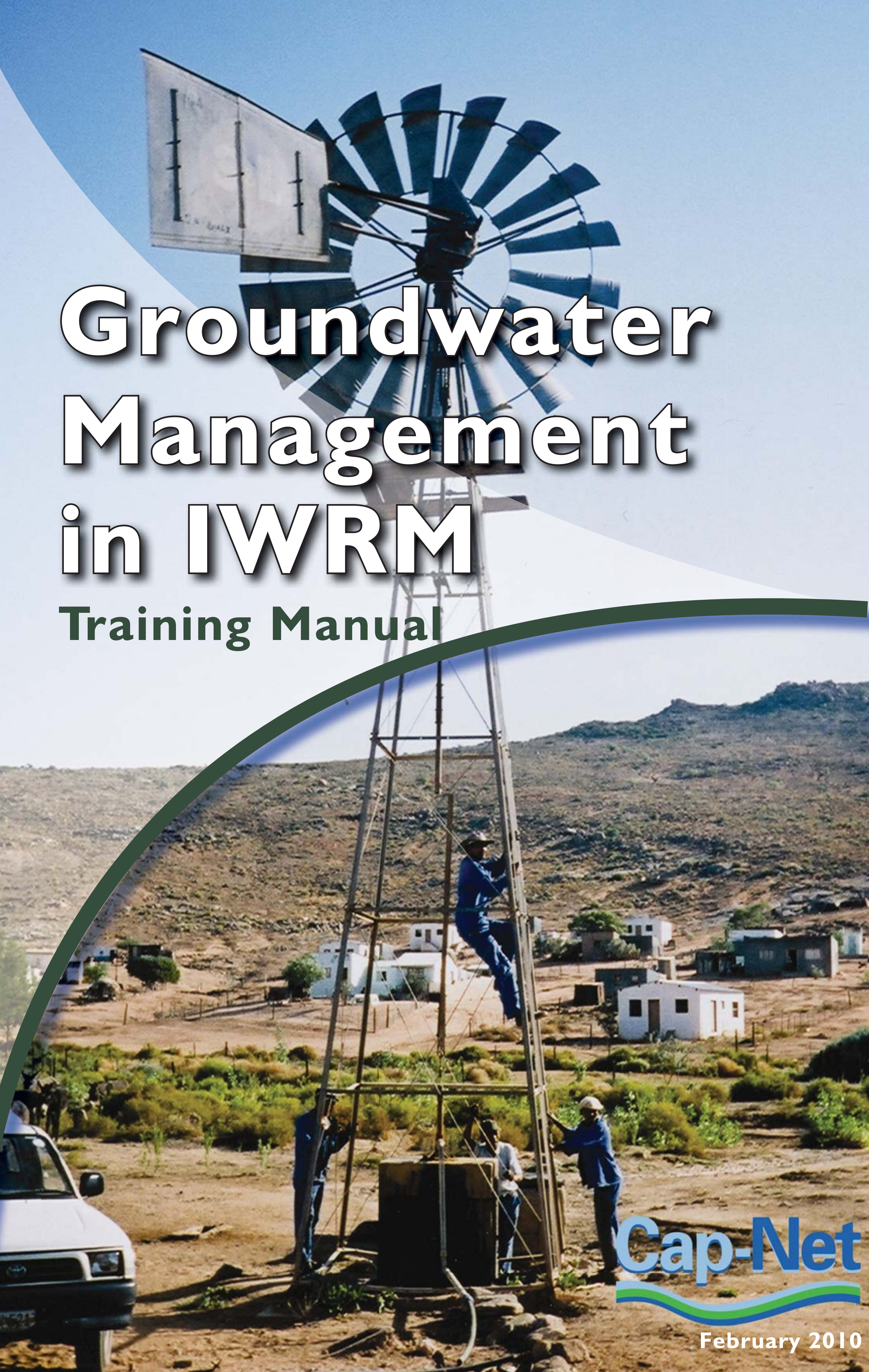

Groundwater Management in IWRM

Training Manual

Cap-Net

February 2010

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Foreword

In many countries, groundwater is of vital importance for the livelihood and health of the people since it is often the main source for domestic water. It is also widely used for irrigated agriculture and industry. This is particularly true in dry regions where surface water is scarce or seasonal, and in rural areas with dispersed populations. Climate change is likely to lead to a greater dependence on groundwater as a cushion against drought and increasing uncertainty in surface water availability.

There is widespread recognition that water resources, including groundwater, are coming under pressure from increasing demand and declining yields. Water supply systems have often been developed in an unsustainable way, threatening vital social and economic developments. As a result many governments have been reforming water resources management to adopt the approach known as Integrated Water Resources Management (IWRM).

One important issue has been the inadequate attention to groundwater management within the reforms towards an IWRM approach. Yet a fundamental observation of IWRM is that water is one (interlinked) resource requiring a holistic approach to management and hence groundwater should be fully incorporated.

After a series of case studies in Africa and some pilot training courses, Cap-Net, the Africa Groundwater Network (AGW-Net) and GW-MATE (Ground Water Management Advisory Team) have collaborated to produce these training materials on groundwater management. An important objective of these materials is to address groundwater in the IWRM perspective. The goal of the course is to introduce the broader framework of groundwater management to groundwater experts and the specific challenges of groundwater management to other water professionals.

Groundwater is technically complex but the technical expert and the water manager must reach a common understanding. We hope that these training materials will assist in achieving that objective.

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Foreword and Acknowledgements

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Acknowledgements

This manual was written by Dr Richard Owen, Dr Muna Mirghani, Dr Moustapha Diene, Dr Albert Tuinhof and Dr Paul Taylor. For most of the modules the manual has drawn liberally from the excellent series of Briefing Notes written by members of GW-MATE, a World Bank programme.

The full collection of briefing notes can be found at:
http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTWAT/0,,contentMDK:21760540~menuPK:4965491~pagePK:148956~piPK:216618~theSitePK:4602123,00.html and are available in English and Spanish. The briefing notes as well as PowerPoint presentations and translations are included in the CD version of the training manual.

Cover photo credit: Water Research Commission, South Africa

Module 1: IWRM and Groundwater Management Framework

Learning Objectives

- To understand key principles and themes in IWRM and the relevance of groundwater;
- To appreciate the special characteristics of groundwater compared to surface water resources;
- To recognise challenges facing groundwater management and the need for new approaches to address the resource management problems.
- To emphasize key advantages of incorporating groundwater management into national and river-basin water resource planning

1. Introduction: Why groundwater management matters

- **Importance of Groundwater.**

  Groundwater is vital to many nations. Worldwide some 2 billion people, innumerable farmers and many industrial premises depend on it for their water supply. Accelerated development over the past few decades has resulted in great social and economic benefits, by providing low-cost, drought-reliable and (mainly) high-quality water supplies for both the urban and rural population and for irrigation of (potentially high-value) crops. Further use will be vital for achievement of 'UN Millennium Development Goals'.

- **Sustainable groundwater use**

  Worldwide sustainable water resources development and management is recognized as an ultimate goal of national water strategies. The sustainability of groundwater is closely linked with a range of micro- and macro-policy issues influencing water and land use, and represents one of the major challenges in natural resource management. Investment in management and protection of the resource base has been seriously neglected. Practical advances are urgently needed; there is no simple blueprint for action, due to the inherent variability of groundwater systems and related socio-economic situations. Many developing nations need to appreciate their socio-economic dependency on groundwater, and invest in strengthening institutional provisions and building institutional capacity for its improved management before it is too late.

Traditional institutional separation of surface water from groundwater has created fundamental communication barriers that now extend from technical expertise to policy developers, operational managers and water users. These barriers impede the understanding of the processes and consequences of groundwater-surface water interactions.

2. What is IWRM ?

Integrated Water Resources Management is an approach that promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

This includes more coordinated development and management of:

- land and water,
- surface water and groundwater,
- the river basin and its adjacent coastal and marine environment,
- upstream and downstream interests.

However, IWRM is not just about managing physical resources, it is also about reforming human systems to enable people, both men and women, to benefit from those resources.

At its simplest, IWRM is a logical and appealing concept. Its basis is that the many different uses of water resources are interdependent. That is evident to us all. High irrigation demands and polluted drainage flows from agriculture mean less freshwater for drinking or industrial use; contaminated municipal and industrial wastewater pollutes rivers and threatens ecosystems; if water has to be left in a river to protect fisheries and ecosystems, less can be diverted to grow crops. There are plenty more examples of the basic theme that unregulated use of scarce water resources is wasteful and inherently unsustainable.

Integrated management means that all the different uses of water resources are considered together. Water allocations and management decisions consider the effects of each use on the others. They are able to take account of overall social and economic goals, including the achievement of sustainable development. This also means ensuring coherent policy making related to all sectors. As we shall see, the basic IWRM concept has been extended to incorporate participatory decision-making. Different user groups (farmers, communities, environmentalists) can influence strategies for water resource development and management. That brings additional benefits, as informed users apply local self-regulation in relation to issues such as water conservation and catchment protection far more effectively than central regulation and surveillance can achieve.

Management is used in its broadest sense. It emphasises that we must not only focus on development of water resources but that we must consciously manage water development in a way that ensures long term sustainable use for future generations.

Integrated water resources management is therefore a systematic process for the sustainable development, allocation and monitoring of water resource use in the context of social, economic and environmental objectives. It contrasts with the sectoral approach that is still applied in many countries. When responsibility for drinking water rests with one agency, for irrigation water with another and for the environment with yet another, lack of cross-sectoral linkages leads to uncoordinated water resource development and management, resulting in conflict, waste and unsustainable systems.

Could you give more examples where integration can be beneficial?

2.1 General Framework

IWRM is about strengthening frameworks for water governance to foster good decision making in response to changing needs and situations. There is, no 'simple blueprint' for integrating water resources management that will fit all

Box 1.1. Dublin statements and principles

Principle No. 1 - Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment
Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or groundwater aquifer.

Principle No. 2 - Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels
The participatory approach involves raising awareness of the importance of water among policy-makers and the general public. It means that decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects.

Principle No. 3 - Women play a central part in the provision, management and safeguarding of water
This pivotal role of women as providers and users of water and guardians of the living environment has seldom been reflected in institutional arrangements for the development and management of water resources. Acceptance and implementation of this principle requires positive policies to address women's specific needs and to equip and empower women to participate at all levels in water resources programmes, including decision-making and implementation, in ways defined by them.

Principle No. 4 - Water has an economic value in all its competing uses and should be recognized as an economic good
Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources.

cases. However, a general framework is established based on Dublin principles (Box 1.1) and the three pillars driving sustainability: Economic efficiency, Environmental sustainability and social Equity (Figure. 1.1).

To implement an IWRM approach the key action areas as shown in Fig 1.1 are:

- Enabling Environment— including Policy, legislation & regulation, financing & incentive structure
- Institutional roles— considering models that allow for Aquifer & River basin, central-local, public-private interests.
- Management instruments— including resource assessment, information management and resource allocation and protection tools.

These three action areas are known to be essential for implementing IWRM and are driving country level reform at all stages in the water planning and management system. This usually begins with a new water policy to reflect the principles of sustainable management of water resources. To put the policy into practice requires the reform of water law and water institutions. This can be a long process and needs to involve extensive consultations with affected agencies and the public.

Implementation of IWRM is best done in a step-by-step process, with some changes taking place immediately and others requiring several years of planning and capacity building.

2.2 IWRM Change Areas

Adopting a more sustainable and integrated approach to water management and development requires change in many areas and at many levels. And while this can be a daunting proposition, it is important to remember that gradual change will produce more sustainable results than an attempt to completely overhaul the whole system in one operation. When beginning the process of change, consider:

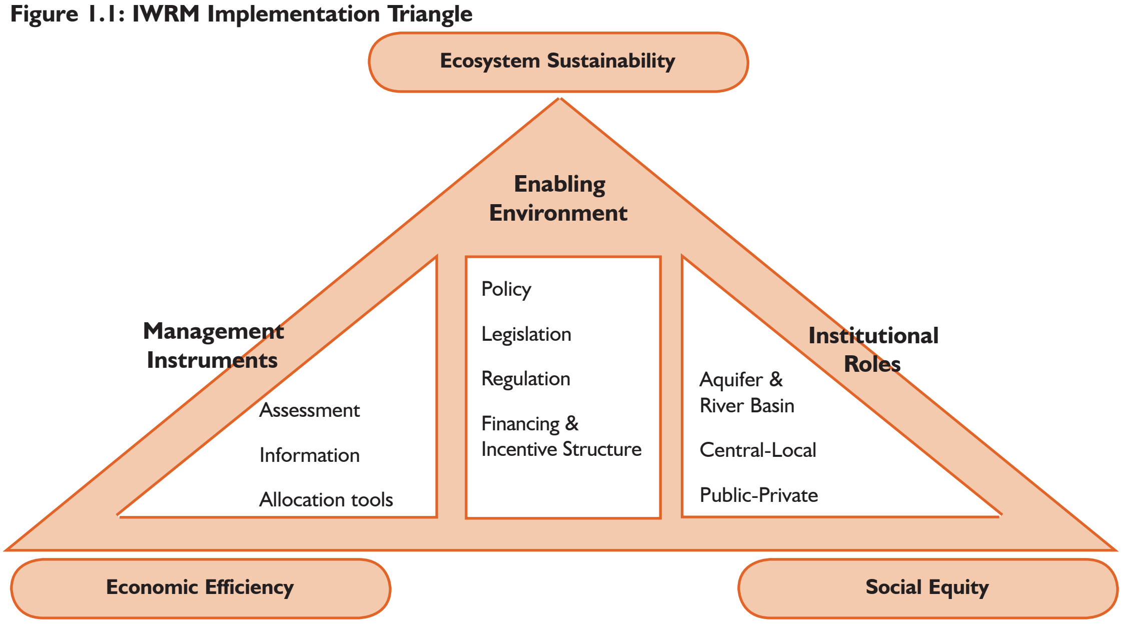
- What changes must happen to achieve agreed-upon goals?
- Where is change possible given the current social, political, and economic situation?
- What is the logical sequence for change? What changes need to come first to make other changes possible?

When considering how water should be managed in the future, the various areas for change available to the planners are identified in the GWP ToolBox and are listed in Box 1.2.

2.3 The enabling environment

This includes policy, legislation, and financing systems. Legislative processes take a long time, frequently several years and changes are cumbersome. Legislation is often lagging behind in terms of responding to the dynamic changes in the water resources situation and the society.

Figure 1.1: IWRM Implementation Triangle



Box 1.2. The thirteen key IWRM change areas

THE ENABLING ENVIRONMENT

1. Policies – setting goals for water use, protection and conservation.
2. Legislative framework – the rules to enforce to achieve policies and goals.
3. Financing and incentive structures – allocating financial resources to meet water needs.

INSTITUTIONAL ROLES

4. Creating an organizational framework – forms and functions.
5. Institutional capacity building – developing human resources.

MANAGEMENT INSTRUMENTS

6. Water resources assessment – understanding resources and needs.
7. Plans for IWRM – combining development options, resource use and human interaction.
8. Demand management – using water more efficiently.
9. Social change instruments – encouraging a water-oriented civil society.
10. Conflict resolution – managing disputes, ensuring sharing of water.
11. Regulatory instruments – allocation and water use limits.
12. Economic instruments – using value and prices for efficiency and equity.
13. Information management and exchange– improving knowledge for better water management.

Typically laws and associated regulations that impact water resources are found in many different sectors and customary laws further make the situation complex. Environmental laws and regulations, sewage discharge regulations, water supply laws and regulations, hydraulic works and well-drilling regulations are often uncoordinated and prepared by different agencies at very different points in time. The overall goal for a legal reform process is to ensure that the key policy aims can be pursued with a legal backing and that there is consistency in laws and regulations across all sectors that impact water resources. Some of the key goals for the enabling environment include:

- Establishing government as the "owner" of all water resources and a selected ministry as a water resources management authority and regulatory agency
- Recognition of international conventions and agreements including transboundary protocols e.g. wetland convention and protocols for shared water courses
- Setting out effective water allocation mechanisms including decision support for prioritisation; e.g. domestic use and environmental flows as first priority
- Setting out mechanisms for pollution management in harmony with the environmental laws and regulations, e.g. classification of water bodies, discharge standards and monitoring standards
- Providing legal basis for institutional reform, e.g. management on a catchment basis, water resources committees, government as an enabler not a provider

Which of these goals will be most difficult to get agreement on in your country?

2.4 Institutional roles

The government institutions, agencies, local authorities, private sector, civil society organisations and partnerships all constitute an institutional framework that ideally should be geared towards the implementation of the policy and the legal provisions. Whether building existing water management institutions or forming new ones, a challenge will be to make them effective and this requires capacity building. Awareness creation, participation and consultations should serve to upgrade the skills and understanding of decision-makers, water managers and professionals in all sectors. The key goals for the institutional framework are:

- To separate water resources management functions from service delivery functions (irrigation, hydro-

How should major water users be involved in making water management decisions?

power generation, water supply and sewerage) and consolidate the government as the owner of the water resources - the enabler but not the provider of services. This will avoid conflicts of interest and encourage commercial autonomy.

- To manage water resources within the boundaries of a catchment, not within administrative boundaries, decentralising regulatory and service functions to the lowest appropriate level and promoting stakeholder involvement and public participation in planning and management decisions.
- To ensure balance between the extent and complexity of regulatory functions and the skills and human resources required to deal with them. A continued capacity building program is required to develop and maintain the appropriate skills.
- To facilitate, regulate and encourage private sector potential contributions in financing and delivery of services (irrigation, hydropower generation, water supply and sewerage).

2.5 Management instruments

The policies and legislation set out the "game plan", the institutional roles define who the "players" are and what they should do, while the management instruments are the "players´ competencies and skills" needed to play the game. The water resources issues in the particular country decide which management instruments are most significant and where efforts should be concentrated. Issues such as flood risks, water scarcity, pollution, groundwater depletion, upstream/downstream conflicts, erosion and sedimentation all require their special combination of management tools to be effectively addressed. The key goals within management instruments are:

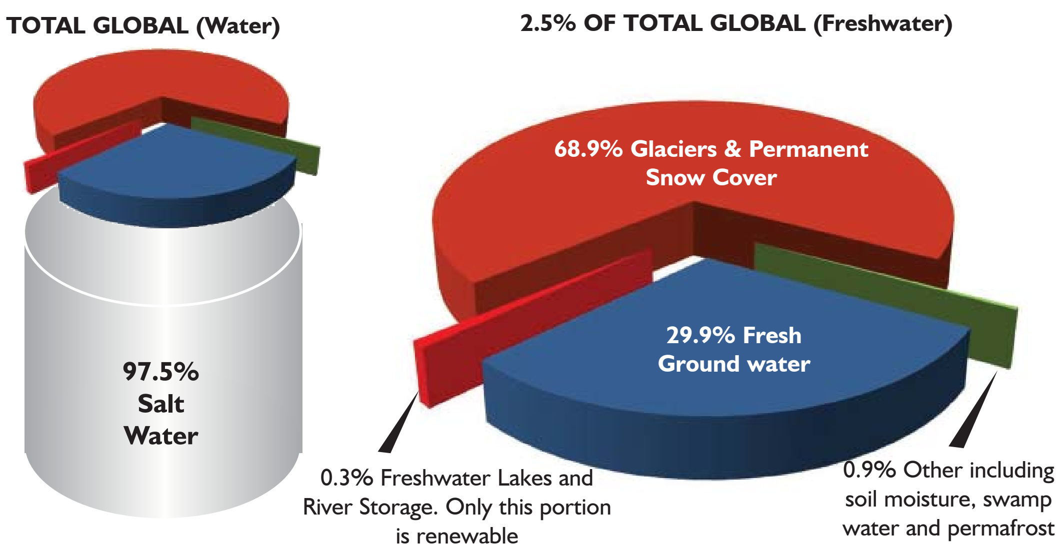
- To establish a hydrological and hydrogeological service tailored for the water resources situation and the key water resources issues;
- To establish a water resources knowledge base derived from monitoring and water resources assessments, supplemented by modelling if necessary and to make suitable parts available as part of public awareness raising;
- To establish a water allocation mechanism, an abstraction and wastewater discharge permit system and associated databases;
- To establish policy and planning capabilities and develop skills in risk assessment, environmental, social and economic assessments;
- To establish competencies in demand management, including the use of economic tools; and
- To establish human resources development and capacity building tailored to the water resources and institutional issues.

We already have many management instruments that don't work – why will it be any different this time?

3. Groundwater Resources

Groundwater is a considerable component of the total global fresh water (Figure 1.2). It represents 29.9% of the Earth fresh water re-

Figure 1.2: Components of the total global water.



sources and 99% of the blue water resources. However, only groundwater storage that exists in connected bores/ openings/ fractures is accessible for use.

Groundwater usually reacts more slowly than surface water; processes usually take longer and recharge and remediation take therefore much more time. Important resource management related differences compared to surface water, are summarised in Table 1.1 below.

Table 1.1: Comparative features of Groundwater & Surface Water

Feature	Groundwater Resources & Aquifers	Surface water Resources & Reservoirs
Hydrological Characteristics		
Storage	Very large	Small to moderate
Resource Areas	Relatively unrestricted	Restricted to water bodies
Flow velocities	Very low	Moderate to high
Residence time	Generally decades/ centuries	Mainly weeks/months
Drought vulnerability	Generally low	Generally high
Evaporation losses	Low & localised	High for reservoirs
Resource evaluation	High cost & significant uncertainty	Lower cost & often less uncertainty
Abstraction impacts	Delayed & dispersed	Immediate
Natural quality	Generally (but not always) high	Variable
Pollution vulnerability	Variable natural protection	Largely unprotected
Pollution persistent	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 & private	Largely public

4. Groundwater Management

Groundwater and surface water are closely linked and within an IWRM approach all water should be managed as one resource. Managing groundwater resources is primarily aiming at sustainable development of the resource for various users. A key issue of sustainable groundwater is balancing the available resources with the increasing demands of water use. To that end, the following resources management objectives are crucial:

a. balancing groundwater recharge against abstraction is the main emphasis of groundwater management, (figure 1.3).
b. groundwater protection from pollution

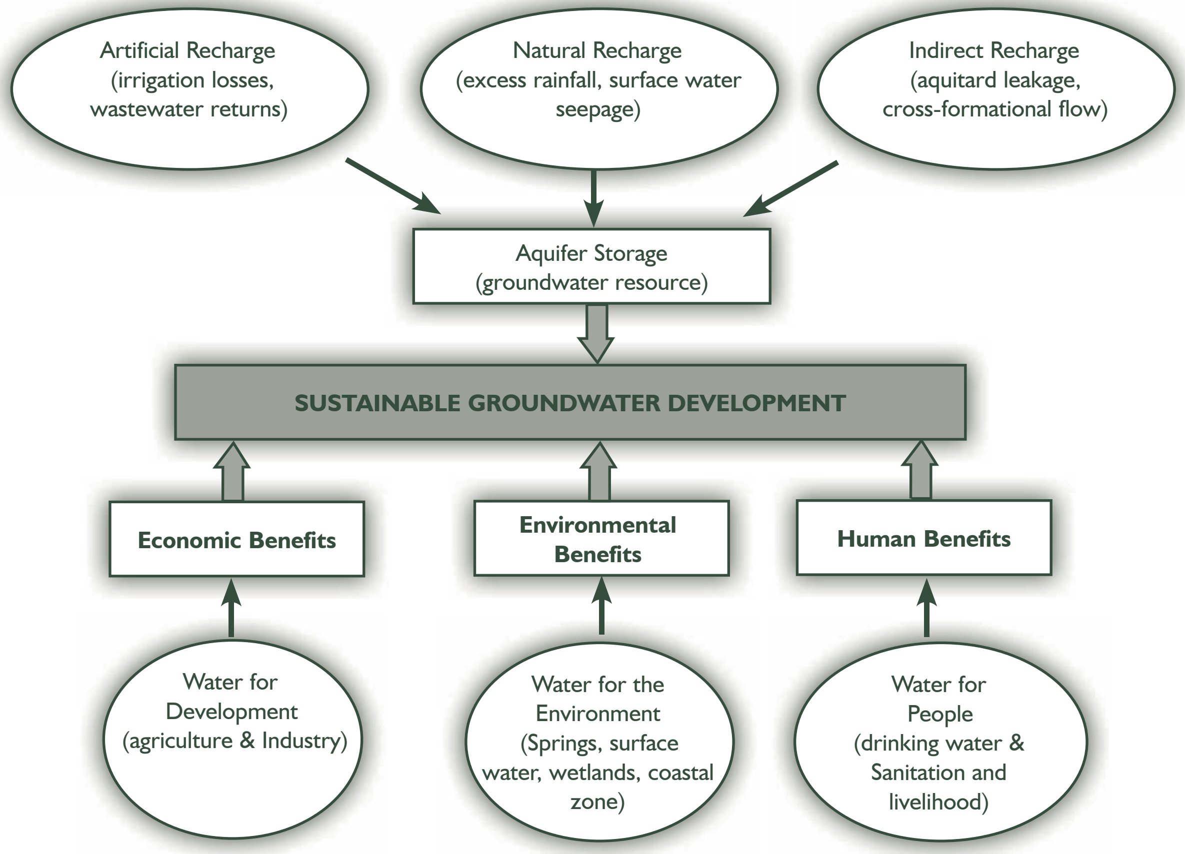
5. Why an IWRM approach to Groundwater management?

Sustainable management of water resources cannot be achieved only by addressing surface water management but must include groundwater. A new approach guided by IWRM principles and goals is needed for groundwater resource governance and management. The IWRM change paradigm addresses the following key issues:
Managing water resources in a basin requires taking into account both surface and groundwater because:

- groundwater recharge is impacted by surface water use;
- surface water downstream may include a significant amount of baseflow from groundwater – especially during the periods of low flow;
- groundwater is more reliable than surface water in times of drought;
- groundwater pollution can last for centuries thereby reducing water resources for generations to come.

Groundwater does not need an IWRM approach. Do you agree with this statement

Figure 1.3: Sustainable groundwater development, modified from Hiscock, 2002.



The approach taken to groundwater management at any moment in time will depend, to a considerable degree, upon information about, and interaction between, the following factors:

- the size and complexity of the groundwater resource;
- the degree of climatic aridity and the rate of aquifer recharge and resource renewal;
- the scale of groundwater abstraction and the number and types of groundwater users;
- the ecological role and environmental services dependent upon groundwater;
- the susceptibility and vulnerability of the aquifer system to degradation;
- natural groundwater quality concerns (trace element hazards and saline water presence);
- Other available water resources.

The Dublin principles (Box 1.1) do not only apply to surface water and groundwater management has to take into account the rationale behind the adoption of the IWRM approach which recognises that:

- Water is a finite and vulnerable resource;
- Water is an economic good;
- Women play a central part in the management of water; and
- Water development and management should be based on a participatory approach.

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Exercise:

Two groups:
Group 1: Discuss how the Dublin principles can be applied in groundwater management.

Group 2: Read the recommendations in the following table. For each situation describe how the management of groundwater and surface water in these areas should be implemented in practice.

Cases illustrating specific hydrogeological settings that require a different approach

Hydrogeological Setting	Main Feature	Recommendation
Significant aquifers with more limited extension than the river basin catchment	Specific aquifer units or groundwater bodies will require independent local management plans	Plans need to take account that groundwater recharge may be dependent upon upstream river flow and downstream river flow may be dependent upon aquifer discharge
River basins underlain extensively by a shallow Quaternary aquifer	Surface water-groundwater relations (and their management) are critical to avoid such problems as salt mobilization on land clearance, soil water logging and salinisation from irrigated agriculture	Fully integrated water resource planning and management is essential
Extensive deep aquifer systems occurring in more arid regions	Groundwater flow system dominates, there is little permanent surface water	It is not helpful to establish a 'river basin organization', and more valid to define a groundwater resource management plan and to manage at 'aquifer level'
Minor aquifers predominant	Characterized by shallow depth, patchy distribution and low potential. (e.g. many parts of the Sub-Sahara African continental shield) – these will have limited interaction with the overlying river basin	Storage is not sufficient to justify comprehensive groundwater resource planning and administration. Given their social importance in rural water supply it is appropriate to put the main effort into the optimum design of water-wells so to maximize their yield and drought security, and to identify the constraints imposed by any potential naturally occurring groundwater quality problems.

Module 2: Aquifer Systems Characterization for Groundwater Management

Learning objectives:

- To understand key properties of aquifers for better groundwater management
- To understand the main hydro-geological environments and groundwater occurrence, and the implications in terms of groundwater development
- To realise the importance of aquifer characterization in groundwater resources management

1. Introduction

Groundwater differs from surface water as a result of the different physical and chemical environments in which they occur. Among aquifers there are huge differences with respect to geological environments in which they occur, affecting their capacity to store water and to transmit water flow. In addition different geological formations vary widely in the degree to which they exhibit these properties and their spatial extent varies, sometimes significantly, with geological structure. Hence the availability of groundwater will depend on hydrogeological setting, which could present significant hydrogeological diversity.

Therefore groundwater management has to be based on a good understanding of the groundwater characteristics of the total groundwater system. This understanding requires good data on the resources from investigations, monitoring and interpretation.

2. Groundwater occurrence

What are the main functions of aquifers?

Groundwater occurs in most geological formations because nearly all rocks of whatever type, origin or age, possess openings called pores or voids or fractures. For the purpose of hydrogeological investigations we have to deal with hydrological units, or the hydrological system; depending of the scale of study we can identify:

- Hydrological basins that correspond nearly to the topographic or drainage basin;
- Groundwater basins that are a component of the hydrological basin located underground;
- Aquifer or hydrogeological units that contain groundwater; one or many aquifers can constitute a hydrogeological basin.

In definition an aquifer is a geologic formation, a group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. Aquifers are often combined into aquifer systems.

An aquifer as a hydrogeological unit is made up of two main phases that interact: a reservoir comprising one or many hydrogeological formations and groundwater.
The reservoir has three important functions:

- Storage capacity expressed through storativity (storage coefficient) or specific yield;
- Transfer capacity by gravity or pressure, expressed as transmissivity;
- Interaction through physical and chemical exchange between the reservoir-rock and the groundwater.

Depending on rock types and hydrogeological environments, an aquifer may fulfil one or more of these functions. For instance a river side aquifer has a predominantly transfer function, whereas a deep confined aquifer presents mainly storage capacity, and an unconfined aquifer may play both roles. The exchange function is related to the length of time that the rock and water interact, the length of flow path and type of materials.

Box 2.1 provides definitions of basic concepts useful for better understanding of aquifer types.

Box 2.1: Basic concepts and definitions

An aquifer is defined as a geologic formation (single layer or group of layers) that can store and yield a significant quantity of water. This function depends on the nature of water-bearing rock; good aquifers are those with high permeability such as sands, gravels, and sandstones or highly fractured rock; they can be excellent sources of water for human usage.

If a geologic layer can store but doesn't have ability to transmit significant amount of water it is called an aquiclude. It may be the case for sandy clay and some consolidated rocks (mudstone, consolidated clays or crystalline rocks) where the fractures are not interconnected.

An aquitard is a confined geologic layer (with low permeability) that transmits low amounts of water compared to aquifers; transfer is mainly vertical from aquifer to aquifer. For instance, clayey sands may be identified as an aquitard.

One can distinguish two main types of aquifers:
- unconfined (free surface), called water-table or phreatic aquifers, which are bounded by free surface at the upper limit ; as a result the water table is under atmospheric pressure;
- confined (under pressure) aquifers are bounded by impervious or semipervious layers; under confined conditions, water may be under pressure and when wells are drilled water rises above the top of the aquifer, or even above the ground surface (artesian well).

Source: Batu, 1998

What are the most common hydrogeological formations?

The availability of groundwater depends primarily on the geologic environment in which it occurs. The most significant elements of hydrogeological diversity are:
- Major variation of aquifer storage capacity (storativity), between unconsolidated granular sediments and highly-consolidated fractured rocks;
- Wide variation in aquifer saturated thickness between different depositional types, resulting in a wide range of groundwater flow potential (transmissivity).

Unconsolidated sedimentary aquifers are composed mainly of loose materials: sands, gravels, alluvial grains, clayey sand, sandy clays and clays. They constitute a porous and continuous medium. Groundwater is stored and transmitted through pore spaces, not fractures. They have large to very large storage capacity and usually huge regional extension.

Compact and fractured rocks or consolidated formations have openings that are mainly composed of fractures; they usually constitute a discontinuous medium. In general one can identify two major types of formations:
- Carbonated rocks like limestones, that are slightly soluble in rainwater and therefore fractures can be enlarged to form karsts (solution channels);
- Ancient crystalline and metamorphic rocks can be highly fractured; they can also decompose in the upper part to form a porous and permeable mantle of weathered materials that may be tens of meters thick.

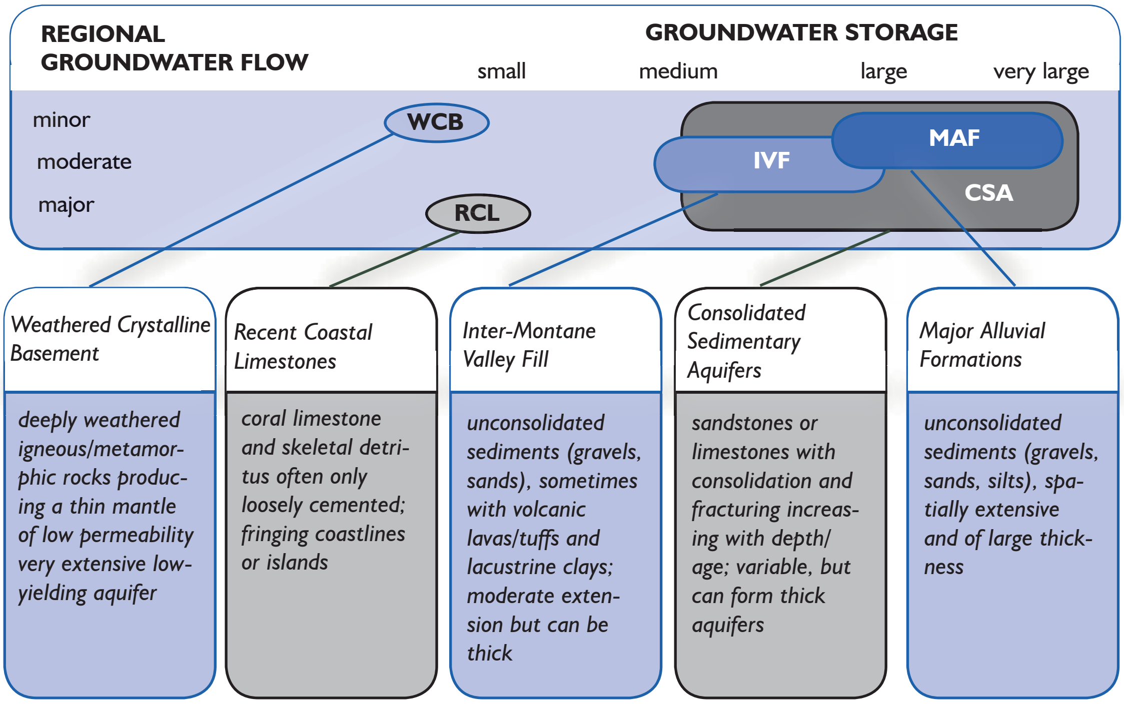
The hydrogeological diversity can be summarised into key elements that identify most aquifer types (figure 2.1). They are characterized by their groundwater storage capacity and the scale (length and travel time) of their flow paths.

What are most-widely occurring aquifers in use in your country?

Sedimentary basins contain large resources of groundwater; two types of hydrogeological environments are particularly excellent aquifers:
- Major alluvial and coastal basins that are prolific aquifers;
- Consolidated sedimentary rocks like sandstone and limestones.

They are spatially extensive and possess large thickness, ensuring great volumes of groundwater storage with regional flow. Also they constitute major transboundary aquifers.

Figure 2.1: Summary of key properties of the most widely-occurring aquifer types. (GW- Mate Briefing note 2).



What are main differences between major and minor aquifers?

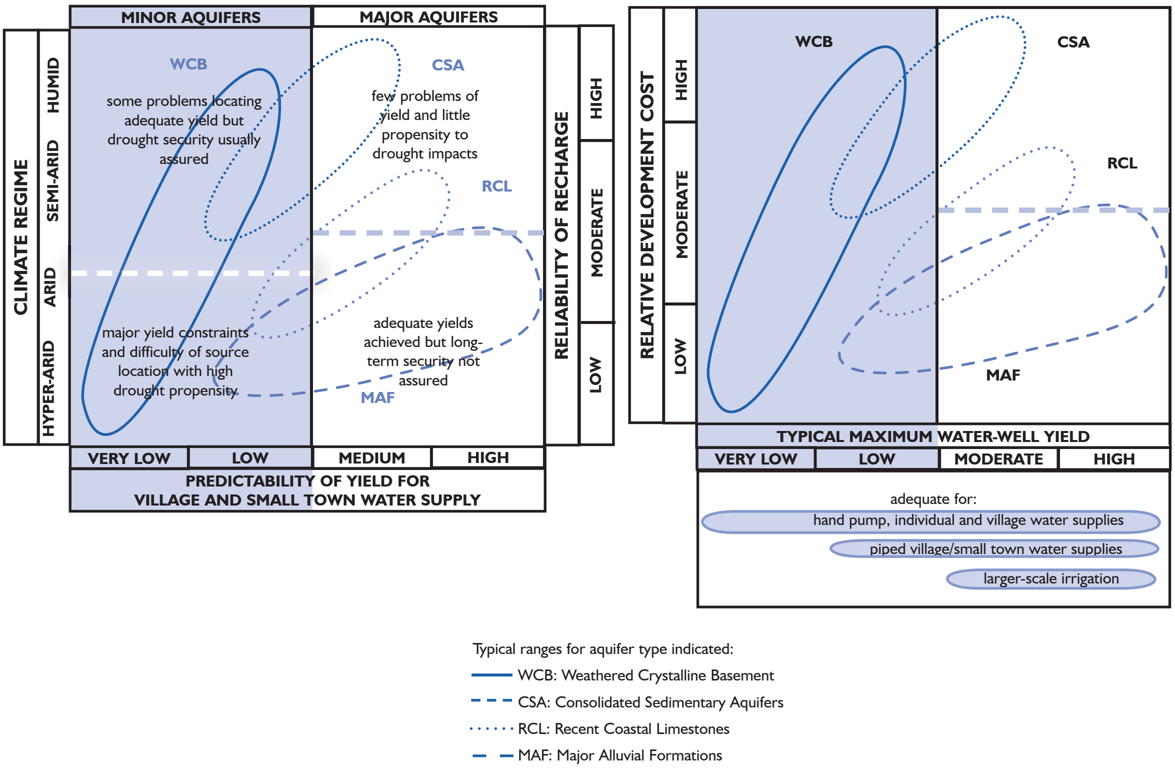
Minor aquifers have yield to water wells that is both more limited and less predictable (Figure 2.2). These aquifers include weathered basement rocks (crystalline, metamorphic and metasediments) and other local aquifers (notably thin Quaternary deposits and older consolidated sedimentary or volcanic rocks). Where situated along rivers or streams they sometimes also allow the development of supplies through bankside infiltration.

Where villages and small towns are situated over major aquifers containing naturally high-quality groundwater, water supply development does not normally encounter significant constraints in terms of access to, and sustainability of, groundwater resources, unless the same aquifer is intensively developed for agricultural irrigation. The principal issues to be confronted are mainly restricted to water well operation and maintenance, which can nonetheless seriously prejudice the reliability and sustainability of groundwater sources.

In territory underlain by only minor aquifers the availability of a groundwater resource of adequate quantity and acceptable quality is the principal concern, although issues of supply reliability and resource sustainability can also arise. Such aquifers usually offer the only feasible prospect for development of low-cost, drought-reliable, acceptable-quality, rural water supplies over extremely large land areas, especially in Sub-Saharan Africa but also in parts of Asia and Latin America.

Give an example on how you are dealing with low yielding aquifers in your community?

Figure 2.2: Variation of water well yield predictability and drought security with aquifer type and climatic regime (GW-Mate Briefing note 13)



3. Groundwater flow

Groundwater is in constant motion, although the rate at which it moves is generally very much slower than surface flow.

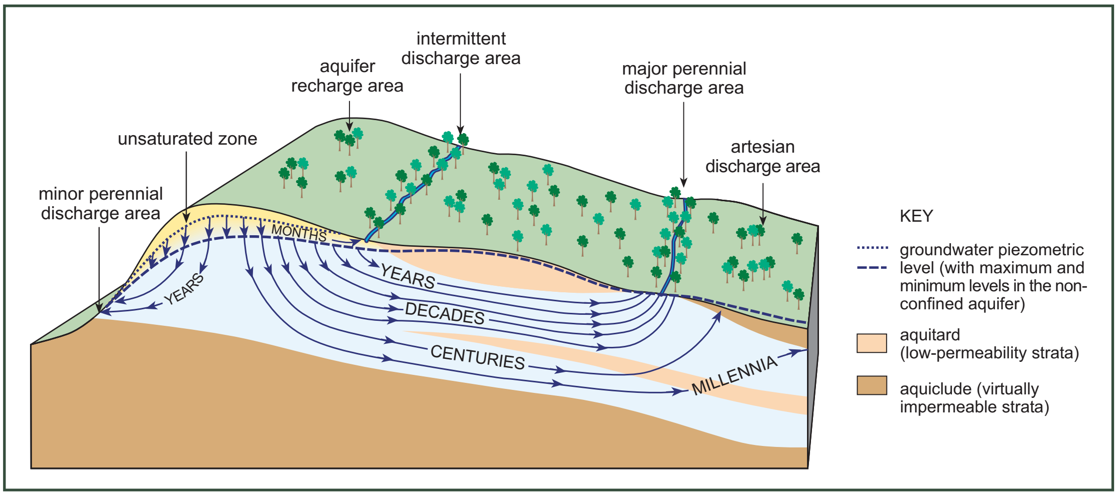
How does groundwater flow?

The vast storage of many groundwater systems (much larger than that of the biggest man-made reservoirs) is their most distinctive characteristic. In consequence most groundwater is in continuous slow movement (Figure 2.3) from areas of natural aquifer recharge (from rainfall excess to plant requirements) to areas of aquifer discharge (as springs and seepages to watercourses, wetlands and coastal zones). The flow of groundwater through an aquifer is governed by Darcy's Law (Box. 2.2)

Where aquifers dip beneath much less permeable strata, their groundwater becomes confined (to varying degrees) by overlying layers. This results in a corresponding degree of isolation from the immediately overlying land surface, but not from the groundwater system as a whole. Drawdown induced by pumping from the confined section of an aquifer is often rapidly propagated to the unconfined section. In various hydrogeological settings, shallow unconfined and deep confined aquifer layers can be superimposed (Figure 2.3) with leakage downwards and upwards between layers according to local conditions.

Box 2.2: Darcy law
Darcy's Law expresses the rate at which groundwater moves through the saturated zone, which depends on the permeability of the rock and the hydraulic gradient.

Figure 2.3: Typical groundwater flow regime and residence times in semiarid regions (after Foster and Hirata, 1988)



Aquifer storage transforms highly variable natural recharge regimes into more stable natural discharge regimes. It also results in groundwater residence times that are usually counted in decades or centuries (Figure 2.3) and sometimes even in millennia, with large volumes of so-called 'fossil groundwater' (a relic of past episodes of different climate) still being held in storage. In Box 2.3 some impacts of residence time in terms of reliability and water chemical load are exposed.

Box 2.3: Groundwater residence time impacts

- Groundwater is a reliable source in periods of drought, or of scarcity.
- Aquifers store vast volumes of groundwater available in long term period.
- There are interactions with geological materials giving groundwater a specific chemical content.
- In unconfined aquifers, usually in shallow aquifers, time residence is shorter which may result in low chemical content.
- In confined aquifers time residence is usually long, resulting in more chemical components in groundwater.

Why recharge estimation matters.

Contemporary aquifer recharge rates are a fundamental consideration in the sustainability of groundwater resource development. Furthermore, understanding aquifer recharge mechanisms and their linkages with land-use is essential for integrated water resources management.

The quantification of natural recharge (Figure 2.4), however, is subject to significant methodological difficulties, data deficiencies and resultant uncertainties because of:

- Wide spatial and temporal variability of rainfall and runoff events, and;
- Widespread lateral variation in soil profiles and hydrogeological conditions.

Nevertheless, for most practical purposes, it is sufficient to make approximate estimates (Figure 2.4), and refine these subsequently through monitoring and analysis of aquifer response to abstraction over the medium term.

A number of generic observations can be made on aquifer recharge processes:

- Areas of increasing aridity will have a much lower rate and frequency of recharge to the water table;
- Indirect recharge from surface runoff and incidental artificial recharge arising from human activity is generally becoming progressively more significant than direct rainfall recharge.

Recharge rates vary with:

- River flow diversion or control;
- Modifications to surface water irrigation;

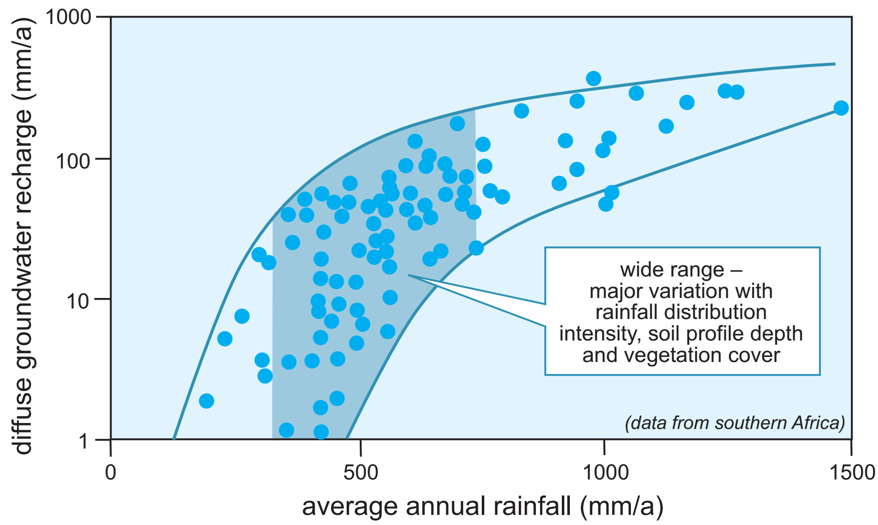
- Changes in natural vegetation or crop type in recharge areas;
- Leakage from urban water-supply networks and in-situ wastewater percolation;
- Lowering of water table…etc.

In fractured aquifers, much more rapid preferential flow to the water table may occur, especially after heavy rainfall. This component of flow can carry pollutants from the ground surface much more quickly, allowing little or no time for attenuation, and such aquifers can be highly vulnerable to pollution. In arid and semi-arid areas groundwater recharge is low in most cases. Its estimation by classical methods is problematic; isotope techniques are likely more efficient.

Give other examples of recharge rate affected by human activities.

Groundwater may be discharging to springs, wetland habitats or to surface water bodies i.e. streams, lakes, sea… etc. Groundwater is a major contributor to flow in many streams and rivers and has a strong influence on river and wetland habitats for plants and animals. It may also gain water from surface water bodies, so the interaction with these bodies is a critical issue in groundwater management. Diagnosing the relationship between surface water and underlying aquifer is an important component of groundwater system characterization.

Figure 2.4: Recharge rate estimation versus annual rainfall (pers comm. A. Tuinhof)



Is there a need to know discharge?

Water is constantly added to the system by recharge from precipitation, and water is constantly leaving the system as discharge to surface water and as evapotranspiration. Over relatively short time scales (days to months) the inflows and outflows may fluctuate significantly, but over longer time scales (years to decades) the groundwater system should be in equilibrium. This means that, averaged over a longer period of time, the volume of water entering (recharging) the system should be approximately equal to the volume leaving (discharging from) the system.

It is important to distinguish between:

- Streams and rivers on which an aquifer is dependent as a significant source of its overall recharge;
- Rivers that in turn depend significantly on aquifer discharge to sustain their dry-weather flow.

It should be noted that in some cases rivers may fluctuate seasonally between the two conditions depicted.

Groundwater pumping for various uses will affect the inputs and outputs to this system. The groundwater system will gradually adjust to a new equilibrium with changed groundwater levels (or piezometric surfaces) and different discharges at internal and external boundaries. Provided these changes are relatively small, their impacts on the environment and on established groundwater uses are generally acceptable. However, if the changes are so large that the groundwater levels and flow characteristics are substantially altered from the natural situation, the consequences may be unacceptable. The sustainability of groundwater resources requires better understanding of the relationship and significance of ground water quantity and quality to the maintenance of surface water bodies and wildlife habitats.

Why a water balance is needed.

Each groundwater system is unique in that the source and amount of water flowing through the system is dependent upon external factors such as rate of precipitation, location of streams and other surface water bodies, and rate of evapotranspiration. The one common factor for all groundwater systems, however, is that the total amount of water entering, leaving, and being stored in the system is in balance. An accounting of all the inflows, outflows, and changes in storage is called a water balance.

Groundwater withdrawals (in its broad meaning) change the natural flow patterns, and these changes must be accounted for in the calculation of the water balance. Because any water that is used must come from somewhere, human activities affect the amount and rate of movement of water in the system, entering the system, and leaving the system. For sustainable groundwater management, the water balance need to be established for a given unit system (hydrologic/river basin, groundwater basin or aquifer unit) over a given period of time. Where possible, the water balance should be undertaken for the aquifer system itself as a single hydrological unit, bearing in mind that it is an integral part of the whole hydrological / groundwater basin.

If the equilibrium is disturbed by increased groundwater pumping, the system gradually adjusts to a new equilibrium, requiring either:

- Increased inflows (e.g. by artificial recharge);
- Reduced outflows in parts of the system;
- Or a combination of the two.

New flow equilibrium is also likely to be accompanied by changes in groundwater levels/pressures in at least parts of the system. Understanding water balance and how it changes in response to human activities is an important aspect of groundwater system characterization.

A water balance provides a means of testing, confirming or refining our hydrological understanding of the system. However, it cannot provide definitive determination and prediction of the implications of groundwater abstraction impacts. The modelling approach may be a useful tool to refine our understanding of the system.

4. Naturally occurring groundwater quality problems

What are the natural water quality hazards?

Groundwater becomes mineralised due to rock-water interactions resulting in the dissolution of certain minerals and chemical elements which remain in solution in the groundwater. The degree of dissolution depends on the length of time that the rock/water is in contact, the length of the flow-path through the rock, the solubility of the rock materials and the amount of dilution by fresh recharge water. All groundwater is to a lesser or greater degree mineralised and in certain circumstances and environments some of these naturally occurring solutes may be toxic. Certain naturally occurring elements (As, F, Mn) present known problems in groundwater. Other elements (notably Ni, U and Al) are of increasing concern.

It is important for management purposes to differentiate human impacts from naturally-occurring problems.

It remains true that by far the greatest water quality problem in the developing world is pathogenic waterborne diseases (faecal origin). Nevertheless problems do arise from natural occurrence of elevated concentrations of certain trace elements in some groundwater supplies.

The origin and occurrence of these natural quality hazards.

Reactions of rainwater in the soil/rock profile during infiltration and percolation provide groundwater with its essential mineral composition. Nine major chemical constituents (Na, Ca, Mg, K, HCO_3, Cl, SO_4, NO_3, Si) make up 99% of the solute content of natural groundwaters. Groundwater in the recharge areas of humid regions is likely to be low in overall mineralization, compared to that in arid or semi-arid regions where the combination of evaporative concentration and slower groundwater movement can produce much higher concentrations.

Some of the common toxic naturally occurring inorganic elements are listed below (Table 2.1):

- Arsenic (As) is the trace element currently giving greatest concern in groundwater, being both toxic and carcinogenic at low concentration;
- Fluoride (F) is an element that is sometimes deficient, but in groundwater supply provision, excessive concentrations can be a problem, especially in arid climates and in volcanic and granitic rocks;
- Manganese (Mn) in soluble aspect occurs widely where reducing groundwater conditions arise, and gives rise to unacceptable groundwater taste;
- Various other trace elements (including notably Ni, U and Al) are listed by WHO as potentially hazardous in drinking water.

The strategy to minimize negative impacts

If excessive toxic trace elements are discovered in a potable groundwater supply, then an emergency plan should be implemented and a longer-term strategy identified (Table 2.2).

Table 2.1: Summary of main characteristics of principal trace elements sometimes causing a health hazard in groundwater (GW-Mate Briefing note 14)

TRACE ELEMENT	WHO DW GUIDELINE	HEALTH SIGNIFICANCE & USE RESTRICTION	HYDROCHEMICAL CONTROLS ON OCCURRENCE	WATER TREATMENT STATUS
Arsenic (As)	10 µg/l	toxic/carcinogenic hazard, especially since inorganic form (arsenite or arsenate) usually present; WHO guideline value thus recently reduced from 50 µg/l	complex—release from bonding on iron oxides under unusual (highly anoxic) hydrogeochemical conditions or during oxidation of sulfide minerals under acidic hydrochemical conditions	oxidation and sedimentation (not requiring chemical additives) tend to suffer from unreliability, but those which include coagulation or co-precipitation or adsorption are more promising Fluoride
Fluoride (F)	1500 µg/l (1.5 mg/l)	essential element but desirable range narrow—at below 500 µg/l dental caries can result while above 2000 and 5000 µg/l severe dental and skeletal fluorosis can occur	dissolution of fluoride-bearing minerals from granitic or volcanic formations under some hydrochemical/ hydrothermal conditions, facilitated by slow circulation	precipitation with gypsum or lime/alum mix and filtration or use of ion-exchange resin (activated carbon, alumina)
Manganese (Mn)	(100) µg/l 500 µg/l	essential element but excessive levels can affect neurological functions; also causes staining of laundry/utensils and imparts metallic taste at lower levels hence dual WHO guideline	abundant solid element in soils/rocks; under aerobic conditions the highly-insoluble form is stable but becomes soluble in increasingly acidic and/ or anaerobic conditions	precipitation by aeration and filtration usually with prior settlement, but less operational difficulty than that normally encountered for soluble iron

Table 2.2: Key issues in the definition of an integrated strategy for mitigation of a naturally-occurring trace element problem in groundwater (GW-Mate Briefing note 14)

ACTION	ISSUES TO BE RESOLVED
SHORT TERM	
Evaluation of Problem	● appropriate scale (local/provincial/national) for groundwater quality survey ● selection of appropriate analytical technique(s) (field kit/lab method) ● government initiative versus private responsibility ● availability of specialist advice for hydrogeochemical interpretation ● assessment of other potential groundwater quality problems
Water Supply Management	● advice on well use (community information/well closure or labelling) ● practical and social considerations on well switching ● prioritization of field analytical screening (to confirm safe wells) ● appropriate screening policy (universal or selective/temporal frequency)
Public Health Programme	● patient identification (active program or via medical consultation) ● establishing relationship between health problem and water source(s) ● diagnosing incipient symptoms ● immediate patient treatment (organization of bottled water provision)
LONG TERM	
Water Treatment Option	● cost at scale of application (town/village/household) and effectiveness/sustainability at scale of operation
Alternative Groundwater Supply	● usually involving (a) water wells with modified (often deeper) intakes or (b)-reticulation from local high-yielding, acceptable quality sources, both of which must be based upon systematic hydrogeological investigation and implemented with appropriate well construction standards
Alternative Surface Water Supply	● sustainability in terms of drought reliability and quality variability ● evaluation of risks associated with treatment plant failure

The emergency plan is likely to comprise the following elements:

- Hydro-geochemical evaluation of the aquifer at an appropriate scale;
- Community guidance on use restrictions and safe locations of water wells;
- Community health program to look for symptoms related to drinking water.

5. Information needed for groundwater management

Groundwater management has to be based on a good understanding of the groundwater characteristics at the scale of the total groundwater system (or river basin if necessary). Depending on the specific situation, groundwater systems may be of relatively small, localised scale (a few hectares or square kilometres) or of regional scale (up to ten or hundred thousands of square kilometres). This understanding requires substantial amounts of data from groundwater investigations and monitoring, interpretation by hydrogeologists, and generally also some groundwater flow modelling.

The characterization of a groundwater system, as a basis for proper groundwater management, requires knowledge of:

- The extent (boundaries) of the aquifer system;
- The aquifer properties;
- The sources of recharge to the system;
- The discharges from the system (incl. extractions from bores);
- Changes of these characteristics with time.

The information on the system characteristics comes from:

- Hydrogeological investigations;
- Analysis of pump test data;
- Data on surface water hydrology (rainfall, evaporation, stream flow, water levels in lakes etc);
- Records of groundwater levels in boreholes, and
- Records of groundwater extractions.

Some of these require expensive investigations. Decisions therefore have to be made on the importance (economic, social, threatened) of the aquifer to justify the appropriate depth of investigation necessary.

Where are the groundwater resources located?

The "starting point" for groundwater management is to map the location of available groundwater. An aquifer is identified by a subsurface field area that is finite and continuous representing a hydrogeological unit. It is characterized by its geometric limits (volume) and the nature of its hydrogeological boundaries.

The data are summarized through different types of map:

- Hydrogeological extent of aquifer;
- Water table depth or the upper surface of the saturated portion of an aquifer;
- Bottom limit of hydrogeological units, and;
- Aquifer thickness.

How vulnerable is a water-table aquifer?

The natural intrinsic characteristics of the geological layers overlying a water-table aquifer determine the groundwater vulnerability to anthropogenic pollution. For groundwater protection purposes, vulnerability maps are needed to assess the tendency or likelihood of contaminants to reach a specified position in the ground water system after being introduced at a location above the uppermost aquifer. Ground water vulnerability maps were developed to determine the potential impact of anthropogenic influences on groundwater quality.

What is the sustainable yield of the aquifer?

The main objective of groundwater management through IWRM is to protect the resources from quality degradation, and to ensure that their use for a range of beneficial purposes is sustainable. In a broad sense, sustainable use of groundwater resources can be defined as that level of use that does not cause unacceptable long-term consequences.

In order to meet the growing water use, it is the responsibility of managers to assess the ability of the groundwater resource to support current and expected demand due to population growth and development. The groundwater resources assessment should be carried out with respect to key planning constraints that vary temporally and spatially as well. Depending on the particular situation, the limiting conditions may be in terms of:

- Depletion of groundwater storage;
- Reduction of groundwater levels (or pressures);
- Reduction in groundwater discharge (e.g. springs, baseflow to streams, inflows to wetlands);
- Deterioration of water quality;
- Land subsidence;
- Other environmental impacts;
- Socio-economic impacts, and political constraints (national policy on development and water).

What is the suitable format to present groundwater information to decision-makers?

Groundwater resources assessment needs to be associated with three terms that are used in efforts to quantify sustainable groundwater development:

- **Safe yield** taken as the maximum groundwater abstraction for which the consequences are considered acceptable, e.g. with respect to specific effects of pumping, such as water-level declines, reduced stream flow, and degradation of water quality;
- **"Groundwater mining"** typically refers to a prolonged and progressive decrease in the amount of water stored in a groundwater system, as may occur, for example, in aquifers with "non-renewable" groundwater resources in arid and semiarid regions;
- **"Overexploitation"** refers to withdrawals of groundwater from an aquifer at rates considered to be excessive with regard to overall negative impacts of groundwater exploitation.

Where are recharge areas located?

Groundwater recharge refers to the water that infiltrates the ground and reaches the water table regardless of the underlying geology. It should be assessed as it represents the input flow to the aquifer system, and is an essential component of the groundwater balance. Furthermore it gives a qualitative indicator of renewability of groundwater resources.

A critical point is determining the areas where an aquifer system is replenished. Indeed these areas should be submitted to specific rules with regards to land-use and access for groundwater protection and abstraction sustainability.

Factors like rainfall variability, climatic changes, land-use and land-use changes are key components in the recharge rate. It is among best practices in groundwater management to check potential opportunities to artificially recharge the groundwater supply in order to renew the resource and provide cost-effective water storage for future use.

Recharge potential maps are useful tools that provide information to decision-makers.

Where does groundwater /surface water interaction occur?

Surface water and groundwater are, in many cases, hydraulically connected (what happens to one affects the other). Yet this crucial fact has been all too often ignored in water management considerations and policies. Usually an aquifer underlying a river system ensures its base flow; this critical parameter is typically not adequately assessed. Groundwater can be a major contributor to streams and rivers, likewise surface water can be a major contributor to groundwater. For instance the eventual reduction in surface water supply as a result of groundwater development complicates water allocation and the administration of water rights. Therefore the relationship and significance of groundwater quantity and quality to the maintenance of healthy rivers, lakes, streams, wildlife habitats, and fisheries are critical issues for a groundwater system management.

Useful management information may be provided through maps of high risk areas where extensive groundwater exploitation should not be considered without additional studies to ascertain the potential impact on streams, wetlands, and other ecosystem habitats in the region.

What are short and long-term changes in groundwater?

For water management purposes it is critical to have trends of changes related to groundwater resources. There is need to get knowledge about (past, current, and expected) changes of aquifer system characteristics such as recharge, storage, flow direction, and quality, as impacted by land use, land-use changes, climatic variability, and water use.

Comprehensive, consistent, and defensible data should be provided from monitoring records (Module 9) to better understand and characterize existing conditions, identify existing and potential problems, establish priorities, and develop viable water policies and strategies.

Are there natural quality concerns?

The water stored in aquifers is of varying quality, depending on its origin, location and exposure to potential sources of contamination. Such contamination is not always as a result of human activities, but may originate from natural causes. It is of great importance for groundwater supply provision to locate areas and levels (vertical) of naturally-occurring hazards. The first step should be to identify geological settings that are potentially bearing affected groundwater.

Information suitable for groundwater managers should be provided in terms of maps presenting spatial and vertical occurrence of groundwater concentration for harmful elements.

6. Summary: What do we need to know for proper groundwater management?

The key aspects of the characterization of aquifer systems that managers need to appreciate for groundwater management are summarized below:

Storage: The relationship between the type of aquifer and potential volume of water in storage is a critical and key aspect related to the nature of the aquifer system, and aquifers have been characterized in the module with regards to their storage function. This storage component is also necessarily related to the scale of the groundwater flow system. Obviously where flow systems have hydraulic interconnection over very large areas, management needs to account for abstractions/aquifer usage over the entire aquifer area; by contrast local groundwater systems with minor flow systems may not warrant the cost of management, since the impact will be limited and to some extent self regulating.

Relationship between aquifer type, climate and water supply options: The module further discusses what water supply possibilities exist for different aquifers under different climatic conditions and what are the risks and costs of developing groundwater under these variable conditions. The sustainability of groundwater developments is a function of the type of aquifer system, the climate and recharge rate and the type and scale of groundwater use.

Groundwater Flow: The impact of groundwater flow, based on the type and extent of the hydrogeologic unit is discussed together with the management implications. The moderating effect of groundwater flow as compared to surface flow is highlighted, due to the long duration of groundwater flows, thus giving rise to a water resource that is more drought resistant than surface water. The hydro-chemical impact of the long groundwater residence times is explained, and the implications in terms of natural water quality are discussed.

Groundwater Recharge and Groundwater Discharge: The importance and complexity of aquifer recharge processes are discussed and the difficulty of assessing groundwater recharge is presented as an important management issue. The identification of recharge areas and the importance of protecting such areas are stressed. Factors that affect groundwater recharge are discussed as are strategies to enhance and protect recharge. Groundwater discharge is discussed and its linkage with groundwater dependant ecosystems. The relationship between abstraction, length of flow path and groundwater discharge are key factors for management of wetlands, springs and other groundwater discharge zones.

The Water Balance: Water balance calculations are presented as a vital management tool for aquifer management and in particular for conjunctive groundwater/surface water management. All the natural inflows and outflows as well as the abstractions by pumping and the anthropogenic recharge by seepage and well injection are highlighted as components of the water budget that must be quantified for effective and integrated groundwater management.

Natural Water Quality Problems: Natural groundwater quality problems are discussed and the more common problems are identified. Mitigation strategies for dealing with such natural problems are presented, including water blending and reservation of different water qualities for different uses.

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Exercise 1 - Characterisation of groundwater systems
Purpose: To appreciate the link between understanding groundwater systems and strategies for management **Duration:** 30 Minutes **Activity:** In 4 groups, participants discuss how the knowledge of specific characteristics of aquifers can improve the management of groundwater. **Report Back:** Each group presents a table with their identified aquifer characteristics and how each one improves groundwater management. **Facilitator:** Point out the characteristics which are commonly not known and stimulate further discussion based on participants experiences on how management decisions are made without the requisite information.
Exercise 2 - Integrated Water Resources Management
Purpose: To appreciate the linkage between groundwater and surface water management Duration: 60 Minutes **Activity: In 3 groups:** Discuss the interaction between groundwater and surface water and the relevance to pollution management and water allocation. Make recommendations on how groundwater and surface water should be managed together. **Report Back:** Each group presents their recommendations followed by a general discussion.
Exercise 3 - Groundwater Management
Role Play: One group of participants (the managers) take the role of various water managers: eg City water manager, National water manager and Water Minister. They ask questions of the hydrogeologists about available groundwater resources The other groups of participants (the hydrogeologists) explain the how various aquifer systems may supply the required water explaining the key benefits and risks. Different aquifer settings are allocated to each group of "hydrogeologists". **Activity:** Dialogue between the "managers" and the "hydrogeologists" is aimed at ensuring that both sides understand one another properly and that the managers get adequate information for managing the water resources.

Module 3: Integrated Groundwater Management in Practice

Learning Objectives:

- To discover the relationship between stress on the groundwater system and the investment in management;
- To appreciate the linkages between groundwater and surface water and how they may be managed together;
- To understand the role of groundwater in planning water management at the national and basin levels;
- To appreciate the importance of good groundwater management for ecosystem protection.

1. Groundwater Flow Systems Framework

Unlike surface water, groundwater occurs in underground basins of controlled structure (Module 2). The groundwater Basin physical boundaries are defined by specific geological features, patterns/structures (faults, fractures, outcropping impermeable bedrock, etc.) formed as a result of various geo-processes such as tectonic movements, metamorphic processes, volcanism, sedimentation, erosion, etc. As in surface water, a groundwater basin can consist of a number of hydraulically connected sub-basins. Multiple investigation tools are required to delineate a groundwater Basin boundary.

Ground water moves along flow paths of varying lengths in transmitting water from areas of recharge to areas of discharge. Accordingly, the so called 'flow system' term has emerged defining hydraulic boundaries for groundwater management units.

Based on the hydraulic connectivity of different parts/units of its aquifer system, a groundwater basin is generally managed within a **flow system framework** to account for downstream-upstream effects. A **groundwater flow system** is defined by a recharge zone and a discharge zone and is separated from other groundwater flow systems by groundwater divides. In recharge zones there is a component of groundwater flow that is downward. In discharge zones, the vertical groundwater flow direction is upward.

Different scales of groundwater management can be considered depending on the flow system boundaries. Groundwater flow systems can operate at one of three typical scales and can overlay each other (Figure 3.1). In local flow systems, groundwater flow paths are relatively short (say <5km), where discharge is typically in the lowland adjacent to the more elevated recharge zone. Deeper regional flow systems have much longer flow paths where the recharge and discharge zones can be separated by tens (or hundreds) of kilometres. In addition to geology, topography plays a significant role in the scale of groundwater flow systems. **Local** flow systems dominate in areas of pronounced topographic relief, whilst **regional** flow systems develop in flat-lying landscapes. As local flow systems are the shallowest and the most dynamic, they tend to have the greatest interaction with surface water features. However, in the more subdued lowland parts of catchments, discharge from **intermediate** to regional-scale flow systems can be significant.

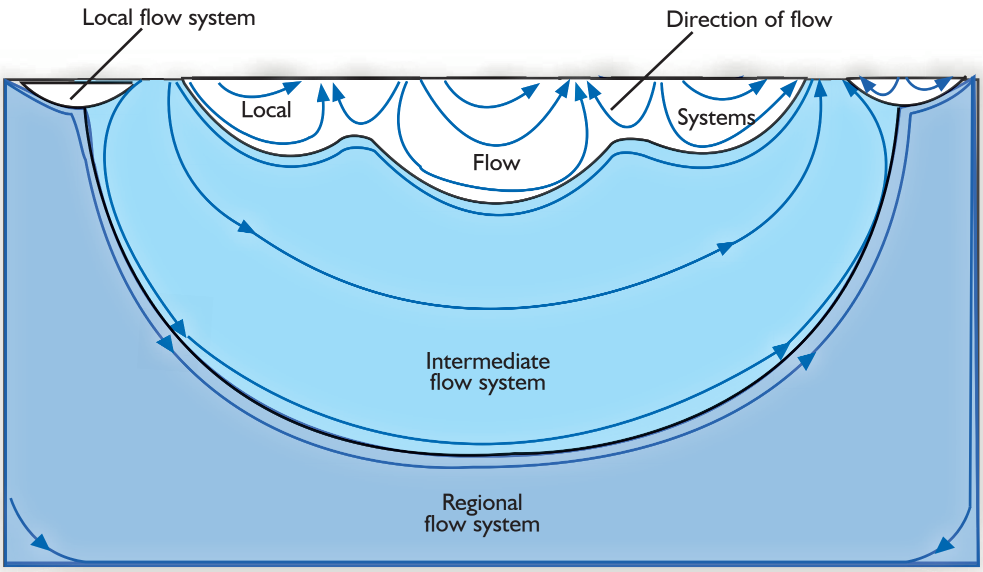
In general, water management is best done within the river basin boundaries. To that end there is a need to identify the overall hydrogeological setting in the basin because hydrogeology can change across the catchment and there can be many groundwater flow systems developed which have the potential to interact with the river, either directly or indirectly.

2. Approaches to groundwater governance and management practice

Practical approaches in groundwater management have been defined as those aiming/seeking to: (GW-Mate Briefing note 0)

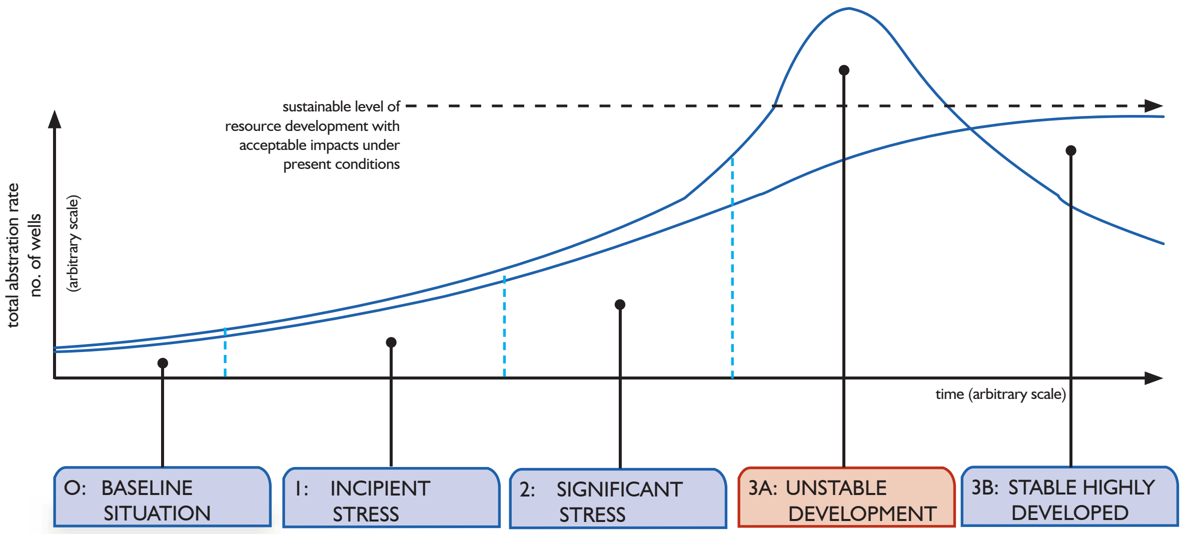
1. maintain reasonable balance between the costs and benefits of management activities and interventions, and thus

Figure 3.1: Groundwater flow systems of varying scale - local, intermediate and regional (Toth, 1963)



2. 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.
3. set possible management interventions in the context of the normal evolution of groundwater development, see figure 3.2

Figure 3.2: Stages of groundwater development in major aquifers



Levels of groundwater development can be identified, taking into account the susceptibility to degradation of the hydrogeological system involved and the legitimate interests of water users. In the situation of excessive and unsustainable abstraction (Figure 3.2: 3A—Unstable Development), which is occurring widely, the total abstraction rate (and usually the number

Table 3.1: Levels of groundwater development & required management Intervention

	Stage of development	Description	Required Management Intervention
Level 0:	Baseline Situation	Availability and accessibility of adequate quality groundwater greatly exceeds small dispersed demand	Registration of abstraction wells and captured springs, together with maps of occurrence of usable resources
Level 1:	Incipient stress	Growth of aquifer pumping, but only few local conflicts arising between neighbouring abstractors	Apply simple management tools (for example appropriate well-spacing according to aquifer properties)
Level 2:	Significant Stress	Abstraction expanding rapidly with impacts on natural regime and strong dependence of various stakeholders on resources	Regulatory framework, based on comprehensive resources assessment with critical appraisal of aquifer linkages
Level 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
Level 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 modelling and monitoring

of production water wells) will eventually fall markedly as a result of near irreversible degradation of the aquifer system itself.

Table 3.1 summarises management interventions necessary for the five stages of resource development shown in Fig 3.2.

Comprehensive groundwater management may be premature for countries whose priority concern is building minimal water supply infrastructure from groundwater to meet basic human needs. Practical approaches are thus recommended based on different situations.

Groundwater management interventions described in column 4 (table 3.1) follow the evolution of groundwater development. While accepted as a practical approach for implementing integrated groundwater management, it should not encourage purely reactive management approach. Preventive approaches are likely to be more cost-effective.

3. Groundwater management functions

Groundwater management interventions can be grouped into three categories:
1. Management functions
2. Technical inputs
3. Institutional provisions

Table 3.2 illustrates the application of management systems according to the level of development and hydraulic stress of the aquifer.

Table 3.2: Levels of groundwater management functions and interventions necessary for given stage of resource development

Groundwater management	Level of development of corresponding function (according to hydraulic stress stage)			
	Base situation	**Some stress**	**Significant Stress**	**Unstable development**
Management Function				
Resource allocation	Limited allocation constraints	Competition between users	Priorities defined for extractive use	Equitable allocation of extractive uses and in-situ value
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 points and diffuse sources of pollution; mitigation of existing contamination
Prevention of side effects	Little concern for side effects	Recognition of (short- and long-term) side effects	Preventive measures in recognition of in-situ value	Mechanisms to balance extractive uses and in-situ values
Technical Inputs				
Resource Assessment	Basic knowledge of aquifer	Conceptual model based on field data	Numerical model(s) operational with simulation of different 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 process understood	Quality integrated in allocation plans
Aquifer monitoring networks	No regular monitoring programme	Project monitoring, ad-hoc exchange of data	Monitoring routine established	Monitoring programmes used for management decisions
Institutional Provisions				
Water rights	Customary water rights	Occasional local clarification of water rights (via court cases)	Recognition that societal changes override customary water rights	Dynamic right based on management plans
Regulatory provision	Only societal 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 resources law discussed	Legal provision for organisation of groundwater users	Full legal framework for aquifer management
Stakeholders' participation	Little interaction between regulator and water users	Reactive participation and development of user organisations	Stakeholder organisations co-opted into management structure (e.g. aquifer councils)	Stakeholders and regulators 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 analysis/ instruments	Economic externalities hardly recognised (exploitation is widely subsidised)	Only symbolic charges for water abstraction	Recognition of economic value (reduction and targeting of fuel subsidies)	Economic value recognised (adequate charging and increased possibility of reallocation)

4. Incorporating Groundwater Management in IWRM Strategies

Groundwater is a component of IWRM strategies although often neglected. As explained in the Module 1, the three E's of IWRM (Economic efficiency, Environmental sustainability and social Equity) are the drivers of water sector reform, including groundwater.

IWRM strategies typically consider tools for change in different areas (Box 1.2, Module 1) to address issues/ problems in water management systems.

This section will focus on policy options, national IWRM planning process, river basin plans, transboundary aquifers, and the ecosystem dimension of integrated groundwater management.

4.1 Key Policy Options

Policy regarding groundwater management should not be separate from that of other water resources although there may be some policy elements that are specific to the groundwater context.

- An integrated approach to (ground)water management has to set goals to:
    - balance increasing resource demands with the needs of aquatic or terrestrial ecosystems and baseflow in upper river reaches as appropriate.
    - take into account two-way relationships between macro-economic policies, broader social and environmental goals, and (ground)water development, management and use.

- Consider **cross-sectoral** integration in *policy development*. This helps to enforce decisions on priorities, e.g. basic drinking water supply. Cross sectoral coordination allows representation of (ground)water interests in non-water sectors such as land-use management. Moreover, put into effect the relation between water abstraction permits and wastewater discharge controls.

- Consider the **value of water** in all its uses to support efficient, equitable and sustainable (ground)water use, as well as its relationship with surface water abstraction where appropriate.

- Careful attention should be paid to the delineation of (ground)water **management boundaries** reconciling the hydrogeological setting, political/administrative boundaries, river basin management structures/ systems, etc., and resource management issues/ needs (Module 1). **Management targets** as well as monitoring and reporting operate at catchment level. Water management units (both surface water and groundwater) tend to be at this scale, so that connectivity properties need to be aggregated to this level to be incorporated into water management plans. Similarly, water quality targets (such as end-of-valley salinity targets) also operate in the catchment context.

What if no river is connected to the groundwater flow system?

- Decentralisation, privatisation and role of government have to be adequately addressed.

- Build **stakeholder** awareness ('bottom-up') and provide an enabling legal and economic climate ('top-down') to strengthen (ground)water governance.

- Demand-side actions should be equally involved in technical strategies for (ground) water management in urban and rural settings. Box 3.1 presents typical examples of demand-management measures for irrigation & Urban Water uses:

Box 3.1. Technical strategies to conform situations of excessive and unstable groundwater exploitation

Level of Action	Demand-side Management Interventions	Supply-side Engineering Measures
Irrigated Agriculture	● Real water-savings secured in part from: - Low-pressure water distribution pipes - Promoting crop change and/or reducing irrigated area ● Agronomic water conservation	● Local water harvesting techniques ● Appropriate recharge enhancement structures (either capturing local surface runoff or sometimes with surface water transfer)
Main Urban Centres	● Real water-savings sometimes secured from - Mains leakage and/or water use reduction - Reduce luxury consumption (garden watering, car washing)	● Urban wastewater recycling and reuse (including controlled and/or incidental aquifer recharge by both in situ sanitation and mains sewerage) (Briefing Note 12)

4.2 Groundwater in National IWRM Planning

Separate groundwater management plans are only likely to be necessary for large, economically important aquifers. Even these should be brought together with surface water planning to produce a national IWRM plan and basin plans.

- The groundwater component of national IWRM plans may be developed from specific aquifer management plans as illustrated in Figure 3.3. First, all available information on national aquifers needs to be compiled, the groundwater systems classified according to their hydrogeological characteristics and management issues, and their 'hot spots' identified. This process can be refined with feedback from local aquifer level and will facilitate the assessment of groundwater management needs at national level.

- Issues such as modifying national food production policy and re-targeting well drilling or pumping subsidies obviously cannot be handled at local water management level and require decisions to be made nationally.

- At national level emphasis should also be placed upon:
  - appraisal of the legal and institutional framework
  - evaluation of available technical and institutional capacity
  - assessment of political will and impediments for moving forward
  - preparation of an 'action-oriented road map', including capacity building where appropriate.

- A national water development plan should be developed with all stakeholders as a component of the national IWRM plan and address issues as in Table 1.2, Module 1. The following activities are relevant to groundwater:
  - agronomic technical and management measures are taken to improve irrigation **use efficiency and result in real water saving**
  - municipal water supply and irrigation development consider resource sustainability as a primary issue by taking action to **protect and conserve groundwater**
  - use of **urban wastewater** as an additional resource for irrigated agriculture, while paying attention to related groundwater pollution and health risks (Module 8)
  - initiatives to **enhance rainfall recharge** are technically and economically effective, and equitable as regards benefits
  - a groundwater dimension is introduced in land-use planning, so as to direct **land-use changes in the interest of groundwater quality** (Module 8).

- The groundwater resource planning process should be dynamic and iterative, and allow for interaction/learning and monitoring/feedback between local aquifer and national levels. **This should allow simultaneous implementation of practical management measures where most required, whilst not losing sight of the bigger picture and dealing judiciously with information gaps and uncertainties.** A sound conceptual model of the groundwater flow and quality regime, and an appraisal of the impact of human activity, is indispensable for the effective management and protection of aquifers. Nevertheless, lack of complete data should not be held as an excuse for not getting on with the job, and much can be done without a comprehensive database — filling key information gaps can become in reality part of the management monitoring process.

- Whether at aquifer or national level, a groundwater management plan must be regarded as a ‘road map’ to guide the changes needed to move from fragmented to integrated management of groundwater resources and to accelerate implementation. A plan should clearly establish the goals and the path to achieve them – with milestones along the way that can be readily monitored.

4.3 Integrated Basin Planning

As the title implies, groundwater planning in a basin cannot be carried out in isolation from surface water planning or the plans for social and economic development of the basin.

- There is no simple blueprint for integrated basin plans that will fit all cases. International experience (as summarised in Table 3.3) may be useful in identifying the essential elements of a plan for the basin and it should be ensured that the plan addresses all water resources of the basin, not only surface water.
- The leadership of a river basin interdisciplinary professional team (hydrogeologists, environmental engineers, economists, sociologists and lawyers) is a pre-requisite for a balanced (ground)water resource plan which will:
  - be based on sound scientific and technological principles
  - recommend economically feasible management options
  - be environmentally sustainable, socially acceptable and institutionally implementable.
- Planning and implementation should be closely interlinked – thus the preparation of a (ground)water management plan should take place in progressive stages, starting from a first draft version that should be assessed in the light of possible institutional impediments to implementation. One or

Fig. 3.3: The groundwater management planning and implementation process

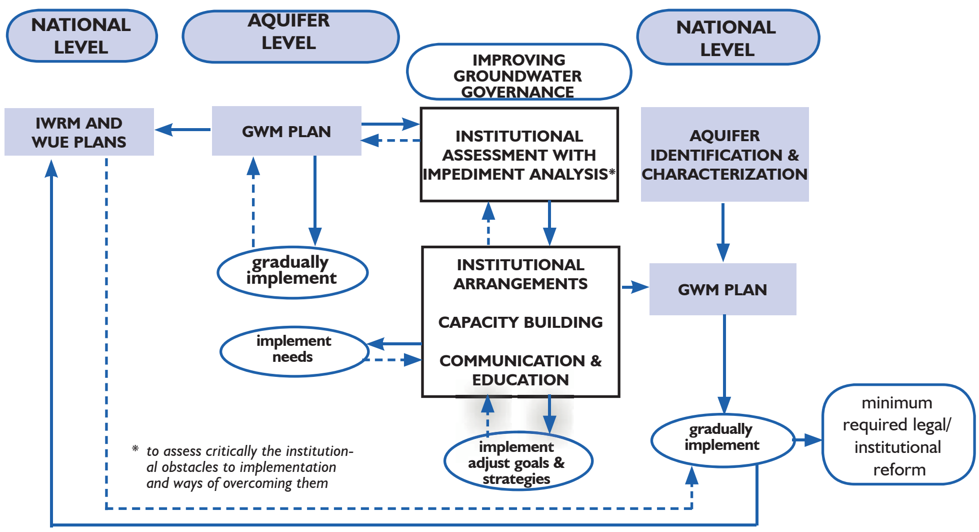


Table 3.3: Checklist for the elaboration of the Groundwater Management Plans (GW-Mate briefing note 10).

Planning Phase	Issue	Activities/Reform
SITUATION ANALYSIS	Groundwater Status & Required Services	Resource Assessment Quality Characteristics Required Services
	Current Management arrangements	Institutional Provisions Water allocation and usage Monitoring Networks Institutional Capacity
STRATEGY CHOICE	Future Management Options/ reform	Economic Analysis Definition of options
IMPLEMENTATION	Implementation Programme	User/Stakeholder participation Monitoring & review Requirements Economic/Financial Analysis Information system
EVALUATION	Assess Progress & revise plan	Water Resources Assessment Water use efficiency Conflicts Cost recovery Regulatory instruments

more of the following actions may be taken both to improve (ground)water resource governance and to prepare more realistic subsequent versions:

- enhancing institutional arrangements
- establishing capacity building programs
- setting-up public education campaigns
- improving (ground)water resource and use information
- assuring that goals are attainable and implementation strategies straightforward.

- The final version of the plan should be approved by the competent authority and should be binding on both the (ground)water resource administration and (ground) water users, without prejudice to periodic revision and updating at intervals which will be indicated by the legislation. The plan can then be gradually implemented, and the lessons drawn from implementation will lead to better subsequent plans.

- From the outset, an IWRM approach is best taken by focusing on real problems and addressing them in a direct manner. Table 3.4 gives examples of some specific groundwater management problems but of course there will also be surface water management problems and where possible the solutions should be integrated. In groundwater planning and management, different stakeholders can take the lead from specific 'entry points' (even before the plan is completed) and according to the issue at stake. In this respect, the identification of easily achieved initial targets to secure clear short-term benefits ('harvesting the low-hanging fruit') can help bolster political support for implementation.

- At aquifer level, the key actors in groundwater resource planning are the groundwater users themselves and other local stakeholders, since they should best know the issues at stake. But it has to be recognized that social participation alone will seldom lead to sustainable groundwater management, and government will normally be needed to facilitate a complementary 'bottom-up' and 'top-down' approach.

reserves — it would be advisable to develop an international groundwater resource plan which includes a 'depletion exit strategy' (GW-Mate Briefing Note 11). But the effects of much smaller scale groundwater development (for example in rural subsistence and small-town water supply) will only be felt very locally, so that there would be no need for a plan of the entire international aquifer system.

Table 3.4: Entry Points for main actors in groundwater management planning and implementation.

KEY GROUNDWATER ISSUES
Rural Development Economical access – need for sound hydrogeological information to ensure groundwater sources can be constructed at tolerable cost
Operational supply reliability – need for solid/ programmatic standards, sound design, O&M, adequate financial arrangements
Aquifer depletion – control groundwater abstraction avoiding well interference, affecting downstream flows, freshwater wetlands or brackish lagoons, saline water intrusion or land subsidence
Diffuse groundwater pollution – aquifer pollution control and groundwater source protection through mainly land use planning and control
Urban Development Inadequately controlled groundwater abstraction within city – reserve deeper groundwater for sensitive uses and encourage use of shallow polluted groundwater for non-sensitive uses
Inadequately controlled groundwater abstraction around city – reserve good quality groundwater for potable water-supply and substitute treated wastewater or shallow polluted groundwater for irrigation
Excessive subsurface contaminant load – define source protection zone for priority control of contaminant load to municipal well-fields and plan wastewater handling taking account of groundwater interests
Excess urban infiltration – reduce infiltration by control of main leakage, on-site sanitation seepage through main sewer installation and increase abstraction of shallow polluted groundwater for non-sensitive uses

5. Approaches for Transboundary aquifers

- There are only limited examples to date of international cooperation in the management of shared groundwater resources, although it is increasingly recognized that such cooperation is beneficial and should be institutionalized if conflicts are to be avoided. Efforts to develop international legal rules on the subject are only recent, and generally do not extend to groundwater planning as such.
- In the case of international groundwater resources it is not possible to adopt a uniform approach. Under given circumstances - for instance mining of non-renewable aquifer
- Different institutional mechanisms may be selected to plan and manage international groundwater resources, depending on the existing level of cooperation among the states concerned (Table 3.5) and on the type and urgency of issues to be addressed. It should be noted that an institutional mechanism may evolve from a simple agreement for handling and exchanging data to an international river basin or aquifer commission that makes autonomous decisions in the interest of the member states. This latter mechanism would be expected to have strong synergy with national governments.

Table 3.5: Levels and evolution of International institutional mechanisms for groundwater resources planning and management

LEVEL OF COOPERATION	INSTITUTIONAL MECHANISMS		
	TYPE	FUNCTION	INVOLVEMENT IN PLANNING
Incipient	Data exchange network of national agencies coordinated by neutral institution	Administration of aquifer database and models	Contributes the necessary information, but planning is still a national function
Moderate	Technical committee with secretariat	Administration of aquifer database and models; preparation of possible strategies, plans and measures	Recommends plan but decision on approval made by national governments
High	Joint commission with secretariat	Administration of aquifer database and models; adoption of strategies, plans and measures, and approval of resource development measures	Autonomous decisions on plans are made by commission itself and binding on member states; strong synergy between national government institutions

6. GW and environment

Types of Groundwater Dependant Ecosystems

One way of classifying groundwater-related ecosystems is by their geomorphological setting (aquatic, terrestrial, coastal etc.) and associated groundwater flow mechanism (deep or shallow). On this basis a number of different classes are recognized (Figure 3.4 A-E illustrates the more important of these):

Additionally upland, surface-water fed, marshes widely form natural groundwater recharge areas, and must also be included, since their integrity can be threatened by excessive groundwater extraction.

Give an example of degraded groundwater-dependent ecosystem in your country.

There will often be some uncertainty as to whether these ecosystems are strictly 'groundwater dependent' or just 'groundwater-using' (that is, capable of surviving without access to the water-table or discharging groundwater).

Groundwater-related ecosystems are either directly (through increased groundwater extraction) or indirectly (through increased groundwater contaminant load) impacted by further agricultural and urban development. Thus an important issue in relation to the implementation of groundwater management is to protect groundwater-dependent ecosystems.

Groundwater and environmental management

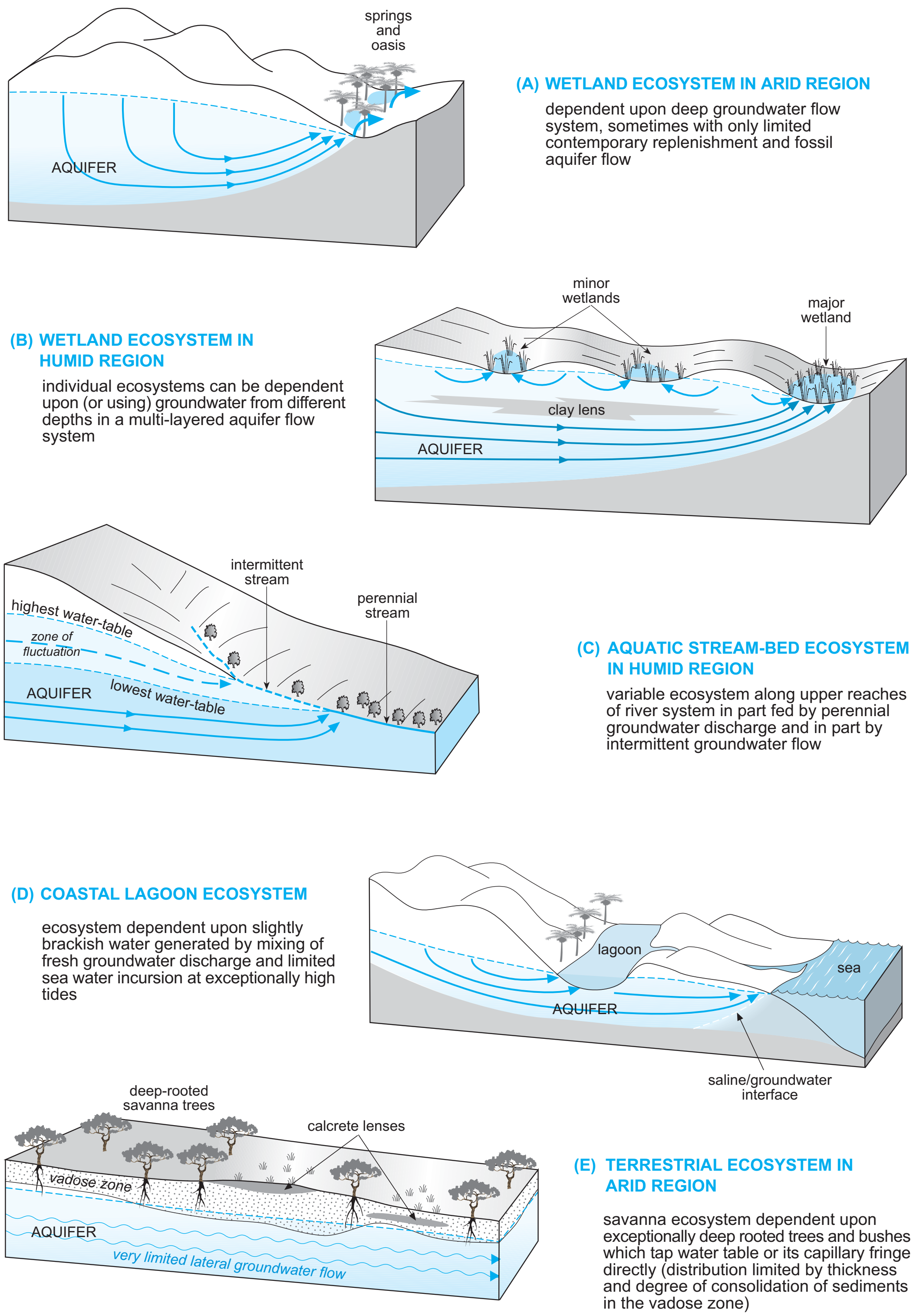
It is of central importance for groundwater management to take into account groundwater ecosystem interaction.

What can be done to protect groundwater-dependent ecosystems?

Options to be considered in groundwater management are similar to surface water management:

- Controlling abstraction/allocation: by including criteria to maintain groundwater levels and conserve groundwater quality to meet the requirements of the ecosystem receptor. A debate may arise over the balance between improving rural livelihoods and sustaining ecosystem health.

Fig. 3.4: Main classes of groundwater-related ecosystems and their associated groundwater flow regimes (GW-Mate Briefing note 15)



- Introduce ‘protection zones’ in catchments: Protect wetland ecosystems by assuring the quality of shallow groundwater flow to wetlands and reducing the degree of groundwater level interference
- Artificial groundwater recharge: to supplement groundwater flows and improve groundwater quality over limited areas in the interest of wetland conservation, or even pumped compensation flows from aquifers to wetlands when groundwater levels fall below some critical level.

7. Summary

Key conclusions from this module are:

- Both hydrogeologic and socio-economic conditions tend to be somewhat location-specific.
- Where physically connected, surface water (including overland flows) and groundwater should be managed as one resource.
- Allocation regimes should assume connectivity between surface water (including overland flows) and groundwater unless proven otherwise.
- Progress toward more integrated and sustainable approaches to water often starts with actions to address concrete and pressing water challenges. Indeed, such actions, while originating in the need to address a specific challenge, can prove useful to address future water and development challenges in a more integrated way.
- Issues that drive change in water management actions are highly linked to the way (rural/urban) water development is managed. Hence, managing water development for different purposes is a key entry point to practise groundwater resources management.
- Involvement of the main stakeholders is an important principle for the development of an effective and sustainable approach to management
- The need for capacity building, both among water resource authorities and water users, is a key driver to implementing management measures.

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Exercise

Role Play: 90 Minutes

Background: You are river basin organisation staff charged with the development of the river basin plan. The river basin is well developed with commercial agriculture and two urban centres with industry. There are scattered subsistence communities. The river is seasonal and many people use groundwater but the availability of the groundwater is not well understood. The RBO is dependent on income from sale of water resources for its operations and therefore has limited budget.

Task: Identify three people who will be the CEO and two deputies. They will be responsible to lead the group and ensure that the task is completed. The remainder of the participants are support staff (engineers, hydrogeologists, monitoring staff, allocation, financial, pollution control and planners). At the end of the allocated time you have to

a) present the draft contents page of the plan that meets the ideals of an IWRM approach and clearly integrates the groundwater and the surface water resources, and

b) describe the process of how you are going to collect the information to produce the plan for the basin.

Module 4: Groundwater Legislation and Regulation.

Learning Objectives:

- To appreciate the need for legislation of groundwater and its integration with surface water legislation;
- To understand the key components of water legislation; and
- To consider the institutional arrangements for groundwater management

1. Why legislation of groundwater?

Among other issues, groundwater legislation is required to regulate groundwater development and to constrain activities that might compromise groundwater availability and quality; and to address increasing competition and conflict between groundwater users, and increasing threat of groundwater pollution.

In some countries there are many different legal instruments that govern water while in others there may be no legislation at all. Reforms to address the need for more sustainable use of our limited water resources have done much to address many of the problem issues of water governance. However, often groundwater has not been well addressed in water legislation or may still suffer from problems of dispersed (sometimes conflicting) legislation provisions.
It is increasingly recognised that groundwater and surface water impact on each other and greater integration of legal provisions on water resources is necessary.

Integrated legislation provides a legal basis for the effective and sustainable management of groundwater and surface water through:
- guidelines for, and limitations to, the exercise of public powers
- provision for the quantification, planning, allocation and conservation of (ground)water resources, including water abstraction and use rights
- a system of wastewater discharge licenses, helping to protect (ground)water against pollution
- definition of the rights and duties of (ground) water users
- protection of use rights, of the rights of third parties and of the environment
- requirements for the registration and qualification of well drillers
- possible administrative intervention in critical situations (aquifer depletion, drought or pollution)
- provision for cooperative interaction between (ground)water administrators and (ground)water users.

2. Basic Legal Concepts

It is important in the present context to note that the concept of 'legislation' differs from that of 'law' (Table 4.1). Legislation is written law,

Table 4.1: Summary of basic legal concepts and scope of water legislation. (GW-Mate, Briefing note 4)

Customary (Unwritten) Law	Custom is considered to be established by: ● consistent repetition of a given conduct by many members of the community ● conviction of the community that such conduct corresponds to a 'legal rule
Legislation (Written Law)	Legislation, taking account of custom as accepted social behaviour, encompasses: ● the fundamental law or constitution of a country ● laws enacted by the legislative body (parliament, national assembly) ● subsidiary legislation (decrees or instruments adopted by the government executive) laws enacted by the legislative body may not repeal constitutional provisions, and in turn may not be repealed or contradicted by subsidiary legislation
Water Legislation	Aims to regulate the relationship between persons (physical and legal) and between the people and the state administration on water resources; it includes all legal provisions on development, use, protection and management of groundwater resources, which may be either scattered in various enactments or integrated into a comprehensive water law

promulgated according to procedures enshrined in the constitution, while law covers both legislation and unwritten rules stemming from custom.

Water Legislation aims to regulate the relationship between persons (physical and legal) and between the people and the state administration on water resources; it includes all legal provisions on development, use, protection and management of groundwater resources, which may be either scattered in various enactments or integrated into a comprehensive water law.

3. Evolution of groundwater legislation

Groundwater legislation has evolved from various traditions and laws. Roman Law, the tradition of the French Napoleonic Civil Code (including France, Spain and many African and Latin American countries) and the traditional English Common Law were among the earliest legislations. Their principles were inherited, sometimes with substantial modification, by those countries deriving their legal system from these regions.

In countries following the Civil Code system and the Common Law tradition, the legal regime of groundwater largely depended on the legal regime of the overlying land, that is, private land ownership equated to unlimited private groundwater use rights.

Some local and variable customary rules were effectively enforced by some communities, such as Moslem countries' principles on water ownership ('gift of God' that could not be privately owned). These customs however did not generally take into account downstream or broader aquifer interests.

Subsequently, however, more comprehensive legislation has been widely (but not universally) introduced (Table 4.2). In most countries surface water regulation is more advanced than groundwater regulation, both in law and in practice. Recognition that water is one linked resource, and the pressures for more sustainable and equitable use for the benefit of society is leading to increasing legislative and regulatory control over both surface and ground water.

Table 4.2: Progressive levels of groundwater resource regulation. (GW-Mate, Briefing note 4)

REGULATION LEVEL	IMPLICATIONS	LIMITATIONS
Minimal Legal Control	no control over groundwater abstraction or wastewater discharge	reduction in natural aquifer discharge and/or progressive salinization and pollution
Local Customary Rules	groundwater rights defined at local level; mechanisms for local conflict resolution	controls limited and do not take account of status of (and impacts on) aquifer system, downstream users or groundwater quality issues
Specific Groundwater Legislation	well construction and groundwater abstraction controlled, but often by a specialist institution in limited contact with those regulating surface water	may result in lack of consideration of groundwater-dependent river baseflows and wetlands; unlikely to be much emphasis on groundwater quality protection
Comprehensive Water Resources Legislation	surface and groundwater resources subject to same legislation and inter-dependence fully recognized; both administered by same institution but quality aspects often under separate agency	much improved capability for water resources management but catchment vision and pollution control may still be deficient; also concerns of water-users may not be taken into account and their proactive support unlikely to be achieved
Fully-Integrated Water Resources Legislation*	catchment or aquifer approach with quantity and quality aspects integrated; more emphasis put on public awareness and water user/stakeholder participation (international nature of some aquifers and river basins recognized)	gives best chance of implementing a balanced and effective regulation policy

4. Components of legislation

Modern groundwater legislation must, in general terms, be flexible, enabling and enforceable. It is thus recommended that the **basic legislation** be restricted to fundamental powers and concepts, and that the detail is dealt with in associated regulations and implementation plans. It also provides a more unified vision of surface water and groundwater resources, but the particular characteristics of groundwater systems and their close relationship with land-use call for specific legislative provisions in different administrative areas and at different territorial levels (Table 4.3). Most of these provisions are the same as for surface water management and where appropriate it makes sense for them to be addressed in one legislative arrangement. Differences between ground and surface water are most likely to be evident in the management systems and tools adopted and the importance attached to the provisions. Some of these specific provisions are discussed further below.

- **Groundwater Abstraction and Use Rights**
  Among other things, (ground)water rights serve as the basis for abstraction charging, and in some countries may be traded.
- **Wastewater Discharge Licensing**
  The licensing of wastewater discharges (especially those to the ground), which is subject to conditions on mode of discharge and level of treatment, is designed to protect (ground) water against pollution. The 'polluter-pays-principle' is normally embodied within this area of legislation.

- **Sanctions for Non-Compliance**
  Penalties may range from modest fines to imprisonment terms, depending upon the severity of impacts and the persistence of the offence.

- **Controlling Well Construction Activities**
  Other provisions of groundwater legislation relate to the licensing of all waterwell drilling contractors, so as to ensure better relations with (and information flow to) the water resources administration, higher standards of well construction, improved reports on the hydrogeological conditions encountered, and reduced likelihood of illegal well construction. Water legislation may also introduce controls over the import of pumps and drilling equipment in an attempt to curb excessive groundwater abstraction.

Table 4.3: Facets of public administration requiring specific legal provision to facilitate groundwater management. (GW-Mate, Briefing note 4)

<table>
<tr><th colspan="2">ADMINISTRATIVE SET-UP</th></tr>
<tr><td>• National authority or inter-ministerial coordinating commission
• Provincial and/or basin agencies</td><td>• procedures for interaction with local authorities
• aquifer management organizations
• water-user associations
• licensing of water-well drillers</td></tr>
<tr><td>(NATIONAL LEVEL)</td><td>(LOWEST APPROPRIATE LEVEL*)</td></tr>
<tr><td>STRATEGIC PLANNING</td><td>LAND-USE MANAGEMENT</td></tr>
<tr><td rowspan="3">• provision for aquifer resource/ vulnerability assessment
• design and implementation of national/ regional/ basin groundwater policies
• definition of protection (conservation or control) area policy
• mandate for drought or emergency actions
• status of groundwater plans and use priorities</td><td>• procedures for groundwater protection zones
• provisions for aquifer recharge area conservation</td></tr>
<tr><td>REGULATION OF WATER USERS</td></tr>
<tr><td>• administration of abstraction/use rights
• administration of wastewater discharge permits
• promotion of user/stakeholders/ associations
• appeal and sanction procedures</td></tr>
</table>

*** depending on size of country or other factors**

- **Catchment or Aquifer Level Resource Planning**
  Water legislation tends to provide for water resources planning with reference to surface water basins and/or aquifer systems. Based on the inventory of water resources and of existing uses, plans provide an integrated basis for the assessment of individual applications for water rights. They normally have a legally-binding nature, and decisions on applications must be consistent with their provisions.

- **Conjunctive Use of Groundwater and Surface Water**
  Acknowledging the advantages of conjunctive water use, one permit may cover both groundwater abstraction and discharge of an effluent of acceptable quality to a surface watercourse, or surface water diversion and use coupled with recharge of an effluent of acceptable quality to the ground.

- **Land Surface Zoning for Groundwater Conservation and Protection**
  In some countries, legislation provides for the water administrators to declare 'special control areas', where exceptional measures (such as restrictions on new waterwell drilling and/or groundwater abstraction rates) become possible in the interest of avoiding further aquifer deterioration. Land surface zoning may also be targeted to serve the purpose of protecting vulnerable aquifer recharge areas and/or ground-water supply sources. In the defined zones restrictions can be applied in relation to potentially polluting activities (such as certain types of urbanization, landfill solid waste disposal, hazardous chemical storage and handling facilities, mining and quarrying, etc.). For the prevention of diffuse pollution from agricultural land use it is more normal to introduce bans or import control mechanisms on certain pesticides and to promote the adoption of codes of good agricultural practices.

- **Facilitating Water-User and Stakeholder Participation**
  The participation of (ground)water users and other stakeholders in (ground)water management (Module 7) is a matter of increasing concern to law-makers, who realize that legal provisions are more likely to be implemented when stakeholders have a say. In addition to local water-user associations, more widely-constituted 'aquifer management organizations' may be needed for large aquifers:
  - to discuss implementation of measures across user sectors and between water-user associations
  - to agree on priority actions in areas with a critical groundwater situation
  - to assist the water resource regulator generally in the administration of groundwater abstraction.

  It is important to endow these organizations with legal status and to integrate them into broader institutional mechanisms for groundwater resource management and protection.

- **Provisions for Groundwater Monitoring**
  (Ground)water legislation should provide for the monitoring of (ground)water status (quantity and quality) and of water use by assigning this task to the water administration at the appropriate territorial level. To be effective, this legislation should set realistic requirements that take into account existing resources and institutional capacity.

5. Institutional arrangements

Water legislation should ensure the enabling environment is established for effective management of water resources, including groundwater. The institutional arrangements for management will bring clarity to the roles and responsibilities of the national and/or provincial institutions responsible for (ground)water resources and define ways of confronting potential constraints to the management process such as inadequate groundwater management boundaries, weak regulatory enforcement, lack of social consensus, poor inter-institutional coordination.

Role of the state

Given the problems created by growing water scarcity and pollution, legislation has been widely enacted to vest all water resources in the state, or to recognize the state's superior right to the management of water resources. The declaration of groundwater as a 'public good' turns the former owner into a user, who must apply to the state administration for a water abstraction and use right. Once the state is the guardian or trustee of groundwater resources, it may (in addition to granting water rights) introduce measures to prevent aquifer depletion and groundwater pollution. Moreover, legislation tends now to require water resources planning at the level of an entire aquifer or river basin.

Idealised structure and functions for a government agency acting as a groundwater guardian is suggested by GWMate in figure 4.1. Only in the case of very large aquifers is there likely to be a separate organisation established for management. In most cases groundwater management will be fully integrated into organisations with responsibility for both surface and ground water. The historical problem that groundwater management receives inadequate attention under this arrangement needs to be addressed.

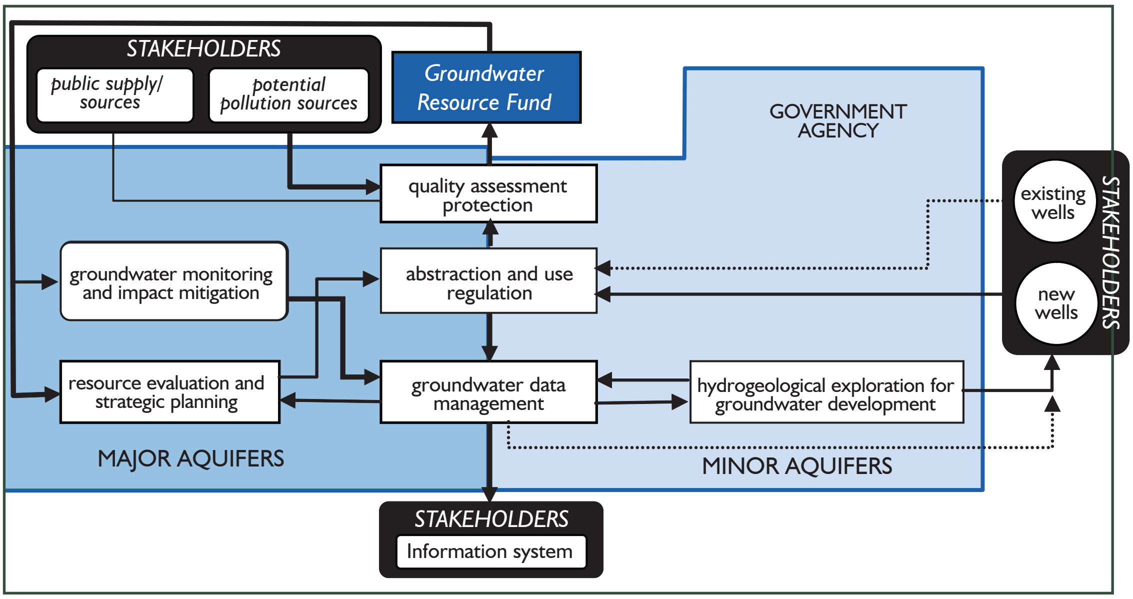
training of water administrators

- a clear understanding of the institutional roles and functions at all relevant levels (Table 4.4)
- an adequate level of public awareness and acceptance of legal provisions
- political willingness to promote and attain sustainable groundwater management.

Groundwater legislation must prescribe an administrative set-up suited to national or state conditions:

- at national level—management functions (covering both quantity and quality aspects) should be vested in a single authority or ministry or (where this is not considered appropriate) clear institutional mechanisms for coordination between the competent bodies must be established
- at river basin or regional level—the specific situation may warrant the establishment of river basin agencies, especially for the performance of some planning and coordination functions
- at intermediate or local level—it is important to pay careful attention to local institutional arrangements for water administration, the role of the local authorities in water resources management (since they represent local interest) and the establishment of intermediate institutions (aquifer management organizations) having legal power in relation to specified aquifers and

Figure 4.1: Idealised structure and functions for a government agency acting as groundwater guardian. (Foster & Kemper, 2002-06)



Implementation of (ground)water legislation

Successful implementation of (ground)water legislation depends on a number of factors including:

- the administrative set-up and the level of with adequate representation of different water-user associations, various water-use sectors and a clear-cut relationship with the water administration.

It has to be acknowledged that there is widespread failure to apply some provisions of water legislation and regulations. A good example is pollution control. There are many reasons for these failures but a common one is poorly crafted legislation which does not respond to the social and economic realities of the country. It is therefore important that water practitioners are involved in the development of water legislation at all stages.

Table 4.4: Key Water Management Function and Institutional roles (modified after GW-Mate, Briefing note 4)

Key Function	Main Activity	Institutional Roles			
		National Water Authority/ RBO	Local Regulatory Agency	Sub-basin/ Aquifer Management Offices	Water Users Associations
POLICY MAKING & STRATEGIC PLANNING					
	– Resource assessment	●	×	×	
	– Use Assessment and Socio-Economic Survey		●	×	×
	– strategic long-term Planning	●	×	×	
	– International agreements	●			
RESOURCE MANAGEMENT/ REGULATION					
Stakeholder participation	– Develop and maintain an active stakeholder participation process through regular consultation activities. – Provide specialist advice and technical assistance to local authorities and other stakeholders in IWRM.	● ●	● ●	×	
Pollution control	– Wastewater Discharge Licenses	●	●	×	×
	– Identify major pollution problems.	●	●	×	×
	– Definition of Protected Areas	●	●	×	×
Water allocation	– Water Rights Administration/ License of water uses including enforcement of these.	●	●	×	×
	– Licensing of development implementers, e.g. well drillers	●	×		
Information management	– Define the information outputs required by the water managers and different stakeholder groups in a river basin.	●	●	×	×
	– Organise, co-ordinate and manage the information management activities.	●	●	×	
Setting economic & financial tools	Set fees and charges for water use and pollution	●	●	×	

Key Function	Main Activity	Institutional Roles			
		National Water Authority/ RBO	Local Regulatory Agency	Sub-basin/ Aquifer Management Offices	Water Users Associations
Basin Action Plans	– Conduct situation analysis with stakeholders.	●	●	×	
	– Assess future developments in the basin.	●			
Emergency Situations	– Structural/ non-structural measures for flood/ drought mitigation	●	×	×	×
	– Disaster preparedness		●	●	×
Monitoring & Enforcement	– Water Status survey/ database (quantity/quality/ socio-economic)		●	×	×
	– Water Use and pollution		●	×	×
	– Conflict resolution	●	●	×	
MONITORING AND EVALUATION					
	– data collection activities of multiple agencies	●	×	×	×
	– Regular stakeholder communication	●			
	– Packaging information in a way that is readily understandable to the target group and that addresses their needs or concerns.	●			

•, × indicate respectively responsibility for, and participation in, the corresponding management function, but the situation will vary somewhat from country to country depending upon their geographical size and political structure.

References and Web Reading

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Module 5: Groundwater Allocation and Licensing

Learning objectives:

- To create awareness of the benefits of a groundwater rights system
- To appreciate how a groundwater rights system may be implemented
- To understand main interactions in a groundwater rights system
- To understand the need to link a groundwater rights system to a surface water rights system

1. Introduction

Water resources have been allocated from the earliest times on the basis of social criteria ensuring that water for human consumption, for sanitation, and for the production of food is available. Population growth has made water scarcity a major problem in many countries, and pollution is more widespread today with degrading water quality resulting in less fresh water availability. As a consequence there is more competitive use of water: drinking water, irrigation, industry, environment...

The majority of countries today designate their water resources as being in public ownership, with government having the overall responsibility for resource management. The right to abstract (or divert) and use water (including groundwater) can be granted to individuals, public entities or private corporations, under certain terms or conditions, and such rights are generally issued by the water resources authority (or by the law courts directly). A 'water right' usually constitutes the right to use (but not ownership of) the water itself. Grants to abstract and use groundwater are instrumented through permits, licenses, concessions or authorizations, generally called here 'water rights'.

2. Why is a groundwater rights system needed?

A system of groundwater rights (permits to abstract and to use groundwater) should regulate interdependencies among users (Box 5.1), it is often first introduced as a means to:

- Reduce interference between abstraction wells ;
- Avoid counterproductive conflicts that may arise, and;
- Resolve emerging disputes between neighbouring abstractors.

However, the development of a stable system of water rights has far wider benefits, since it provides a sound foundation for the development and protection of water resources and for the conservation of aquatic ecosystems. Also, certain other steps towards more integrated water resources management can only be effectively tackled when groundwater rights have been adequately defined:

- Fostering the participation of water users in groundwater management;
- Improving economic efficiency;
- Implementing demand management programs to reduce groundwater abstraction;
- Systematic collection of abstraction charges to raise revenue for resource management;
- Possible subsequent trading of abstraction rights to promote more efficient water use;
- Developing conjunctive use of surface water and groundwater resources.

The existence of a groundwater right cannot guarantee water supply of a given quantity and quality, and thus consideration might be given to prescribing the right in terms of a 'share in aquifer production capacity' (as opposed to a specified abstraction rate). However, they offer water users greater supply security for investment purposes and a valuable asset as bank collateral to obtain development credits.

Box 5.1 Users' interdependencies

- Groundwater pumping by one user may lower the water table and increase pumping costs for all users;
- Pollution by one user affects others especially those located downstream.
- These interdependencies suggest that having all users follow the rules will improve the social value of water resources.

Table 5.1: Terms and conditions usually specified in groundwater abstraction and use rights (GW-Mate Briefing note 5)

TERM OR CONDITION	COMMENTS
● duration of right	allocation flexibility requires some time limitation (say 5 years)
● point of abstraction and use	these should be specified and may be different
● purpose of use	important to distinguish consumptive and non-consumptive use rights
● rate of abstraction	specify annual maximum together with any short-term limits
● specification of works	details of depth, diameter, completion, sanitary protection, etc.
● environmental requirements	linked specification of location/quality of return flow
● cost of right	fee usually paid for holding and/or using right
● record of transactions	obligation to declare transfer of right (when permitted)
● loss or reduction of right	forfeiture without compensation for non-use or non-compliance
● suspension of right	as a penalty or in emergency without compensation
● review of right	periodic adjustment with compensation according to supply/demand
● renewal of right	facility to apply for continuation before expiration

3. What does a groundwater rights system imply?

Water abstraction and use rights should be a comprehensive and unified system covering groundwater and surface water together. Part of the system should be made in sufficient detail to minimize conflict between users, and should specify the condition under which groundwater is abstracted, which may include time, the rate, the volume and the priority that applies in case of scarcity.

However, water users should be entitled to reasonable security in their continuing right to abstract and to use groundwater in the interest of stability and to encourage investments. Thus, appropriate judicial or review mechanisms should be in place to enable groundwater users and others affected by the impacts to question and to challenge decisions.

The table 5.1 summarizes the main conditions that are usually specified in groundwater abstraction and use rights.

4. Groundwater allocation

4.1 What are the main criteria of allocation?

Water allocation objectives should be clear and include economic, social and environmental factors. Appropriate means of resource allocation are necessary to achieve optimal allocation of the resource. There are several criteria used in water allocation (Howe et al. 1986):

- Flexibility in the allocation of water, so that the resource can be reallocated from use to use, place to place, for more social benefits, economic and ecological uses through periodic review, and avoiding perpetuity in allocation;
- Security of tenure for established users, so that they will take necessary measures to use the resource efficiently; security does not conflict with flexibility as long as there is a reserve of the resource available to meet unexpected demands.
- Predictability of the outcome of the allocation process, so that the best allocation can be materialized and uncertainty (especially for transaction costs) is minimized.
- Equity of the allocation process should be perceived by the prospective users, providing equal opportunity gains from utilizing the resource to every potential user.
- Political and public acceptability, so that the allocation serves values and objectives, and is therefore, accepted by various segments in society.
- Efficacy, so that the form of allocation changes existing undesirable situations such as depletion of groundwater, and water pollution, and moves towards achieving desired policy goals.
- Administrative feasibility and sustainability, to be able to implement the allocation mechanism, and to allow a continuing and growing effect of the policy.

4.2 How can groundwater rights be administered?

Groundwater rights should be included with surface water management under a single water allocation system. Where administration systems were separated for various reasons, attempts should be undertaken to integrate them, or if necessary to introduce coordinating mechanisms. In this way physical interactions between count in water allocation. As a consequence, the responsibilities of the agency that manages groundwater should include aquifer recharge event and actions.

Conjunctive use of both groundwater and surface water should be encouraged, and administration systems should ensure that:

- The limits to acceptable use of groundwater are clearly specified, and;

Table 5.2: Special considerations related to groundwater rights administration (GW-Mate Briefing note 5)

CONSIDERATION	COMMENTS
Technical	
● groundwater quality concerns	in terms of possible effect of new abstraction and impact of wastewater discharge have to be considered
● level of surface water connection	varies widely and needs to be considered when evaluating effects on third parties and environment
● resource replenishment	some aquifers have limited present-day recharge and use of 'fossil groundwater' requires special criteria
● dual purpose of some wells	investigation boreholes may have to be used as production water wells since exploratory drilling is too costly
Managerial	
● well-drilling trade	parallel regulation required in view of special skills needed and pollution hazard caused by improperly constructed wells
● flexibility in water allocation	has to be provided for dealing with hydrogeological uncertainty and need to prioritize resource reallocation for potable use
● groundwater conservation areas	may need to be designated to mitigate degradation due to excessive abstraction or pollution threat
● transboundary aquifers	can lead to disagreements between neighbouring states/nations over resource behaviour and use priorities

Box 5.2 Critical considerations:

Complexities and obstacles in implementation:

- Many historical, social, ecological, economic and political circumstances influence the exploitation of groundwater resources
- The complex challenge of monitoring the compliance of groundwater users, paying attention to existing institutional capacity and the essential role that users themselves have to play.

'Enabling environment' for implementation by:

- Recognizing that water rights administration must be tailored to the specific local circumstances
- Ensuring political support at the highest level, since strong economic interests are usually affected when allocating/reallocating water resources
- Thinking twice before calling for legal amendments, to make sure that any identified shortcomings could not be better overcome without the lengthy process of legal reform
- Starting with definition of water resources policy, which includes the rationale for amended/new water legislation and an outline of how existing water-use rights will be handled
- Admitting that "good" comes before "perfect", and that a groundwater rights system does not have to be comprehensive but does have to be workable
- Being convinced that there will always be room for incremental improvement; it is not necessary to await the perfect law and ideal institution before starting action
- Accepting that the task cannot be achieved overnight; international experience has shown the design and implementation of water rights systems always to be a lengthy endeavour
- Involving all actors from the outset to ensure wide ownership of the system introduced; both water-user sectors and government personnel administering the system should participate
- Stressing that regulatory instruments alone are not enough and that water rights administration requires a finely-tuned balance of regulatory, economic and participatory instruments.

Source: Batu, 1998

users (i.e. of both sources) is determined with regard to other users who have only one source.

The table 5.2 summarizes main points to be considered when administrating groundwater rights. The level of surface water connection should be assessed in terms of effects on third parties (users downstream), on ensuring watercourse baseflow, environmental ecosystems, and sustainability of springs.

At what level are users required to seek permits from the relevant authorities? Are such procedures enforced?

To ensure better compliance of groundwater users, stakeholder participation (module 7) should be enhanced in parallel with information management (module 11) to give transparency to the allocation process. Monitoring of water use and water resources (module 9) is also critical to better water allocation enforcement.

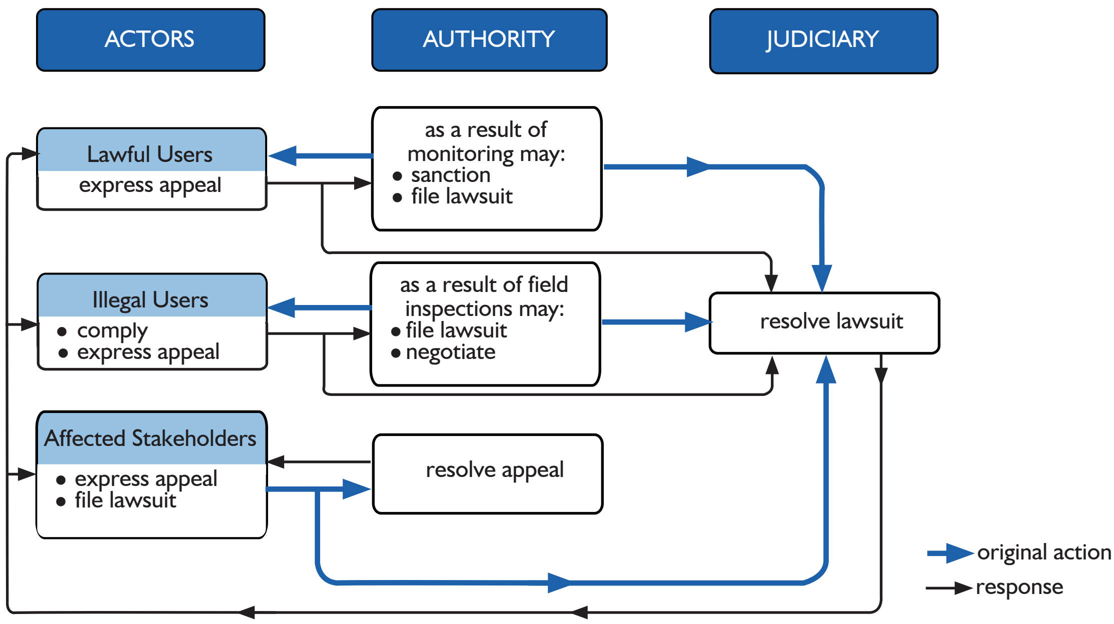
A number of implementation tools are required, which should be kept as simple as possible:

- Planning Instruments: spreadsheets of water users and polluter populations, and aquifer quantity/quality models for prioritization of areas to be controlled;
- Managerial Guidelines: procedures for receiving, reviewing and monitoring of applications;
- Information System: based on adequate software to manage applications, monitor user compliance, carry out operational quality control and deliver easily understood information to water users;
- Public Education: for raising political and public awareness in general.

Critical aspects that need to be considered in implementing groundwater allocation (Box 5.2) include the complexity of the implementation process, and the enabling environment that may facilitate user compliance.

In Kenya it was shown that about 90% of surface water abstracted is used by only 10% of water users. A step-wise approach was therefore adopted to implement the water allocation system starting with licensing the 10% biggest users. The other users will be addressed later. This is the kind of practical approach necessary to ensure a system is workable.

Figure 5.1: Main interactions on the introduction or consolidation of a groundwater rights system (GW Mate Briefing note 5)



4.3 What are the main interactions in groundwater rights administration?

In managing a groundwater rights system, the most important actor is the applicant or holder of a water-use right (Figure 5.1). But other users in the same aquifer and its dependent surface water may also be involved. Other stakeholders (not only water users but those whose interests might be affected) may also want to express an opinion regarding an application for a new water right, to file a complaint or lawsuit against an existing user, or to appeal against decisions.

The water resource authority can deny the applicant a new water right, or may grant and register it. Once the application is granted, the applicant becomes a lawful user who will often have to pay fees and charges according to the terms and conditions attached to the right. The water resource authority should keep records and monitor compliance through field inspections and other means. On discovery of non-compliance, the authority can impose a warning, or a sanction, or seek prosecution by the judiciary if a criminal offence has been committed. In addition, the judiciary may hear appeals from the water-right holder or from affected third parties. In order to ease the burden on the judiciary, appeals may be addressed in the first instance to the highest ranking officer of the water resource authority.

Management style is as important as management process, because users prefer a water authority to work with (rather than against) them. This can be achieved by ensuring that:

- Conflict resolution mechanisms are well-accepted, economic and rapid;
- Sanctions are balanced to discourage non-compliance but not to cripple water users;
- Monitoring is realistic and commensurate with institutional capacity;
- Record-keeping procedures ensure complete copies are available for public scrutiny;
- Water authority discretion is limited to discourage corruption but reduce bureaucracy;
- User bribery and administrator corruption is dealt with decisively.

When water legislation is updated or new laws adopted, difficulties arise because of pressures from existing users and their political associates to concede exceptions. No universal rules are applicable, but the following guidelines should be useful.

- Existing uses should be effective and beneficial to qualify for automatic recognition. If it is not possible to compute an accurate groundwater balance, all users should be given permits of short duration, which can be revised in the light of more reliable information.
- Customary rights should be dealt with comprehensively, either formally recognized or appropriately compensated.
- Not only unlawful users are to blame for the unsatisfactory current status of groundwater resources; past water administrations may also be responsible because of lack of capacity or corrupt tendencies.
- No exceptions should be tolerated; all existing groundwater users, including public water-supply utilities, must be brought into the fold of the law.
- Specification of abstraction rate thresholds by water use should be a dynamic process. Certain minor uses may be exempted from water rights bureaucracy, but simple declaration of existence will prove useful to recognize such lawful users, should more stringent measures be eventually needed.

5. Allocation of non-renewable groundwater resources

In case of non-renewable aquifer systems, implementation of a groundwater abstraction rights system is of high priority. It must be consistent with the hydrogeological reality of continuously-declining groundwater levels, potentially decreasing well yields and possibly deteriorating groundwater quality. Thus the permits (for specified rates of abstraction at given locations) will need to be time-limited in the long term, but also subject to initial review and modification after 5–10 years. At this time more will be known about the aquifer response to abstraction through operational monitoring. It is possible that use rules set by appropriately empowered communal organisations could take the place of more legally-formalised abstraction permits.

Many major aquifers containing large reserves of non-renewable groundwater are trans-boundary, either in a national sense or between autonomous provinces or states within a single nation. In such circumstances there will much to be mutually gained through harmonisation of relevant groundwater legislation and regulations, particularly groundwater rights systems.

The water allocation system should take special considerations of:

- The impacts of new water allocation on traditional groundwater users (some compensations may be provided);
- Ensuring that sufficient reserves of extractable groundwater of acceptable quality is left in the aquifer system;
- The difficulties in estimating impacts of draw-down in a given ecosystem;
- Considering "what happens after?" and then identifying and costing the probable "exit strategy", and;
- Envisaging re-use of urban, industrial and mining water supplies, and carefully-controlled agricultural irrigation.

6 Summary points:

The module has dealt with the following issues:

- The benefits of groundwater rights systems
- The terms or conditions of groundwater rights systems
- Criteria that should be used to allocate resources
- The need to manage groundwater rights together with surface water
- The implementation process of groundwater rights in general and non-renewable groundwater resources in particular.

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Exercise Groundwater rights and allocation system
Purpose: To share experience on groundwater allocation systems implementation and enforcement **Activity:** Break into three groups and discuss for 45 minutes. • Discuss how to implement groundwater right system and mechanism of enforcement in the context of non renewable aquifer system **Report back:** 30 minutes

Module 6: Economic and Financial Instruments in Groundwater Management

Learning Objectives

- To understand the difference between financial and economic instruments.
- To appreciate how to apply financial and economic instruments for improved management of groundwater resources, including:
  Cost recovery;
  Behaviour change
  Address equity and the poor
  Environmental protection

1. Why are economic considerations important in groundwater management and protection?

With improved water resources management and the creation of new management structures, increasing attention is being given to the financial viability of water management systems and the use of subsidies and charges to change the way water is being used. This module addresses the use of financial and economic instruments in water resources management and how they can be used to contribute to more sustainable management and development of groundwater resources.

Linkages between surface and groundwater

While economic instruments to manage surface water and groundwater are similar, they are not the same as a result of certain peculiarities of the groundwater resource:

- relatively high cost and complexity of assessing groundwater
- highly-decentralized resource use, which increases management monitoring costs
- invisibility of groundwater to the general public, and time-lags with regard to resource impacts
- varying impacts of contaminant load depending on aquifer vulnerability
- long time-lags and near irreversibility of most aquifer contamination.

These peculiarities explain why groundwater management tools are generally less developed and applied than those for surface water. However, with increasing water scarcity the economic value of groundwater, and thus the benefit to investment in management, is increasing.

This module focuses on economic and financial considerations as one important part of the groundwater management equation. Firstly, financial and economic instruments will be explained, and then we will examine water as a social and economic good, before moving on to examine how economic and financial instruments can be used to contribute to GW management within the principles of IWRM.

2. Explaining Economic and Financial Instruments

Economic and financial instruments, defined in very simple terms below, affect behaviour (through the creation of incentives and disincentives related to water management activities and water use) and determine to a large extent the financial viability of water resource management activities and the viability of water management institutions.

2.1 Economic instruments.

Basically economic instruments are charges levied to encourage people to change their behaviour in a particular direction (Table 6.1). They are not charges to recover costs. Tariffs, subsidies, cross subsidies and other incentive-based measures such as water trading and effluent charges are typically used to promote the efficient allocation and use of the water resource. Economic instruments may also be used to achieve the broader objectives of equitable allocation and the sustainable use of the water resource. They work best when they complement (and are complemented by) appropriate policy, regulatory, institutional, technical and social instruments.

For example:

- While groundwater could be widely used in high-value enterprises and create more income, jobs and wealth, too often it is still put to low-value economic uses and thus is increasingly over-abstracted, creating social tension between users;
- The poor or disadvantaged groups (women?) may not be able to access groundwater for development and subsistence purposes because the cost of abstraction is too high;

For both of these cases economic instruments can assist to correct a perceived problem. In the first example, higher tariffs can provide incentives to allocate and/or use groundwater more efficiently, thus helping to stabilize groundwater levels by reducing over-abstraction and directing water to higher value activities.

would set tariffs to meet its financial objectives of adequately covering operation, maintenance and capital costs. The utility's performance would be measured by various financial indicators, such as net profit, return on capital, credit worthiness (ability to service loans) etc. By contrast, the economic viewpoint on tariffs is to assess their contribution to a combination of water sector objectives, not just limited to ensuring adequate service delivery to existing water consumers, but also requiring equity improvements (increasing people's ac-

Can you give some examples of how we value water differently?

Table 6.1. Economic instruments and behaviour change

Instruments to change behaviour	Behaviour change required
Abstraction costs: • Abstraction fees; • Indirect pricing e.g. power; • Groundwater markets.	**Conservation of the water resource;** • Reduce polluting behaviours; • More efficient use; • Greater economic value of use; • Improve social equity; • Environmental protection.
Operational costs: • Subsidies to water saving measures; • Subsidies to wastewater treatment; • Subsidies to irrigation technology that reduces agrochemical leaching.	

In the second example targeted subsidies, (subsidised power, or pumps or reduced water fees) may provide the incentive for the poor or disadvantaged to access groundwater for agricultural and other developmental activities.

2.2 Financial instruments

Financial instruments refer to mechanisms that are used to raise money to finance activities (of both operating and capital nature). They are primarily concerned with the income that will result and how this relates to the financial costs of the activities that must be funded.

These distinctions are not as neat as the above definitions imply as both financial and economic objectives may be met in a single instrument, water tariffs being a clear case in point. A commercially-oriented water utility

Can you link the behaviour change to the economic instrument in the table?

cess to water) and ensuring environmental sustainability.

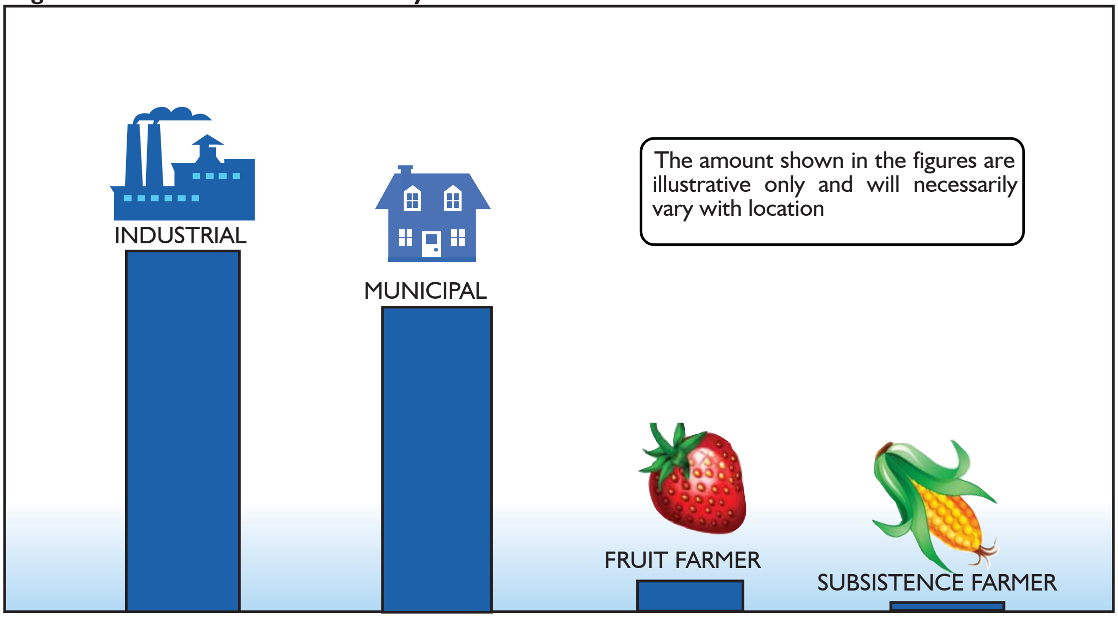
An independent regulator with adequate powers is the best way of ensuring that the financial orientation of a water utility is tempered by the economic or national interest viewpoint.

2.3 Value of water.

The **value of water** in alternative uses is important for the rational allocation of water as a scarce resource, whether by regulatory or economic means (Fig. 6.1).

Value is related to availability and expected benefit. Where good quality ground or surface water is abundant it tends to be undervalued. In situations of scarcity, whether due to absence or pollution, the value to the user is much greater and can be linked to the eco-

Figure 6.1 Economic value of water by use.



Box 6.1: The use of economic and financial instruments is important for groundwater management because:

- As water is becoming scarcer, its economic value is rising;
- Economic and financial instruments can be used for achieving management goals in terms of efficiency, equity and sustainability;
- Without financial viability for water-related projects and decisions, there will not be a sustainable flow of benefits for users; and
- Economic instruments tend to send appropriate signals to producers and consumers about the increasing scarcity of water (something that is less likely when using only non-economic measures).

In general, economic and finance instruments for IWRM are becoming more and more important for taking better decisions that improve water management as well as social goals not only for current but also for future generations.

nomic outcomes of the use or the social and health value of use.

Management of water has a cost and it has generally been discussed that it is better to start improving water management in those situations where there are already problems being experienced. Here the value of water is being recognised due to competition, scarcity or pollution and therefore management interventions are more likely to be acceptable and successful.

3. Water as an Economic and Social Good

The Dublin Principles state that water is an economic (and a social) good. Some people find it difficult to accept that water should be paid for citing, for example, that water is a gift from God. Applying a price to water is not only done because of cost recovery but is equally important

Table 6.2 Measuring the costs of groundwater use.

Water supply costs				Social opportunity costs	External costs
COSTS OF GROUNDWATER ABSTRACTION	CAPITAL COST	OPERATION AND MAINTENANCE COST	RESOURCE ADMIN COSTS	FORGONE VALUE OF ALTERNATIVE USES	IN-SITU VALUE (cost of saline intrusion, land subsidence etc)

as a tool to change behaviour and make sure that water is distributed more fairly. The cost components of water are shown in Table 6.2.

Water has a value as an economic good as well as a social good. Many past failures in IWRM are attributable to ignoring the full value of water. The maximum benefits from water resources cannot be derived if misperceptions about the value of water persist.

When is water an economic good?

Treating water as an economic good is essential for logical decision making on water allocation between different, competing water sectors, especially in an environment of water resource scarcity. It becomes necessary when extending supply is no longer a feasible option. For groundwater, the economic value of alternative water uses helps guide decision makers in the prioritisation of investment. In countries where there is an abundance of water resources, water is less likely to be treated as an economic good since the need to ration water usage is not so urgent. However water has a very important role in economic development which cannot be ignored.

Is there anywhere where water is not an economic good?

Why is water a social good?

Apart from its economic value, water is also a social good. It is particularly important to view water allocation as a means of meeting social goals of equity, poverty alleviation and safeguarding health. In countries where there is an abundance of water resources, there is more of a tendency to treat water as a social good to fulfil equity, poverty alleviation and health objectives over economic objectives. Environmental security and protection is also part of the consideration of water as a social good.

In most traditions water is respected as an important resource and there are systems to manage water and water shortages at the community level.

4. Applying Economic and Financial Instruments

More rational use of water

Economics is about making choices when resources are scarce. This is certainly the case when water is polluted and needs to be consumed, or when investments are necessary to connect more people to drinking water and sanitation systems. It is also the case if there are competing claims: water for human consumption, for agriculture and for industry. In a context of scarcity, competition comes into existence where a price is paid.

Water management is characterised by monopolies and vested interests which is why regulatory systems are necessary to correct for these. The application of financial and economic instruments can help to apply the regulations and obtain the desired results of a rational and acceptable allocation of scarce resources.

The rational use of resources usually requires that consumers, farmers and industrialists contribute to the cost of managing the water, cleaning it and bringing it to their houses, farms or factories.

The instruments

The best-known economic instruments are taxes, subsidies and the determination of prices, or, once such price is fixed by some authority, the tariff. The fixing of these prices is usually not left to the market because the price is very important for poor people.

If there are no water problems in an area do we need to implement expensive management structures?

Financial instruments help in the making of specific investment decisions. One way of improving water efficiency is by investing in and improving infrastructure. This may also lead to more attention to operations and maintenance (O&M) and to a reduction of losses in the system. However, any investment made must be rational and weigh the resources necessary (capital, labour, raw material, etc.) to ensure the optimal use of such resources. Tools developed for this purpose are cost benefit analysis, life cycle costing and multi-criteria analysis.

Related principles, which are also used in water and environmental economics, are cost recovery and the polluter pays. These are based on the objective to recover costs from those who receive the benefit. The water user receives the benefit of access to water and should therefore pay for the costs incurred by the service provider. Similarly a polluter affects water quality for other users and receives the benefit of being able to dispose of waste. The polluter should pay for the environmental cost and the cost of the management agency in policing the polluter.

The primary instruments therefore used are:

- **Direct Groundwater Pricing through Resource Abstraction Fees**
  This is the most direct method, since users have to pay an abstraction fee based on volume—preferably metered (rather than licensed) use to ensure that an incentive exists. Unfortunately, groundwater use by agriculture (usually the largest consumer) is rarely metered and thus controlling irrigation use is not straightforward. Alternative techniques to estimate actual agricultural water use include:
  - deriving volume pumped from electrical energy use
  - assessing actual water consumption by remote sensing techniques.

- **Indirect Groundwater Pricing through Energy Tariffs**
  The major cost in groundwater abstraction (once a well is installed) is the energy required to lift water. This cost will depend not only on water table depth, aquifer characteristics and well efficiency, but also on the unit cost of energy for pumping. Thus, energy (electricity or diesel fuel) pricing can be a powerful tool to influence groundwater pumping trends. Paradoxically, in many areas of the world, energy prices are used in the opposite way, with large subsidies in place to decrease farming costs. While it can be legitimate to subsidize poor farmers to improve their livelihood, subsidizing groundwater abstraction in general may not be the best vehicle to do so, because excessive groundwater abstraction can erode the same farmers' resource availability in the longer term.

- **Groundwater Markets**
  Water markets have been advocated to improve resource management, especially with regard to more efficient water use, and allocation within and between sectors. They are more flexible than command-and-control instruments in allocating water to higher-value uses in a manner acceptable to all parties, thus promoting economic growth and diminishing social tension. However water markets reduce the opportunity of the state to respond to social needs and emergency situations.

5. Economic and Financial Instruments and Groundwater management

How should groundwater management be financed and what control should there be over water tariffs? This is not an easy question to answer and whilst situations are different the challenge is whether the chosen financial management systems are adequate to meet the water management objectives – if not, they should be changed.

In a society in which water is considered a scarce resource and water tariffs are set up to reflect the total economic value of water, it will be easier to generate financial resources for water management. In this case, the costs of water management will be incorporated in the water tariff system, and functions related to water management will have financial support. In other circumstances, financing of water management may not be done via water tariffs but mainly

Who pays for groundwater resources management in your country? Is it the user of raw water or the general taxpayer?

via fiscal expenditure, coming from the general taxation system.

In general, it seems preferable to have a system in which water users pay for any private benefits from water they get, whereas the public sector mainly finances activities and functions which are related to the provision of public goods in water-related activities.

This is equivalent to having a system with cost-covering water tariffs for residential, industrial, electric and agricultural water use (including payments for water polluting activities), whereas public or tax financing can be oriented to the provision of water management for aesthetic and recreational water values, prevention of water-related disasters and water-related health problems, and for protecting some non-use values (preservation of areas or endangered species). This water management system will likely be more effective in terms of efficiency, equity and sustainability for water management.

6. What steps are needed to introduce economic instruments for groundwater management?

A first step is to analyse whether the situation is such as to warrant establishing an expanded water management system to include a pricing system.

The introduction of economic instruments will depend on current hydrologic, economic, social and political conditions. The **feasibility analysis** should include an assessment of costs and benefits of each instrument and possible combinations. It should also take into account long-term recurrent costs and institutional capacity (for administration, monitoring, enforcement) and the transaction costs involved to set up systems. The expected costs and benefits would also influence the trade-off between the use of economic instruments and other groundwater management tools.

The most crucial element in making economic instruments work is to ensure the proposed system is viable and **enforceable**.

Groundwater use is a decentralized activity with many private users normally involved, who drilled their own wells, installed their own equipment and follow their own pumping schedules. In the case of major aquifers, with hundreds of thousands of users, enforcement of well discharge metering is impossible if users have no incentive to comply. Consequently, it is essential that incentives be created for users to participate actively in aquifer management. This can be supported by providing data on the status of groundwater resources and promoting stakeholder participation in management (through which users exert peer pressure to achieve management goals).

What economic instruments are available to aid groundwater pollution control?

The instrument usually prescribed to decrease water pollution is the polluter-pays-principle, by which an industry is charged for the amount of pollution it produces. The less it pollutes, the less it pays.

This approach is not directly applicable to aqui-

Table 6.3: Examples of financial and economic instruments being applied in water resources management

Function	Financial instruments/ purpose	Economic instruments/ purpose
Allocation of the water resources.	Permit charge, Raw water volume charge. Cost recovery admin; Cost recovery basin management; cost recovery investment; cost recovery monitoring.	Volume / use charge. Incentives for efficiency, or equity considerations.
Pollution control	Permit charge, pollution charge. Cost recovery admin; cost recovery monitoring; cost recovery environmental clean-up.	Volume and quality related charges. Self monitoring requirement. Penalise for poor quality and high volume discharge.
Monitoring water use, water pollution, compliance, water resources.	% of raw water charges and pollution charges. Cost recovery	Penalties. To ensure compliance.

fer protection because of the special characteristics of groundwater, notably the time-lag of impacts, the persistence of some groundwater contaminants, and the potential cost of some pollution episodes. Instead economic incentives are required for industry and water utilities to invest in adequate wastewater treatment and recycling especially where aquifer vulnerability assessments suggest high risk of groundwater pollution.

Another important issue is the control of non-point pollution from agricultural cultivation. This can have a major negative impact on groundwater quality due to agrochemical leaching. Pollution control is often managed in a separate agency from water. This can be problematic if they pay little attention to groundwater.

Economic instruments and water management functions

An important consideration in setting tariffs is a justification of the costs charged and transparency in what constitutes management costs, monitoring costs etc. The costs of running the water management system should be carefully analysed and justified on the basis of the activities and effort involved. This justifies what may otherwise be an arbitrary fee. Nevertheless, fee levels are a political issue and income may not meet expenditure. This is acceptable if it is an agreement of government to subsidise the basin for development or other reasons and the government is willing to make up the cost difference. Otherwise with a budget deficit systems will fail and management of the water resources will be limited to those activities of economic priority.

Box 6.2: Key questions to be clear about

- Who pays?
- Which institution receives the payment?
- What are the financial elements?
- What are the economic elements?

Often central government may receive the revenue and the local water management system may be financed from central taxes. This is not a recipe for efficient management of water resources in the basin and runs contrary to the philosophy of financial and economic instruments being applied to the water users. In such circumstances it is still advisable to maintain an expenditure and income comparison.

A final point is on the poacher (water user) and the gamekeeper (water manager). Often, water resources management functions are being developed within an agency that has other functions such as irrigation, or water supply services. This immediately raises a conflict of interest which may result in a lack of trust or cooperation from other sectors. It is advisable in such circumstances that the water resources management functions are ring-fenced and separated from the other functions both financially and from a decision making perspective.

7. Points to remember

- Economic tools are an essential groundwater management instrument.
- Cost recovery is both a component of equity and critical to effective water management institutions.
- Good application of financial and economic tools can assist service development.

References and Web Reading

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EXERCISE
Economic and Financial Instruments (EFI)

Purpose: To identify the barriers and opportunities for applying economic and financial instruments in groundwater management.
Activity: 90 mins – 60 mins group work, 30 mins report back and discussion.
Group 1: Discuss how to apply financial instruments for cost recovery in groundwater on the basis of your experience. In particular:

- What groundwater management costs need to be recovered and who should pay?
- What conditions need to be in place before payment systems can be applied?
- How would you apply the payment system in practice?

Group 2: Discuss how to apply economic instruments to change behaviour.

- What behaviours do you want to change?
- How can you apply economic instruments to change the behaviour? Is it feasible?
- What other mechanisms can you use to change the behaviour and get the result you want?

Report back: 30 minutes

Module 7: Stakeholder Participation in Groundwater Management

Learning objectives:

- To identify and categorise stakeholders.
- To consider different stakeholder structures and responsibilities in groundwater management.
- To receive guidance on maintaining stakeholder participation over time.

1. Why stakeholder involvement?

This module will give an overview on how stakeholders should be involved in groundwater management and describe how to identify and mobilise stakeholders. We also look at stakeholder structures in the basin and the roles and responsibilities that they may have and finally some pointers are given to maintain active participation.

The notion that stakeholders should have a say in the management of the water resources on which they depend is one of the building blocks of the concept of integrated water resources management (IWRM).

The main reason why stakeholder participation is important is that only the stakeholder interest in, and acceptance of, the groundwater management system will make it possible to implement.

Stakeholders **want** to participate because:

- They have an important interest in the resources of a specified aquifer that they want to protect or advance. This may be because they use groundwater, or because they practise activities that could cause groundwater pollution, or because they are concerned with groundwater availability and environmental management.

Stakeholders **need** to participate because:

- Management decisions taken unilaterally by the regulatory agency without social consensus are often impossible to implement. Essential management activities (such as monitoring, inspection and fee collection) can be carried out more effectively and economically through cooperative efforts and shared burdens. The integration and coordination of decisions relating to surface and groundwater resources, land use and waste management are made possible through stakeholder cooperation. For smaller aquifers stakeholder management may be the only realistic option.

Other **benefits** arise from stakeholder participation:

- More informed decision-making as stakeholders often possess a wealth of information which can improve groundwater management;
- Conflict prevention by development of consensus and information sharing;
- Social benefits, because they tend to promote equity among users;
- Economic benefits, because they tend to optimise pumping and reduce energy costs;
- Technical benefits, because they usually lead to better estimates of water abstraction.

What are other benefits of stakeholder involvement?

It is clear that the stakeholder engagement strategy is an integral component of groundwater management and is not a one-off event.

2. Identification of key stakeholders.

Who is a stakeholder? It is very easy to be overwhelmed by the potentially large number of stakeholders with an interest in water so it is important to take a careful look at who should be involved and why.

Stakeholder analysis essentially involves three steps:

- Identify the key stakeholders from the large array of groups and individuals that could potentially affect or be affected by changes in water management.
- Assess stakeholder interests and the potential impact of groundwater management decisions on these interests.
- Assess the influence and importance of the identified stakeholders.

This analysis should be linked to the development of an institutional process of long term engagement with stakeholders in GW management (see section 4 in this module).

Why is it necessary to pay attention to gender when doing stakeholder analysis?

Step 1: Identification of key stakeholders

A first step is to identify and group the stakeholders in the groundwater management area.

- Who are the potential beneficiaries?
- Who might be adversely impacted?
- Have vulnerable groups who may be impacted been identified?
- Have supporters and opponents of changes to water management systems been identified?
- Are gender interests adequately identified and represented?
- What are the relationships among the stakeholders?

Answering these questions will lead to a simple list, which forms the basis of the stakeholder analysis. As mentioned above not all stakeholders want or need to be involved in groundwater management. One purpose of stakeholder analysis is to ensure that the groundwater managers adequately understand the stakes of different interest groups, where they wish to participate, and what are their expectations and skills.

One common problem, especially with groundwater, is to define the system boundaries. Water affects society in many ways and the socio-economic development of a major aquifer in a country may affect stakeholders on the national and even international scale.

An actual inventory of stakeholders is demanding and should not be underestimated. It is also important to note that for many stakeholders the inventory is the first time they come in contact with water managers. Often groundwater abstractions are uncontrolled and a visit from a governmental body is not always seen as positive.

Step 2: Assess stakeholder interests and the potential impact of the project on these interests

Once the key stakeholders have been identified, the possible interest that these groups or individuals may have in groundwater can be considered (Table 7.1). Questions to answer in order to assess the interests of different stakeholders include:

- What are the stakeholder expectations?
- What benefits are likely to result for the stakeholder?

Table 7.1. Potential range of interests and activities of groundwater stakeholders

SECTOR	WATER-USE CLASSES	POLLUTING PROCESSES	OTHER CATEGORIES
Rural	domestic supply; livestock rearing; subsistence agriculture; commercial irrigation.	household waste disposal, farmyard drainage; intensive cropping; wastewater irrigation.;	drilling contractors; educational establishments; professional associations; journalists/mass media.
Urban	water utilities; private supply.	urban wastewater; disposal/reuse; municipal landfills.	
Industry & mining	self-supplied companies.	drainage/wastewater discharge; solid waste disposal; chemical/oil storage facilities.	
Tourism	hotels and campsites.	wastewater discharge; solid waste disposal.	
Environment	river/wetland ecosystems; coastal lagoons.		

- What resources might the stakeholder be able and willing to mobilize?
- What stakeholder interests conflict with groundwater management and IWRM goals?

It is important to realize when assessing the interests of the different stakeholders that some stakeholders may have hidden, multiple, or contradictory aims and interests that they will seek to promote and defend.

Step 3: Assessing stakeholder influence and importance

- The informal influence of the stakeholder (personal connections, etc.).
- The importance of these stakeholders to the success of groundwater management.

Both the influence and importance of the different stakeholders can be ranked along simple scales and mapped against each other. This exercise is an initial step in determining the appropriate strategy for the involvement of the different stakeholders. As with the second step, in order to make sure the assessment is as accurate as possible it would be preferable to have 'on-the-ground' consultations.

Table 7.2. Categories of Stakeholders

A. High interest/Importance, High Influence These stakeholders are the basis for an effective coalition of support.	**B. High Interest/Importance, Low influence** These stakeholders will require special attention if their interests are to be protected.
C. Low Interest/Importance, High influence These stakeholders can influence the outcomes but their priorities are not those of groundwater management. They may be a risk or obstacle to progress.	**D. Low Interest/Importance, Low influence** These stakeholders are of least importance to the project.

In the third step the task is to assess the influence and importance of the stakeholders identified in earlier steps. Influence refers to the power that the stakeholders have such as formal control over the decision-making process or it can be informal in the sense of hindering or facilitating implementation of groundwater management processes.

Stakeholders who are important are often stakeholders who are to benefit from groundwater or whose objectives converge with the objectives of the groundwater management. Some stakeholders who are very important might have very little influence and vice versa.

In order to assess the importance and influence of the stakeholder try to assess:

- The power and status (political, social and economic) of the stakeholder.
- The degree of organization of the stakeholder.
- The control the stakeholder has over strategic resources.

A problem is one of representation - it is not possible to consult everyone and for formal stakeholder structures there is need for representation to be legitimate.

It is particularly important to identify government stakeholders (see below) with influence or impact on groundwater management such as agriculture (land use), environment (land use, pollution management, ecosystem health) so as to engage them in strategy development and implementation.

3. Stakeholder functions in GW management

There are many ways in which stakeholders may participate in the management of groundwater resources and aquifer systems. A summary of the potential functions that can be performed, and the management levels to which these functions generally correspond, is given in Table 7.3. Approaches will vary somewhat according to both the specific interests of the stakeholders and the nature of land and water rights in the area concerned.

In order to ensure stakeholder ownership of decisions, participation should start when resource issues and concerns are first being identified and profiled, and then continue through the management planning, implementation and monitoring stages.

One of the difficult challenges in participatory groundwater management is to include, and to define a role for, those who have no direct vested interest in resource management, since they are neither well users nor potential polluters, but may still be seriously affected by management decisions—such as employees in agricultural or industrial enterprises and environmental NGOs representing wetland conservation interests.

Government as a stakeholder

Cross-sectoral coordination deserves a special mention under stakeholder participation. Coordination between different sectors often means the cooperation, or at least exchange of information, between different governmental ministries and departments.

To achieve an integrated approach to water resources management it is therefore essential to coordinate groundwater management with other ministries, either through inter-ministerial structures or directly with corresponding local departments of other ministries. This coordination is in many cases needed in parallel with river basin management where there may be ministry representatives.

As indicated in Figure 7.1 inter-ministerial committees are located in between the columns for stakeholders and governmental bodies. This is because many governmental organisations may be managing water resources, users of water resources or have responsibility for programme areas that directly impact on water resources management. Local Governments are in many cases responsible for the water supply and sanitation and are therefore in the category of water user. At the same time Local Government is obviously an important stakeholder when it

Table 7.3 Summary of functions commonly performed by stakeholders in participatory schemes of groundwater administration and management.

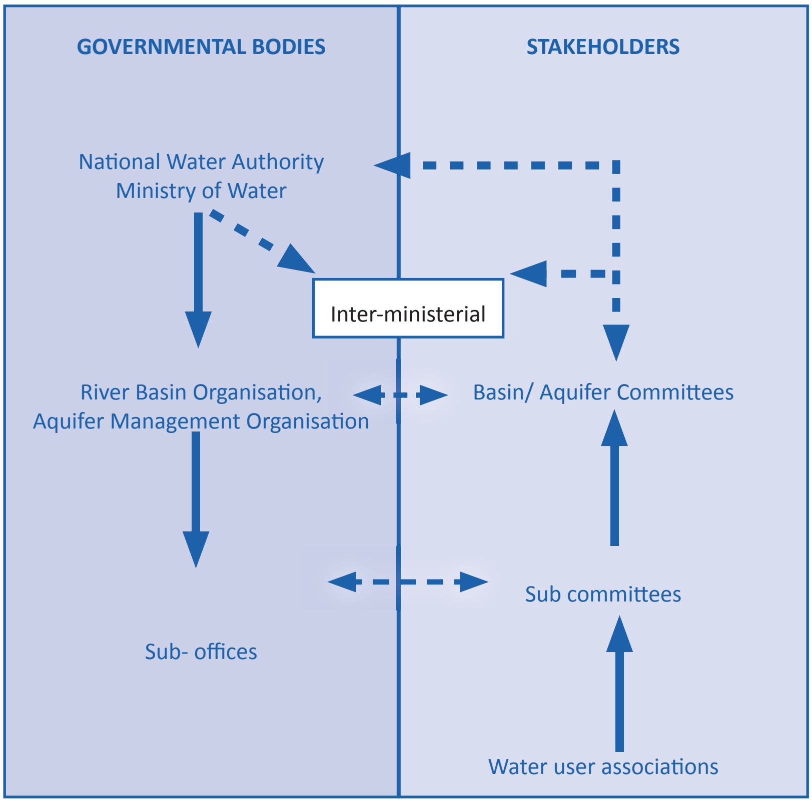
FUNCTIONS	Level at which function performed	
	Water user assoc.	Aquifer or basin organisation
hold groundwater rights	Yes	
maintain groundwater supply/distribution	Yes	
collect water-use charges at distribution level	Yes, x	
perform operational groundwater monitoring	Yes, +	
make binding rules on water-use	Yes, x	Yes, x
undertake policing of groundwater use	Yes, x +	Yes, x +
participate in setting criteria/targets		Yes, +
formulate/implement aquifer management plans		Yes, +
implement groundwater protection measures		Yes, x +
settle groundwater resource disputes		Yes, x +
review conjunctive use and water transfer schemes		Yes, +

x needs legal status of the organisation or association;

\+ Requires formalisation of relationship with water regulatory agency.

In countries where water reforms have taken place and water laws have been revised it is often found that stakeholders are identified in the water law and have the possibility to contribute to water management through legal stakeholder structures. This provides an important platform for their formal involvement and collaboration with water management organisations of government.

Figure 7.1: Possible links between stakeholders and governmental bodies



comes to water resources allocation or basin planning for development and may have local responsibilities in groundwater management.

The Environment Agency is another example in that they often have responsibility for water pollution management. The groundwater management organisation should then act as a stakeholder to influence how the Environment Agency sets policy and implements this programme. Agriculture may establish policies and programmes on land management, cropping or irrigation that directly affect the management of water resources in a basin and again the groundwater management should see itself as a stakeholder in the policy decisions of the Ministry of Agriculture.

4. Institutional mechanisms for stakeholder participation in GW management

Stakeholder and community participation in groundwater management should take place at various territorial levels, ranging from the individual well to the aquifer system, and even to the basin or national level. It should be encouraged at all levels where the stakeholders may make an important contribution to groundwater conservation and protection and is likely to be integrated with surface water management in many situations.

Local entities have been in existence since time immemorial in some countries, distributing groundwater from wells or springs to their members, mostly for irrigation, collecting operational charges, maintaining infrastructure and settling water disputes, in accordance with customary rules. These groups may form an important basis for sharing good practices with other communities and may be provided with recognition under the law so as to facilitate their work and enable them to enter into contractual relations with local water and land regulatory agencies.

Water sector reforms under IWRM often identify stakeholder structures (such as Water User Associations) and provide them with specific roles and responsibilities in surface or groundwater management. In the case of groundwater resources there may be specific need for an aquifer management organization in large aquifers, especially those under threat. However the reality in most situations is for groundwater management to be incorporated within surface water management systems such as River Basin Organisations which is consistent with the philosophy of managing water as one resource.

In some water sector reforms stakeholder structures have been delegated water allocation authority at the local level and may also be represented at higher levels up to oversight of the National Water Authority (Fig 7.1). In other countries the stakeholders have only an advisory function. Formalising stakeholder participation in structures is particularly important as a formal stakeholder structure makes the work of the water manager much easier, limiting the need for continued stakeholder mobilisation and ensuring a formal and regular link to the stakeholders.

There is no blue-print for how to build the structure of stakeholder representation. Figure 7.1 shows the possible links between governmental bodies and stakeholder organisations at different levels. Where possible and appropriate groundwater and surface water should be managed within the same structures.

It is important to clarify early on the roles and responsibilities of the stakeholder structures in the water resources management process. For example, the water users may be given the responsibility to do monitoring on the local scale under supervision of the water management authority. In this case the structure of the stakeholders must be designed to enable easy communication on the local scale. Another example is development of plans for the water management area. This may require consensus building among the major stakeholders and consultation with major groups. In this case formal stakeholder structures are invaluable.

In such stakeholder structures an essential issue is representation. Procedures and guidelines must be clarified on how different groups are represented and how these representatives are selected and replaced from time to time. Clear and documented rules for this are important to obtain equitable participation.

5. Stakeholder mobilisation

At the beginning it is important to be clear on the purpose of the mobilisation. It may be for information gathering; to persuade them to carry out tasks such as monitoring; or it may be for them to undertake management of the groundwater system in their local area.

Stakeholder mobilisation may take place at any time for a variety reasons. People have often been mobilised to provide information or to contribute to a planning process but when, as is often the case, there is no further communication, one finds that they will not be very receptive in the future. It is important to be honest to oneself as well as to the community as to what the expectations are, as stakeholder participation is often carried out just to say it has been done. (Table 7.4)

6. Final remarks

Despite the long and difficult process of mobilising and organising the stakeholders, the largest challenge is probably to maintain active

Box 7.1 Gender in Stakeholder mobilisation
Achieving economically efficient use of groundwater requires attention to gender. It enables:

Effective investment: Groundwater infrastructure can be more widely and optimally used, maintained and sustained when women's and men's demands, expectations, experience, involvement and knowledge are considered. Such consideration enables targeted solutions in technology, payment and management systems and can result in better use of limited funds, human resources and water.

Enhanced cost-recovery: Recovery of investment in water services can be improved if traditional women's and men's roles in water management are recognized and promoted in an equitable manner.

Enhanced ownership: Communities feel more committed to water projects that properly target gender-specific issues. A 1993 World Bank study of 121 water projects showed that the systems that include users (both women and men) in planning, building and management usually perform better. Gender-sensitive participation was consistently a factor for success in quality of design, quality of implementation, project efficiency, operation and maintenance.

(Cap-Net, GWA, 2005)

Table 7.4: Types of stakeholder participation

	CHARACTERISTICS
Manipulative participation	Participation is simply a pretence
Passive participation	People participate by being told what has been decided or has already happened. Information shared belongs only to external professionals
Participation by consultation	People participate by being consulted or by answering questions. No share in decision-making is conceded and professionals are under no obligation to take on board people's views
Participation for material incentives	People participate in return for food, cash or other material incentives. Local people have no stake in prolonging practices when the incentives end
Functional participation	Participation is seen by external agencies as a means to achieve project goals, especially reduced cost. People may participate by forming groups to meet predetermined project objectives
Interactive participation	People participate in joint analysis, which leads to action plans and the formation or strengthening of local groups or institutions that determine how available resources are used. Learning method is used to seek multiple viewpoints.
Self-mobilization	People participate by taking initiatives independently of external institutions. They develop contacts with external institutions for resources and technical advice but retain control over how resources are used

SOURCE: Dalal-Clayton B, Bass S (2002)

stakeholder participation over time. A key is to ensure that the stakeholders see the benefit of their participation. For many stakeholders water resources management may seem only negative since they are suddenly faced with restriction of water abstractions and effluent discharges or demands with regard to self-monitoring. In addition they have to take time from their own work activities and means of income generation. In this regard, it is a responsibility of the water management agency to provide and present concrete benefits of being involved in the water resources management process in the river basin.

Some mechanisms that build commitment:
- Make complex groundwater situations understandable
- Empower stakeholder organizations
- Ensure all stakeholders are properly represented
- Where necessary, establish a sound groundwater rights system.

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Meta Meta, participatory groundwater management –
http://www.groundwatermanagement.org

EXERCISE
Stakeholder Participation

Purpose: Examine the roles that stakeholders can play in groundwater management.
Activity: Group work 45 mins, report back 35mins
Group 1: You are water managers responsible for groundwater management and development in part of your country where groundwater is being over-exploited. You are not going to be allocated more staff or resources.:

- What steps will you take to involve the community?
- What tasks/ responsibilities will you allocate to them?
- How will you make sure that the tasks are carried out?
- What will be your role?.

Group 2. You are stakeholders in part of your country where groundwater is being over-exploited and you are affected by poor water quality, lowering of water table and periodic lack of water. Some farmers are believed to be pumping too much water for their crops and contributing to the problem.

- How do you plan to solve the problem?
- What role would you be prepared to play and what role should government play?
- What powers and responsibilities can be given to the community?
- How will the actions be financed?

Report back: Report back from each group (20mins) then discussion (15mins).

Module 8: Groundwater Quality Management

Learning Objectives:

- To appreciate the importance of protecting groundwater quality
- To understand the role of risk assessment and vulnerability mapping in managing groundwater quality
- To examine the specific case of Urban Wastewater and Groundwater Quality

1. Introduction

Groundwater quality is a hidden issue inside a hidden resource, and as a result far too little attention is given to it. Most groundwater comes out of the earth as good quality potable water that needs almost no treatment before distribution and use. This good quality is a result of the protection that the ground affords the water by filtering out bacteria and protecting the water from pollutants generated at the land surface. In a piped supply system, precautionary disinfection and liming to reduce corrosion in the piping network may be the only treatments required. As a result groundwater is a highly valuable resource for water resources managers. On the negative side, once groundwater has become polluted, it is usually a very long, complex and expensive task to restore the water quality, and in many cases the groundwater resource may be effectively destroyed as a potable water supply

It is for these reasons that the monitoring, prevention and remediation of groundwater pollution is a vital management issue. The specific objectives of this module are to:-

- provide guidance on the identification and assessment of threats to groundwater quality
- introduce management tools and strategies that may be used to either avoid or ameliorate such threats.

Why do groundwater supplies merit protection?

Groundwater is a vital natural resource for the reliable and economic provision of potable water supply in both the urban and rural environment. For municipal water supply, high and stable raw-water quality is a prerequisite, and one best met by protected groundwater sources. Too often those exploiting groundwater for the provision of potable water supply have taken no action to protect water quality. Aquifers worldwide are experiencing an increasing threat of pollution from urbanization, industrial development, agricultural activities and mining enterprises. It may take many years or decades before the impact of a pollution episode by a persistent contaminant becomes fully apparent in groundwater supplies abstracted from deeper wells and take even longer to clean up.

Are you aware of any significant groundwater quality issues in your country in either the urban or rural environment?

- Groundwater supplies merit protection because they are a vital resource for the supply of potable water in both rural and urban environments.
- Water managers need to initiate proactive campaigns and practical actions to protect the natural quality of groundwater.

2. Risk Assessment

2.1 How do aquifers become polluted?

Aquifers may become polluted by specific point sources, such as waste ponds or effluent discharge from factories and mines, or they become polluted from diffuse pollution such as the application of agricultural fertilizers and pesticides. Groundwater may also become polluted through well head contamination from poorly constructed/designed boreholes (Fig. 8.1).

When subsurface contamination is inadequately controlled, and exceeds the natural attenuation capacity of the underlying soils and strata, then the groundwater system becomes contaminated by this waste. In the vadose (unsaturated) zone, natural subsoil profiles actively and effectively attenuate many water pollutants especially human excreta and domestic wastewater by biochemical degradation and chemical reaction.

Concern about groundwater pollution relates primarily to the phreatic (water table) aquifers, especially where the unsaturated zone is thin and the water-table is shallow. Deeper and confined aquifers are afforded much greater natural protection by the overlying ground. The threats to groundwater arise from a variety of different sources (Fig 8.1) and many of these are quite different from sources that typically pollute surface water bodies, due to differences in the mobility and persistence of contaminants in the subsurface as compared to surface water bodies. What is clear is that if the source, nature and pathways of the pollutant(s) are properly understood, then sharply-focused pollution control measures can produce major benefits for relatively modest cost if correctly targeted at key point sources.

Saline intrusion is a very special case of groundwater pollution that occurs due to over-pumping fresh water aquifers in coastal areas resulting in up-coning of saline water and mixing with the fresh water giving rise to 'irreversible' aquifer salinization. This is a major problem for a great number of coastal cities around the world.

Naturally occurring groundwater quality issues are discussed in Module 3 on groundwater characterization.

In summary:

- Aquifers may be polluted by point source discharges or from diffuse pollutants.
- Typically aquifers become polluted when pollution is inadequately controlled and exceeds the natural attenuation capacity of the ground.
- Groundwater quality management requires the assessment of pollution hazard and risk to groundwater, delineation of groundwater vulnerability zones, control of effluent discharges (e.g. by a system of permits), as well as the construction of containment structures (e.g. lined waste ponds) in order to avoid or reduce groundwater pollution.

Give examples of groundwater pollution in your country. How can it be avoided in future?

2.2 How can groundwater pollution hazard be assessed?

Groundwater pollution hazard assessment is needed to appreciate the actions required to protect groundwater quality and it should be an essential component of environmental best practice. Groundwater pollution hazard is the interaction between the aquifer pollution vulnerability and the contaminant load (Table 8.1). Aquifer vulnerability is essentially fixed by the natural hydrogeological setting but the contaminant load varies. Groundwater levels and water pressures do modify the vulnerability of aquifers to some extent.

Aquifer pollution vulnerability can be assessed from the hydrogeological characteristics of the overlying material to produce a vulnerability index that can be mapped. There are a variety of

Figure 8.1 Land use activities commonly generating a groundwater pollution threat (GW-Mate. Briefing note 8).

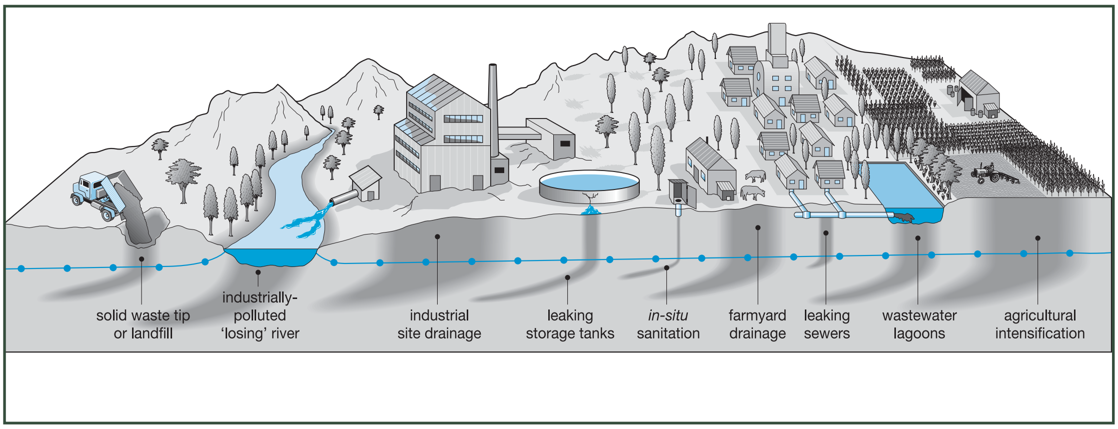


Table 8.1 Definition of Common Terms Relating to Groundwater Pollution.

Term	Definition
Aquifer Pollution Vulnerability	Sensitivity to contamination determined by the natural intrinsic characteristics of the geological strata forming the overlying confining beds or vadose zone of the aquifer concerned
Groundwater Pollution Hazard	Probability that groundwater in an aquifer will become polluted to concentrations above WHO drinking water guidelines when a given subsurface contaminant load is generated at the land surface
Groundwater Pollution Risk	Threat posed by this hazard to human health due to pollution of a specific groundwater supply source or to an ecosystem due to pollution of a specific natural aquifer discharge

vulnerability assessment tools that can be used eg: the DRASTIC method where D = Depth to water, R = net Recharge, A = Aquifer media, S = Soil media, T = topography, I = Impact of vadose zone and C = hydraulic Conductivity of the aquifer.

The resultant groundwater vulnerability map is an important tool for management of infrastructure/ industrial development to reduce the impacts on groundwater quality. The potential contaminant load can also be mapped and overlaid on the aquifer vulnerability map to provide a map of the groundwater pollution hazard (e.g. Figure 8.2).

Whether any hazard will result in a threat to groundwater depends primarily on its location with respect to the groundwater flow-zones and capture areas, and secondly on the mobility of the contaminant(s) concerned. A number of areas and zones should normally be defined with different hazard indices. In terms of new developments, industries and activities that generate significant pollutant loads should not be located over areas with high hazard indices. Different survey scales will apply for water-supply protection and aquifer resource protection. Ideally aquifer resource protection should be the focus.

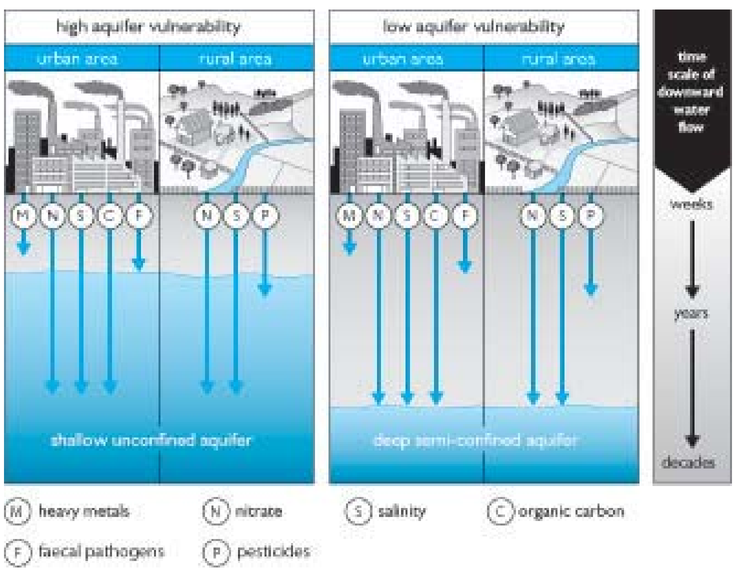
In summary:

- Groundwater pollution hazard can be assessed by considering the combination of the aquifer vulnerability and the distribution, amount and nature of the contaminant load.
- Groundwater pollution hazard assessments should prompt authorities to take both preventive actions and corrective actions to stop activities that are an existing threat to groundwater quality .

2.3 How is groundwater quality measured and monitored?

A key aspect for management of groundwater

Figure 8.2. Groundwater Risk is a combination of pollution hazard and aquifer vulnerability.



quality is the application of water quality monitoring at selected boreholes, especially in areas considered to be at risk. Groundwater quality may be measured by sampling and analysing the groundwater from selected wells. Monitoring may be pro-active with monitoring wells installed prior to a planned activity that may generate pollution, so that changes to the groundwater condition can be measured as they occur. Alternatively monitoring may be reactive with monitoring wells installed to monitor possible pollution from an already existing facility/activity. This subject is dealt with more fully in the Module (9) on Groundwater Monitoring.

There are several issues involved in groundwater quality monitoring that need to be considered, adding considerable complexity to the task. The cost of chemical analyses may be very high, depending on the parameters analysed. In many instances, especially for organic agrochemicals and industrial reagents, local laboratories may not be equipped to carry out the required analyses. Where possible, cheap indicator parameters should be identified and measured as an alternative to a full chemical analysis. Sampling wells, if not in regular daily use, need to be thoroughly flushed before sampling. Sampling points need to be carefully selected, which requires a clear understanding of the groundwater flow patterns and knowledge of the location of the sources of pollution.

What controls over groundwater pollution do you have? Are they effective?

Sampling frequency needs to also be considered and will be based on the sensitivity of the pollution problem, and the frequency of flow inducing or flushing events such as groundwater recharge.

3. Groundwater pollution and quality management systems

3.1 Protecting groundwater from pollution

Management of groundwater quality requires both the protection of aquifers and groundwater from ingress of pollutants and also the remediation/treatment of polluted resources. It should be noted that treatment of polluted groundwater is complex, expensive, often only partially successful and it may take many years of treatment before groundwater quality can be restored.

Groundwater quality can range from high quality potable water to something that is entirely toxic, with a full range of water qualities in between. In addition to protection and remediation, groundwater quality management may include the matching of different water qualities to different uses and blending of different water qualities to provide a larger groundwater resource of intermediate but still acceptable quality for a particular use requirement.

Groundwater quality management should be pro-active and attempt to prevent the contamination of groundwater resources, and thus avoid the lengthy, expensive and often ineffective remediation of contaminated aquifers.

Groundwater protection initially involves two key aspects. These are

1. assessment of aquifer pollution vulnerability (Fig. 8.3) and
2. mapping of groundwater pollution hazards

Together these two factors may be then used to generate a groundwater pollution risk map. Such maps may be used to guide the location of proposed new developments such that the risk of groundwater contamination is reduced in sensitive area and they can be used in already developed areas to assess probable zones already at risk or polluted from ongoing activities.

Once the risk has been identified and assessed, then certain groundwater quality management practices may be introduced. These may include:

- groundwater quality monitoring to assess actual groundwater quality status and changes to quality over time
- prohibition of certain activities in sensitive or vulnerable areas
- prohibiting the disposal of certain levels of waste except in sealed facilities
- management of both the quality and quantity of effluent and waste disposal by a series of permits
- monitoring of compliance with regulations/ permits

In addition remedial actions may be initiated in areas where this is deemed necessary and feasible; e.g:

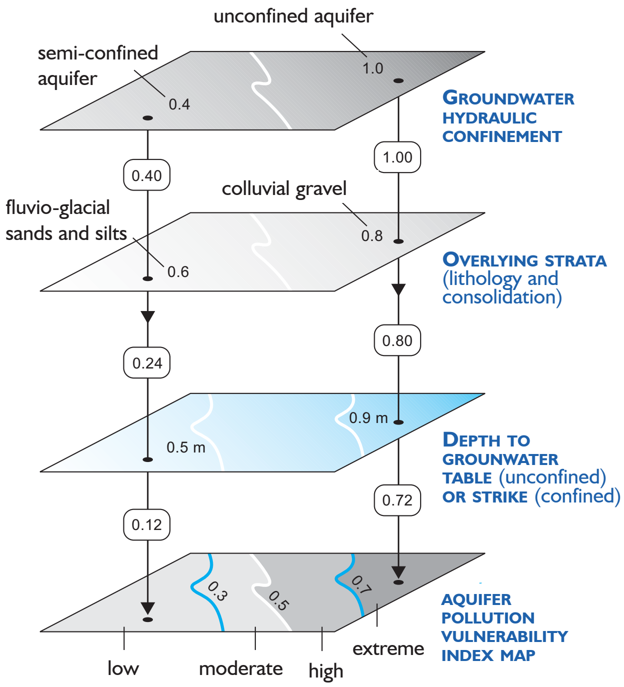
- pumping and treating polluted groundwater
- pumping/well injection to reverse the hydraulic gradient in order to protect sensitive groundwater resources by changing the groundwater flow pattern.
- construction of physical barriers such as grout or slurry walls
- chemical or bacterial in situ treatment of contaminated groundwater

Figure 8.3 Aquifer pollution vulnerability maps represent a fundamental input parameter in managing and protecting groundwater quality. As shown in the GOD methodology below, key factors in aquifer vulnerability include the hydraulic confinement, the permeability of the unsaturated zone and the depth to the water table.

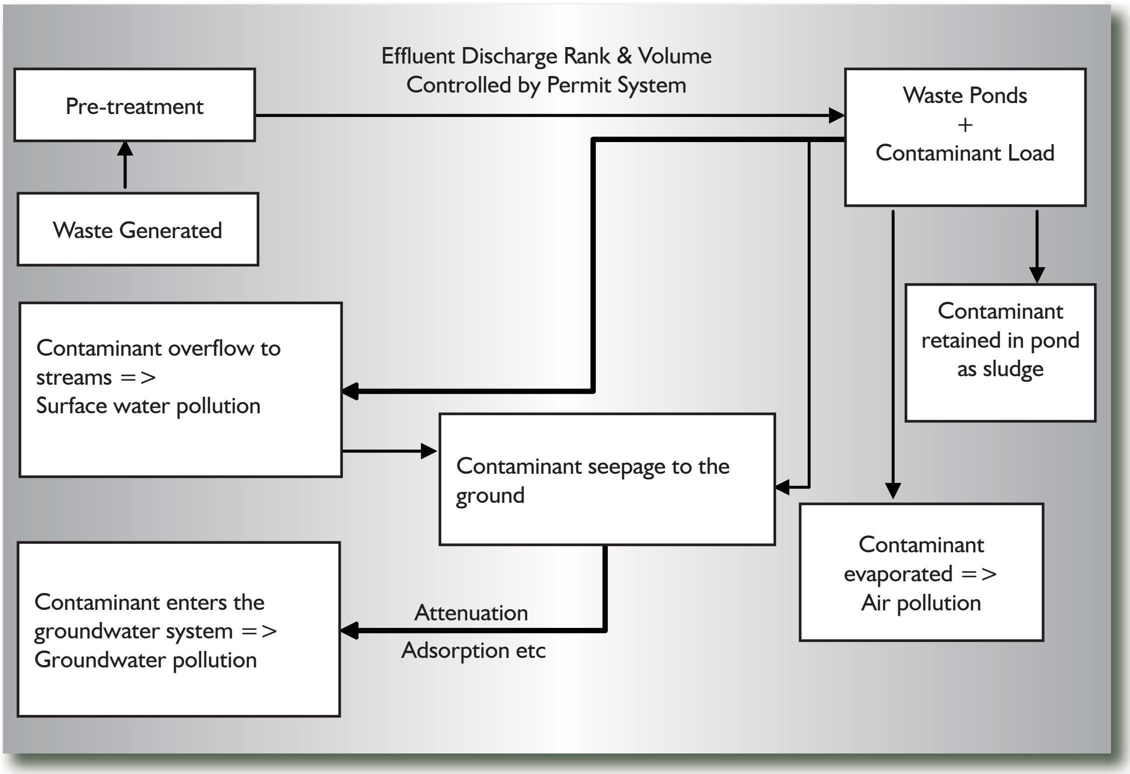
3.2 The waste life cycle and groundwater pollution

Waste material is generated by various industrial, mining and domestic processes. It may or may not be pre-treated to either extract valuable components or to reduce its environmental toxicity. A worst case scenario is discharge straight to the environment but ideally the waste or effluent is discharged into waste ponds; such ponds or waste receptacles may be lined or otherwise engineered to reduce or avoid waste entering the subsurface and then subsequently contaminating the groundwater resource. Box 8.1 shows the full ideal life-cycle for a contaminant, with various stages of treatment and management. In a poorly managed situation, many of these steps may be absent.

Figure 8.3 Aquifer pollution vulnerability maps represent a fundamental input parameter in managing and protecting groundwater quality. As shown in the GOD methodology below, key factors in aquifer vulnerability include the hydraulic confinement, the permeability of the unsaturated zone and the depth to the water table.



Box: 8.1. Life Cycle of Contaminant: Sources and Sinks of the Contaminant Balance



It is increasingly recognised that pollution must be controlled, usually by a permit system. A permit will specify the pollutant ranking and volume of the waste; the higher the contaminant risk, the higher the ranking and cost of the effluent discharge permit. A contaminant balance study may be used to assess the final destination of the waste materials, and determine how much contaminant has actually entered the ground.

3.3 What does groundwater pollution protection involve?

As we have seen, to protect aquifers against pollution it is essential to constrain land-use, effluent discharge and waste disposal practices.

One widely used strategy has been the establishment of groundwater protection zones (Fig. 8.4). Simple and robust zones may be established with indications of which activities are permissible/possible. Such zones need to be incorporated into the town/city planning maps and legislation and used to guide various developments. Such zones have a key role in setting priorities for groundwater quality monitoring, environmental auditing etc. and can help to reduce the costs involved in producing groundwater quality maps.

There is need for sensible balances between protecting aquifers and boreholes, but aquifer oriented strategies are more acceptable. It may not be cost-effective to protect all parts of an aquifer equally. This will depend on the groundwater use, the contaminant loads, flow paths etc.

In summary:

- Land-use, effluent discharge and waste disposal practices must all be managed in order to protect aquifers against pollution.
- Simple and robust zones need to be established with indications of which activities are permissible/possible.

3.4 Who should promote groundwater pollution protection?

The principle that the “polluter pays” should be applied in cases of groundwater pollution. However the source of pollution may be difficult to definitively ascertain in cases of diffuse pollution and in urban/industrial environments where there are multiple point sources causing pollution.

The ultimate responsibility for groundwater pollution protection must lie with the relevant agency of national or local government. Nevertheless, an obligation also exists on water-service companies to be proactive in undertaking pollution hazard assessments for their groundwater sources.

Who manages/maintains groundwater protection zones in your country? Are there any reforms that you would recommend?

A technical guide has been produced by GW-MATE (2002) for groundwater professionals to help them undertake groundwater pollution hazard assessments for water-service utilities, and to develop pollution protection strategies for environmental agencies. There should be interaction between the relevant groundwater authority or environmental agency and the various industries/developments that generate pollution loads based on groundwater pollution hazard maps and the contaminant loads generated.

A system of permits and regulations may be used to manage waste discharges and to specify what may be discharged and the design parameters for different waste receptacles/ponds, depending on the mobility and toxicity of the waste material. To be cost effective, such systems should not ignore natural aquifer protection and vulnerability considerations.

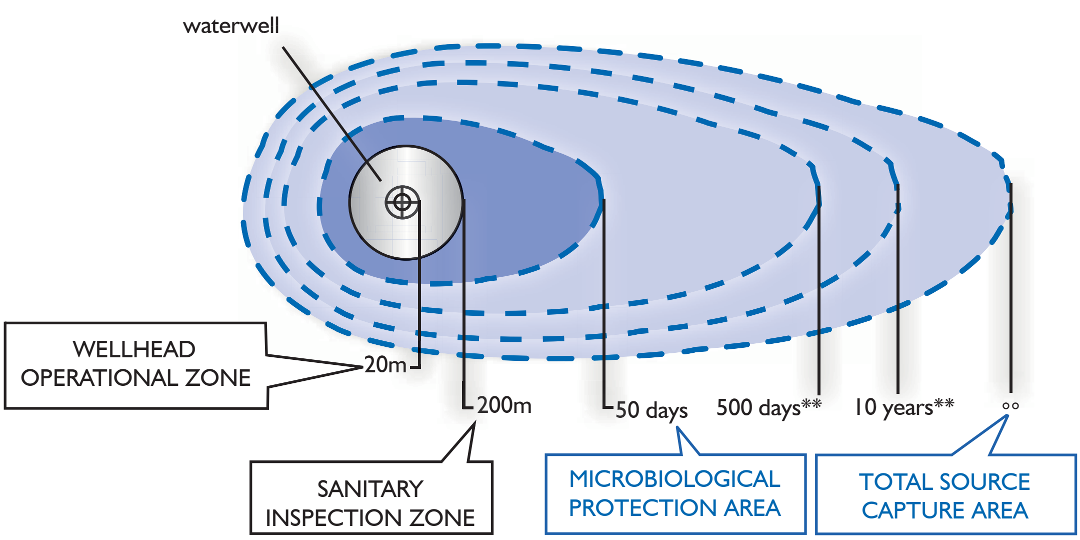
In summary:

- The principle that the "polluter pays" should be applied in cases of groundwater pollution.
- The ultimate responsibility for groundwater pollution protection must lie with the relevant agency of national or local government.

3.5 Urban wastewater and groundwater quality

Urban wastewater may be considered as a special case for groundwater quality management. This is because urban wastewater generation is unavoidable, ubiquitous and growing in volume all the time as cities grow. In addition, there are very real benefits that can be realized from urban wastewater such as groundwater recharge

Figure 8.4. Groundwater protection zones are a simple but powerful tool for protecting important groundwater sources. Restrictions on various activities are imposed, depending on the zone, typically based on the flow time to the abstraction point.



* *empirical fixed radius area*
** *intermediate flow-time perimeters sometimes used*

and the provision of irrigation water for certain crops. Alongside such benefits, urban wastewater also contains real hazards in terms of bacterial pathogens and industrial wastes with a wide range of organic and inorganic substances.

How does urban wastewater relate to groundwater?

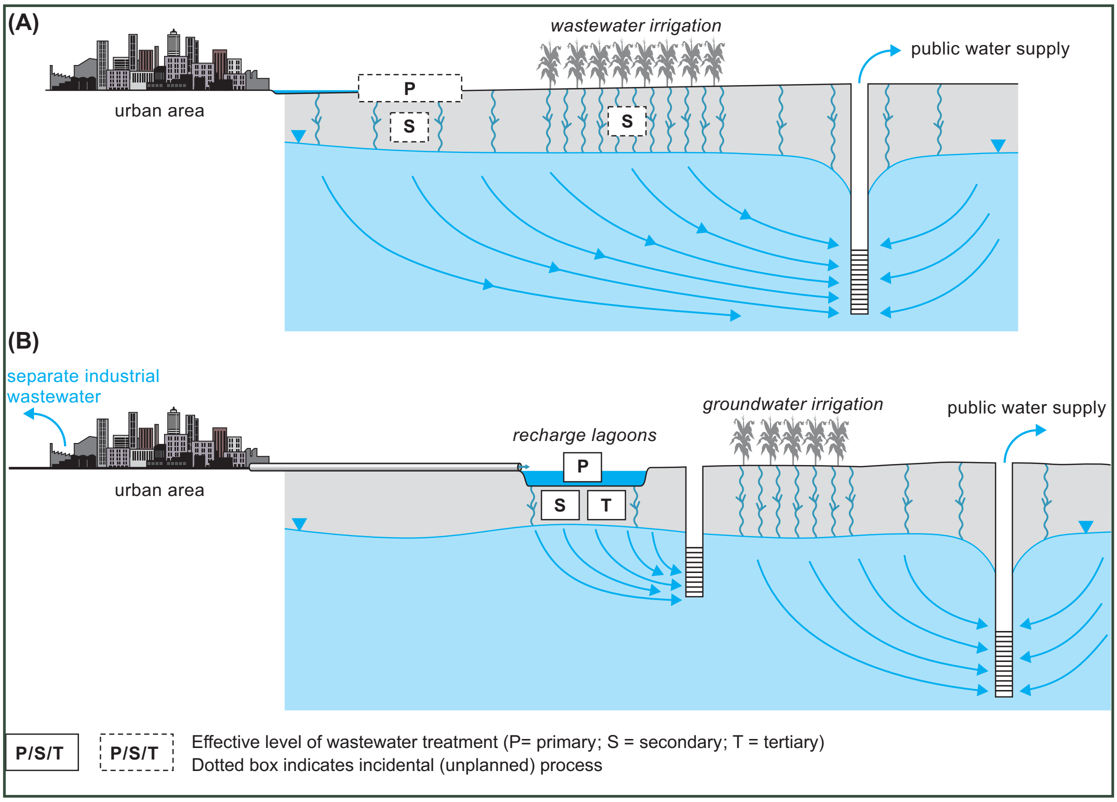
There is steadily-increasing wastewater generation by most growing cites and the management of this wastewater is a significant problem for cities, especially in developing countries. Unfortunately many sewerage systems discharge directly to surface watercourses with minimal treatment and little dilution in the dry season. The rather rudimentary and common wastewater handling and reuse practices in developing nations tend to generate high rates of infiltration to underlying aquifers especially in the more arid climates. Infiltration through the ground improves the wastewater quality and stores it for future use, but can also pollute groundwater. Figure 8.5 (A) illustrates typical waste water management practice in many developing cities, while figure 8.5 (B) indicates some simple adaptations that help to improve the situation.

Wastewater infiltration to groundwater occurs directly from sanitation and wastewater facilities and agricultural irrigation with wastewater. Aquifer recharge is an integral part of the wastewater reuse processes. Moreover wastewater is very popular with poorer farmers due to its year round continuous availability and high plant nutrient content, but nevertheless it does constitute a public health risk.

What types of measures are available for reducing risks and increasing benefits?

Because groundwater is often preferred for public water supply and also widely used for private domestic use, wastewater pollution of aquifers is a serious consideration. Little progress in reducing this hazard is likely to be made in the developing world by simply advocating rigorous quality standards, which may not be attainable.

Figure 8.5 General schemes of wastewater generation, treatment, reuse and infiltration to aquifers.
A: commonly occurring unplanned and uncontrolled situation;
B: treatment/ recharge lagoons.



Rather it is important to identify cost effective interventions and incremental investments to reduce the risks to groundwater users. A high priority is to improve wastewater characterization to assess the groundwater pollution hazard. If there are persistent contaminants in the waste water, it is generally better to control at these at the source by separate collection and disposal.

Major incidental recharge of aquifers through wastewater handling and reuse is so widespread that it should always be contemplated as an integral part of wastewater management, and thus planned for accordingly. It is always important to consider both the benefits and the hazards of wastewater recharge to aquifers and how hydrogeological environments vary with regard to pollution vulnerability.

- Compatibility between wastewater reuse and groundwater supply interests can be achieved through:
  - increasing the depth and improving the sanitary sealing of potable waterwells;
  - establishing appropriate source protection areas for such waterwells;
  - seal wastewater treatment ponds (Fig. 8.5 B);
  - increasing groundwater monitoring for contaminants ;
  - using irrigation wells to recover most of the wastewater infiltration and provide a 'hydraulic barrier' for the protection of potable water supplies (Fig. 8.5 B);
  - improving irrigation water-use efficiency and thus wastewater recharge to underlying aquifers;
  - urging constraints on the use of shallow private domestic wells.

What happens to waste water from your cities?

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Purdue University, GROUND WATER PRIMER - Water Quality. www.purdue.edu/envirosoft/groundwater/src/quality.htm

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EXERCISE

Purpose: To share experience of groundwater quality problems.
Activity: Break into groups of 4 or 5. 1 hour.
Each group to

1) Identify a common groundwater quality problem in one of your countries.
2) Discuss the nature and scale of the problem – is it anthropogenic or natural?
3) How is the problem being managed and who is responsible for the management?
4) What have been the aims of the management and has it been successful?
5) What would you change to improve the management of the problem?

Report back: 15 minutes per group.

Alternate Exercise:
Waste Management – Role Play.

You are required to improve waste management/effluent disposal in the capital city in your country. Participants divide into stakeholders: Water/groundwater managers; waste disposal companies; industry discharging effluent; citizen groups; politicians.

The water managers must propose sweeping reforms to improve all aspects of waste management in the city for the specific purpose of protecting water quality of groundwater (and surface water). The other stakeholders should raise queries about the impact of the changes on them, and make objections or suggestions to the water managers.

Preparation: 20 minutes
Debate: 40 minutes.

Module 9: Groundwater Monitoring

Learning Objectives:

- Why and how to monitor aquifer water level changes over time.
- Why and how to monitor water quality changes over time.
- How to monitor compliance.
- How to manage aquifer response and quality threats.

1. Introduction

Groundwater monitoring and groundwater data acquisition are pre-requisites for any effective management of groundwater resources. Monitoring makes groundwater visible. Monitoring may include the quality and availability of the resource itself, and compliance with abstraction and disposal regulations and permits. In the absence of monitoring, groundwater abstraction and waste disposal take place without any safeguard for this essential resource, and excessive use and contamination of an aquifer may continue unchecked for years until that groundwater resource is effectively destroyed.

The design and operation of any groundwater monitoring system needs to be carefully planned so that relevant and useful information for management purposes can be obtained in a sustainable, cost effective manner. In the initial stages, it is advisable to focus monitoring activities on critical targets such as heavily pumped aquifers and strategic groundwater resources. The monitoring network can then be developed incrementally, expanding as required and as resources and personnel become available.

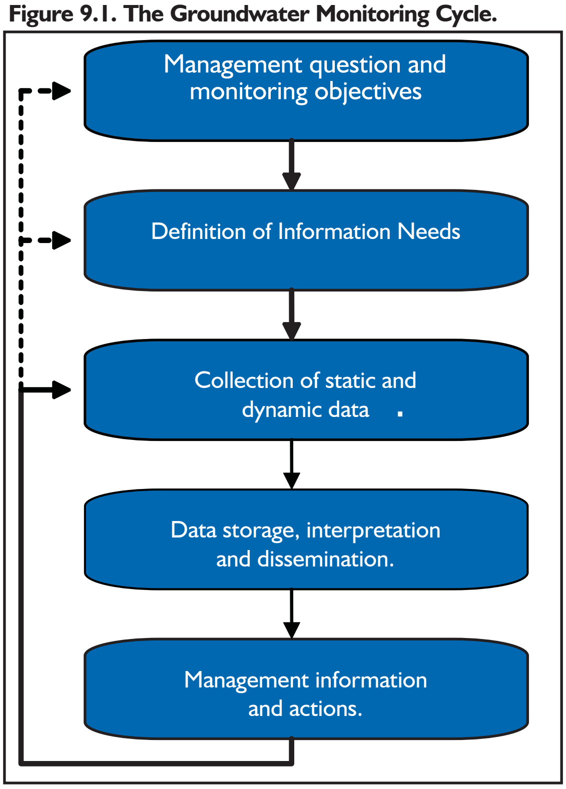
1.1 The groundwater monitoring cycle

Groundwater and aquifer monitoring improves the evaluation and management of groundwater resources. Since groundwater is an extensive, concealed and relatively inaccessible resource, its management is far from simple and requires data that can only be collected by monitoring a variety of groundwater parameters over time. Changes in quantity and quality are often very slow processes occurring below large land areas that cannot be determined by simple, one-off snapshot surveys. As a result, elaborate monitoring networks and data interpretation are needed in order to provide key inputs for effective aquifer management of the various effects of groundwater abstraction and contamination.

The monitoring cycle includes a complete system of problem definition, management objectives, information needs, data acquisition, data storage, interpretation and dissemination, giving rise to relevant accurate information and consequent management actions. All too often data is collected, but never stored adequately, nor interpreted for practical management needs, nor disseminated to stakeholders. Such incomplete monitoring may be entirely ineffective, and worse, it may delude stakeholders into believing that the groundwater resource is being managed effectively. Figure 9.1 explains the monitoring cycle.

There are two fundamentally different types of monitoring. These are resource monitoring which is essentially a scientific activity, and com-

Figure 9.1. The Groundwater Monitoring Cycle.



pliance monitoring which is more of a community activity.

Resource monitoring considers the changes in quality and quantity of the groundwater resource over time, while compliance monitoring assesses the behaviour of the groundwater stakeholders/users and the impact of their activities on the resource

1.2 Benefits of monitoring

One of the most important reasons for monitoring is to ensure that "excessive" groundwater abstraction does not take place, and the consequences, Fig 9.2, are avoided.

- As groundwater is pumped, the water levels decline, cost of pumping increases, and baseflow/spring-flow is reduced. These are normal consequences of any groundwater pumping and are reversible impacts.
- As pumping is further increased, aquifer compaction starts to occur with a consequent reduction in aquifer transmissivity and further reduction in well yields. Ecological impacts also escalate with damage to and loss of phreatophytic vegetation. Water quality may start to decline.
- When pumping becomes excessive, irreversible impacts start to occur and there is permanent aquifer damage. Saline water intrusion and the ingress of polluted water are two effects that are very difficult or even impossible to reverse on any reasonable timescale. Land subsidence can occur with permanent aquifer compaction and a consequent major loss of storage capacity.
- It is such impacts that can be avoided by a well designed monitoring of aquifer responses to pumping, combined with effective management interventions to reduce abstraction.

1.3 How is monitoring done?

Any monitoring network should be designed to achieve specific objectives as determined by a number of management questions with regard to one or more aspects of the groundwater resource.

In an ideal situation, dedicated monitoring or observation wells will be installed. Such wells are **keyholes to aquifers**, which allow groundwater level, piezometric pressure and water quality measurements to be made. These wells should be located and designed to detect potential changes in groundwater flow and quality. A series of observation wells coupled with a selection of abstraction wells normally comprise a **monitoring network**, designed to

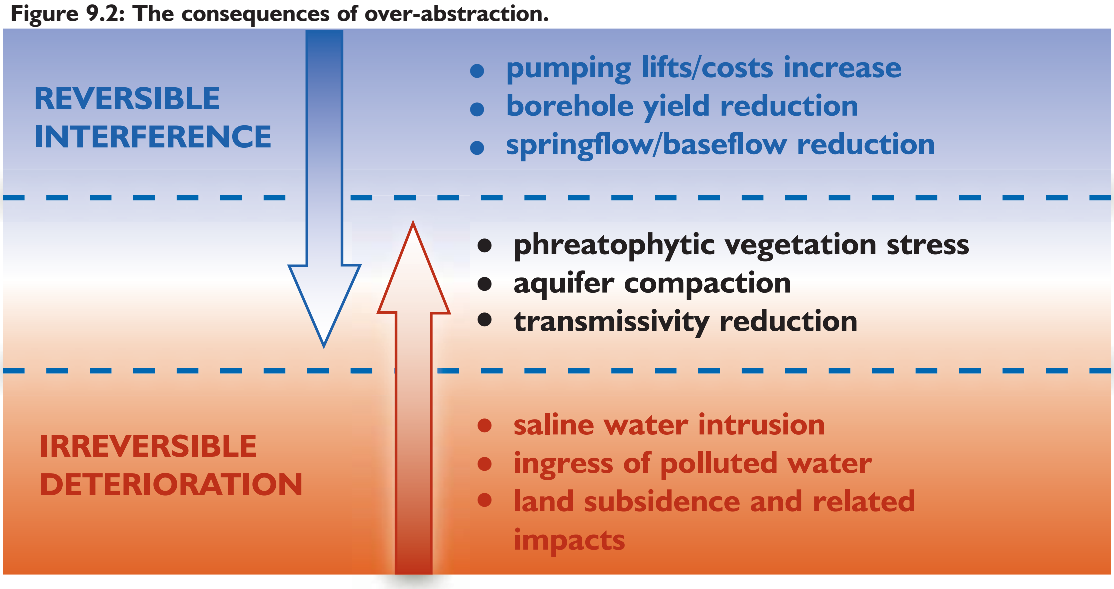
- Detect changes in groundwater storage, flow and quality
- Assess specific risks to the aquifer
- Assess aquifer recharge and discharge

Can you comment on the benefits and challenges of GW monitoring in your country?

In order to provide a complete picture, monitoring systems need to also assess

- Abstraction rates
- User compliance with both abstraction and effluent discharge permits.

Figure 9.2: The consequences of over-abstraction.



The following table 9.1 summarises the type of data needed for monitoring.

Fig. 9.3 shows a theoretical condition where monitoring has revealed over-abstraction, and management actions to reduce pumping have been introduced to stabilize the situation. The continued collection of monitoring data will allow the managers to review the efficiency of the restrictions introduced, and allow modification if necessary. This example simplifies the reality quite considerably, since aquifers are generally highly heterogeneous, recharge highly variable both spatially and temporally, and groundwater flow systems are complex.

Table 9.1. Types of data required for groundwater management

TYPE OF DATA	BASELINE DATA (From Archives)	TIME VARIANT DATA (from field stations)
Groundwater occurrence and aquifer properties	• Water well records (hydrogological logs, instantaneous groundwater levels and quality) • Well and aquifer pumping tests	• Groundwater level monitoring • Groundwater quality monitoring
Groundwater use	• Water well pump installations • Water use inventories • Population registers and forecasts • Energy consumption for irrigation	• Water well abstraction monitoring (direct or indirect) • Well groundwater level variations
Supporting information	• Climatic data • Land use inventories • Geological maps/ sections	• Riverflow gauging • Meteorological observations • Satellite land use surveys

2. How can we ensure that groundwater monitoring is cost effective?

It is costly and unnecessary to implement groundwater monitoring for its own sake, and it leads to inefficient use of manpower and budgets. Effective groundwater monitoring should be driven by a specific objective and the data collected should not only be used for the explicit purpose of the monitoring program, but should also be systematically stored for future use.

In Fig. 3.2 (Module 3), the various stages of aquifer exploitation are indicated. During the early stages, it is not essential to monitor, although baseline monitoring is advisable if resources are available. As the aquifer becomes more heavily used, then groundwater monitoring becomes essential. At any stage it is advisable to monitor strategically important groundwater resources and groundwater under potential threat from pollution or salinisation.

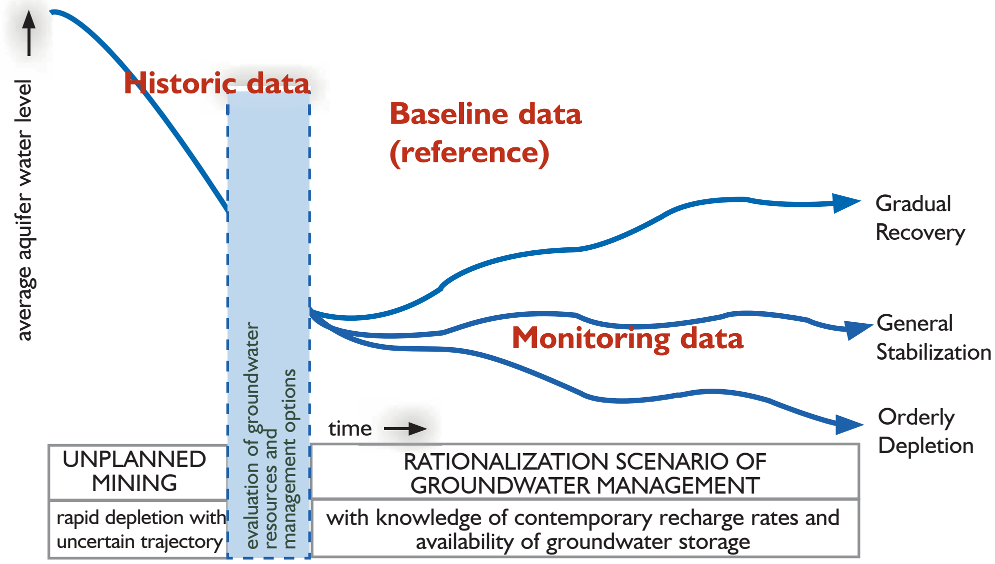
The objective of monitoring is to reveal the changes taking place in the groundwater resource over time, and thereby allow managers to introduce changes and restrictions on the way the groundwater resource is used to minimize the negative effect of these impacts.

The effectiveness of groundwater monitoring can be improved by careful attention to network design, system implementation and data interpretation. Data collected by past monitoring activities should be used and not discarded or lost. If possible, monitoring stations should be easily accessible. Where possible, the use of indicator determinants can reduce analytical costs very significantly. Monitoring accuracy, both for physical and chemical parameters, must be ensured by incorporating quality control procedures. Complementary self-monitoring amongst water users helps reduce costs and also has the benefit of increasing stakeholder awareness and participation in groundwater management.

Figure 9.3: Monitoring combined with management actions (reduced pumping in this case) can lead to more stable development of the groundwater resource.

Although groundwater monitoring is often considered expensive, in the longer run the return

Figure 9.3: Monitoring combined with management actions (reduced pumping in this case) can lead to more stable development of the groundwater resource.



can be substantial in terms of saving groundwater resources & reducing treatment costs.

- Groundwater monitoring for its own sake is unnecessary and wasteful.
- Monitoring systems / networks should be specifically designed for an explicit purpose
- Although groundwater monitoring is expensive, in the long run, it can be very cost effective by saving groundwater resources and reducing remediation costs.
- Stakeholder participation in monitoring can assist in reducing costs and improve awareness of the groundwater resource.

2.1 Basic design of a monitoring network

Although the design of an effective monitoring network requires a significant amount of data and specialized knowledge, some basic guidelines can be given to provide an initial understanding on monitoring design.

What is the objective of monitoring?

This is the first basic question to be answered. Is monitoring to ensure compliance with abstrac-

Table 9.2. Classification of groundwater monitoring systems by function.

SYSTEM	BASIC FUNCTION	WELL LOCATIONS
Primary (reference monitoring)	**Evaluation of general groundwater behaviour:** • Trends resulting from land use change and climatic variation • Processes such as recharge, flow and diffuse contamination	• In uniform areas with respect to hydrogeology and land use
Secondary (protection monitoring)	Protection against potential impacts on: • Strategic groundwater resource • Wellfields/ springs for public water supply • Urban infrastructure from land subsidence • Archaeological sites against rising water table • Groundwater dependent ecosystems	• Around areas/ facilities/ features requiring protection
Tertiary (pollution containment)	Early warning of groundwater impacts from: • Intensive agricultural land use • Industrial sites • Solid waste landfills • Land reclamation areas • Quarries and mines	• Immediately down and up hydraulic gradient from hazard

tion or effluent discharge permits; or is it to assess the effects of heavy pumping from a major well field supplying a critical industry; or is it to monitor the effects on groundwater quality in a vulnerable aquifer from a waste disposal facility? Or is monitoring being carried out as scientific baseline data for the purpose of assessing natural recharge rates and water quality? (Table 9.2)

It should be noted that monitoring need only take place if there is some form of threat to the groundwater. Aquifers that are heavily utilized, or are showing large declines in water levels, or are highly vulnerable to a pollution threat are the ones that need to be monitored first. Small aquifers serving isolated rural communities may not warrant the cost of monitoring.

What to monitor?

The purpose of the monitoring controls the parameters that need to be monitored. For resource management purposes, specific abstraction rates from high yielding production wells and spatially distributed water levels over time will be required to assess the effect of pumping on the aquifer.

Pollution monitoring will require groundwater sampling and analysis for the specific pollutant of concern (or an alternative indicator parameter that is easier and cheaper to analyse) to provide an adequate representation of the location and concentration of the actual pollutant. Monitoring of effluent discharges is an important part of pollution monitoring.

Monitoring for saline intrusion will require the monitoring of the electrical conductivity in wells at different depth. Monitoring for pollution in recent recharge would require monitoring of either the unsaturated zone or the upper levels of the aquifer.

There are many possible reasons for establishing a monitoring system, and what is monitored will be as diverse as these reasons. It may also be necessary to monitor a number of different parameters to adequately characterize the groundwater system response over time.

Where to monitor?

In order to monitor effectively, it is essential to understand the groundwater flow system and the location of the recharge and discharge areas. Monitoring wells should be located in the correct areas in order to provide the required information. For example, there is little value in monitoring water quality up gradient from a point source of pollution, since the groundwater flow will carry the pollutants away from the monitoring well. The effects of density, solubility, diffusion, dispersion and adsorption on the movement of each particular contaminant also have an impact on how it will spread in the groundwater system. Dense immiscible pollutants may sink to the base of the aquifer, while light liquids will float on top of the groundwater.

In terms of aquifer resources, the recharge and discharge areas may be significant. Considerable water level declines may be occurring in the recharge and mid-flow regions of the aquifer, while at the discharge area, the water level declines may be much less. The cone of depression generated by well field pumping is likely to have an irregular profile that has been distorted both by the groundwater flow direction and by the natural anisotropies occurring in the aquifer material, and such considerations need to be factored in when selecting monitoring points and when analysing the data. Confined aquifers exhibit pressure declines over a much wider areal extent than phreatic aquifers, and sampling points need to be more widely spaced. If economically possible the monitoring should focus on the overall impact to the aquifer, rather than just the impact in the vicinity of the well or well field.

How to monitor?

Monitoring should be carried out in a correct and controlled manner, with clearly laid out procedures for data collection, quality control, data storage, parameter analyses and data interpretation. There should be a specific organization tasked with the monitoring in each instance. The flow of information from the monitoring program to the groundwater managers should follow a clear routine. Participatory monitoring by groundwater users, particularly for abstraction/use and also for water levels, can assist in

Table 9.3. Basic success rules for groundwater monitoring programmes

NETWORK DESIGN	• Objectives must be defined and the programme adapted accordingly • Groundwater flow systems must be understood • Sampling locations and monitoring parameters must be set by objectives
SYSTEM IMPLEMENTATION	• Appropriately constructed observation and abstraction wells must be used • Field equipment and laboratory facilities must be appropriate to objectives • A complete operational protocol and data handling system must be established • Groundwater and surface water monitoring should be integrated where applicable
DATA INTERPRETATION	• Data quality must be regularly checked through internal and external controls • Decision makers should be provided with interpreted management – relevant data sets • Programme should be periodically evaluated and reviewed

reducing monitoring costs and also helps to integrate users into the management of the resource.

Monitoring may require specifically constructed and designed monitoring wells. These wells may penetrate a number of different aquifer strata which need to be monitored and sampled independently. This will require a series of access tubes sampling different levels in the well and separated by appropriately positioned impermeable seals. Specific sampling procedures are required to avoid various impacts such as degassing, air entry, etc. Some analyses should be carried out on site; other samples need to be collected and stored in specific different ways depending on the parameters to be analysed (see Table 9.4). The field sampling structure should be integrated with the available laboratory capacity and funding.

When to monitor?

Monitoring is the collection of time variant data from sampling points, and the time interval between samples should be such as to avoid unnecessary expense, while making sure that all significant variations are captured. Typically sampling will be carried out seasonally to capture the impact of natural recharge and discharge. When new external stresses are placed on the aquifer system, then the sampling program should be adjusted to try and capture the impact of those stresses.

Data interpretation.

Data from groundwater monitoring should be analysed in conjunction with available data from surface water monitoring for integrated water management. Effective communication of the results from data interpretation to water managers is an essential component of monitoring, and it is hardly worth monitoring if the information is not put to use. Complex tools for data interpretation such as numerical models are useful for preparing predictive scenarios for management of the water resources.

In summary, it can be seen that the design and implementation of a monitoring network may be a highly complex task, but even some basic monitoring can be very useful, provided it is carried out in a well structured and intelligent manner.

Is there any stakeholder participation in monitoring?

3. How should the responsibility for groundwater monitoring be shared?

Groundwater legislation should make provision for monitoring groundwater use, levels and quality status. Both water resources administrators and water users should assume some of the responsibility for these tasks.

A typical division of responsibilities may be:

- Central Government/National Water Authority—basic reference network
- Regional/Basin/Aquifer Water Resource Agency—resource regulation and protection functions
- Water Well Contractors/Drilling Companies—obligations for well logs and pump testing

- Large Groundwater Abstractors—records of metered well abstraction and water levels
- Small Groundwater Abstractors—general feedback on well characteristics and performance
- Potential Groundwater Polluters—defensive quality monitoring at site level.

The storage of groundwater monitoring data is an important issue, and data storage at the lower territorial level will be more effective but copies should be kept centrally for public access. It is vital that data should be accessible to water managers and users but also that it be kept securely for future reference/use.
Participatory groundwater monitoring by users can help to reduce the burden on the authorities and also increase understanding of the groundwater system amongst water users, but may be difficult to implement, particularly when the groundwater system is not under stress. It will require significant capacity building and training to establish an effective participatory groundwater monitoring regime.

How is monitoring information used and are there effective mechanisms for information feedback to stakeholders?

4. Monitoring network design

Measuring Groundwater Use & Aquifer Response.

By monitoring abstraction and changes to water levels, the effect of pumping from the aquifer can be assessed and this provides key information for groundwater resource management. Well-fields are typically designed on the basis of an **acceptable predicted aquifer response** for a certain level of abstraction – based on numerical modelling which simulates different abstraction scenarios. Well-field construction and abstraction licenses are then issued on the basis of such predictions.

The groundwater flow direction & rate is controlled by the gradient, which can be determined from the observed water levels in the aquifer. If the area over which the water level changes take place and the porosities of the aquifer are known, then the volumetric recharge or discharge can be computed.

Aquifer monitoring plays an important role in this context because:

- historic data are used to calibrate numerical aquifer models, and allow reliable simulations of future abstraction scenarios
- measuring (and archiving) the reference situation for new abstraction wells is important to provide baseline information for the evaluation of future changes
- observations of groundwater levels and pumping rates during well-field operation provides information to verify the predicted aquifer response and, if necessary, take timely action to reduce abstraction
- the information collected can also play a key role in increasing awareness among water users, and thus facilitate the introduction of required groundwater demand management measures. This can then lead to participatory monitoring.

What are key issues in monitoring groundwater level fluctuations and trends?

Groundwater level measurements in observation or abstraction wells can be made manually or automatically, and should always be subject to quality checks. Groundwater level changes observed through monitoring may have widely differing causes and should be carefully evaluated to determine the correct management action required.

Groundwater monitoring networks must be designed by specialists on the basis of management requirements with a special focus on recharge or discharge areas. Determining the extent of the recharge areas can be complex, since they are generally diffuse extensive areas with different lithologies, soils, and land uses.

How to monitor abstraction.

Direct monitoring of groundwater abstraction by water meters is accurate but costly since meters have to be fitted to all pump outlets, and requires the full cooperation of water users, which is not always easy to achieve.

Indirect monitoring of groundwater abstraction can be carried out by:

- Collection of indicative data—for example irrigation groundwater use can be estimated indirectly using hours of pump operation (from energy consumption) multiplied by average pumping rate
- Use of remote sensing—satellite or airborne sensors can provide objective measurements at potentially large scales, with quasi-continuous cover at low cost per km2. These techniques are expanding rapidly with different sensors and approaches all the time. Such information as the areal extent of irrigated land, or the daily and cumulative actual evaporation can be assessed.
- Estimates of change in regional groundwater abstraction can also be obtained through information on demographic changes and random checks on per capita water use.

Detecting Groundwater Quality Changes

What is the purpose of water quality monitoring?

The purpose of water quality monitoring is to:-

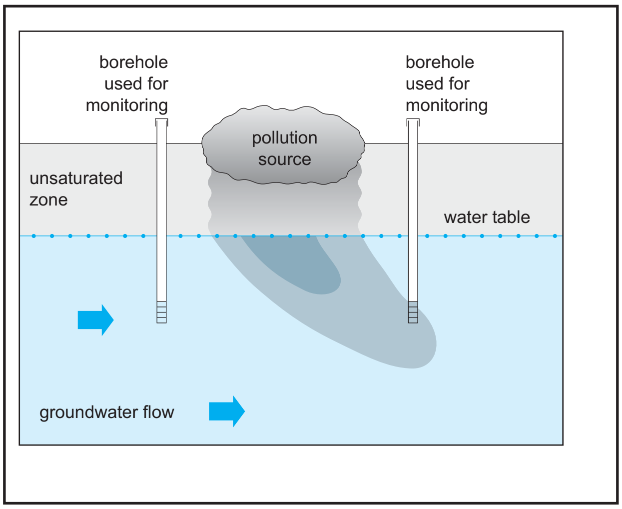
- to facilitate the early warning of the onset of groundwater pollution from a given activity and allow the timely introduction of any necessary control measures
- to provide advance warning of the arrival of polluted water at an important groundwater supply source and thus make provision for treatment or other mitigation
- to identify any contamination reaching an aquifer from a potential major pollution source and thus take early remedial action

Table 9.4 Summary of sampling procedures and precautions for specific groups of groundwater quality parameters

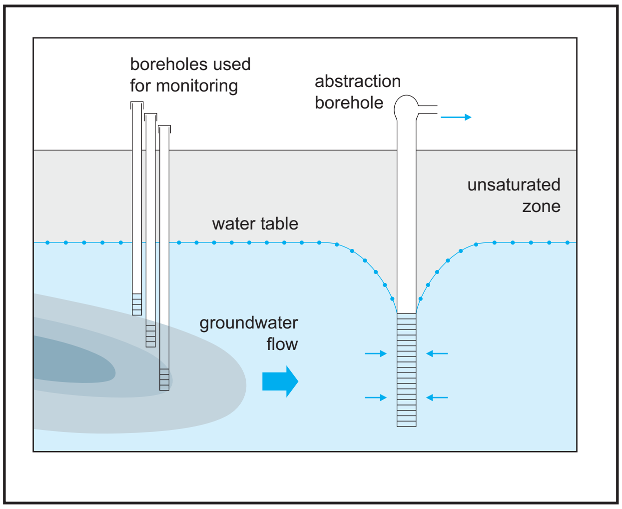
DETERMINAND GROUP	SAMPLING PROCEDURE	PREFERRED MATERIALS	STORAGE TIME/ TEMP	OPERATIONAL DIFFICULTY/ COST
Major Ions Cl, SO_4, F, Na, K	• 0.45 μm filter only • no acidification	Any	7 days/4 °C	Minimal
Trace Metals Fe, Mn, As, Cu, Zn, Pb, Cr, Cd, etc	• sealed 0.45 μm filter • acidify (pH <2) • avoid aeration through splashing /head space	Plastic	150 days	Moderate
N Species NO_3, NH_4 (NO_2)	• sealed 0.45 μm filter	Any	1 day/4 °C	Moderate/ low
Microbiological TC, FC, FS	• sterile conditions • unfiltered sample • on-site analysis preferred	Dark glass	6 hours/4 °C	Moderate/ low
Carbonate Equilibria pH, HCO_3, Ca, Mg	• unfiltered well-sealed sample • on-site analysis (pH, HCO_3) (Ca/Mg at base laboratory on acidified sample)	Any	1 hour (150 days)	Moderate
Oxygen status pE(EH), DO, T	• on site in measuring cell • avoid aeration • unfiltered	Any	0.1 hour	High/moderate
Organics TOC, VOC, HC, ClHC, etc	• unfiltered sample • avoid volatilization • (direct absorption in cartdridges preferred)	Dark glass or teflon	1–7 days (indefinite for cartridges)	High

Figure 9.4 Schematic representation of groundwater quality monitoring network design for specific management objectives.

a) Offensive detection monitoring



b) Defensive detection monitoring



Who carries out ground water monitoring in your country? Is the data collected used for aquifer management?

- to establish evidence to determine legal liability for groundwater pollution incidents.

How to monitor for groundwater quality.

A primary focus of groundwater quality monitoring is usually the public water supply from water wells and springs via piped distribution systems (Fig 9.4). A "full" water quality analysis is initially required (ideally), followed by more limited analysis of carefully selected indicator parameters with periodic checks on other important parameters that are more complex or expensive to analyse. However this type of monitoring does not normally correspond to the condition of groundwater in situ, which is essential for aquifer monitoring programs which have to define the subsurface distribution of groundwater of inferior quality, its variation with time and its response to management mitigation measures.

The process of well pumping and sample handling may cause major sample modification such as air entry, degassing and volatile losses which need appropriate sampling procedures. In addition, such sampling provides a mixed sample with ground water obtained from all the aquifer strata intersected by the well. Depth specific sampling can be used to sample specific strata/depths and is needed to determine the different water quality (and head) in different units in layered aquifer systems.

In many cases the critical requirement is to obtain an early warning of potential quality problems that may threaten the groundwater source and the aquifer system. To achieve this, it is necessary to design monitoring networks that obtain groundwater samples that are representative of the quality of the more recent recharge. This will often be markedly different from the average quality of groundwater in aquifer storage. Moreover, vertical changes in the groundwater quality need to be assessed by depth specific sampling.

The rapid growth of urban and industrial waste disposal to the ground, and intensive agriculture, is necessitating a major expansion of focused groundwater quality management monitoring.

5. Summary

There may be several reasons for a groundwater monitoring. Whatever the reason, groundwater monitoring is always expensive and requires skilled human resources and funding over a long time period. Monitoring may be to ensure equity in access to the groundwater resource or to reduce abuse of abstraction or effluent discharge permits, etc. Wherever possible it will be beneficial to involve stakeholders and groundwater users in the monitoring process.

Monitoring is a fundamental component of aquifer management and provides the necessary information for management decisions to protect the groundwater resource from excessive abstraction and from pollution. Permanent negative impacts associated with over-pumping and pollution can be avoided by a well designed and managed monitoring system that provides timely information on aquifer responses to pumping or contaminant loading.

References and Web Reading

European Environment Agency, 1997. Groundwater Monitoring in Europe. www.eea.europa.eu/publications/92-9167-032-4

GW•MATE, 2002-2006, Briefing Note 9. http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTWAT/0,,contentMDK:21760540~menuPK:4965491~pagePK:148956~piPK:216618~theSitePK:4602123,00.html

University of California, Groundwater level monitoring: what is it? How is it done? Why do it? http://ucce.ucdavis.edu/files/filelibrary/2280/12024.pdf

Waterwatch Australia, National Technical Manual, Module 6 - groundwater monitoring. www.waterwatch.org.au/publications/module6/index.html

EXERCISE
Break into groups of 4 or 5 Design a monitoring system either for groundwater quality or for groundwater abstraction/ water levels. Explain the key steps in your design in terms of: 1) installation/selection of monitoring wells based on the aquifer characteristics and aquifer use; 2) data acquisition (who, frequency, etc); 3) data storage and interpretation; 4) implementation of aquifer management as a result the monitoring program. Table 9.3 is a good starting point for this exercise. **Time: 1 hour.** **Feedback: 15 minutes per group.**

Module 10: Groundwater and Climate Change

Learning Objectives[1]:

- To become familiar with the basic concepts of the impacts of climate change on groundwater
- To appreciate the main implications of climate change on groundwater dependent system and sectors
- To understand the basic concepts of adaptive groundwater management

1. Fundamental concepts

1.1 Groundwater and the hydrologic cycle

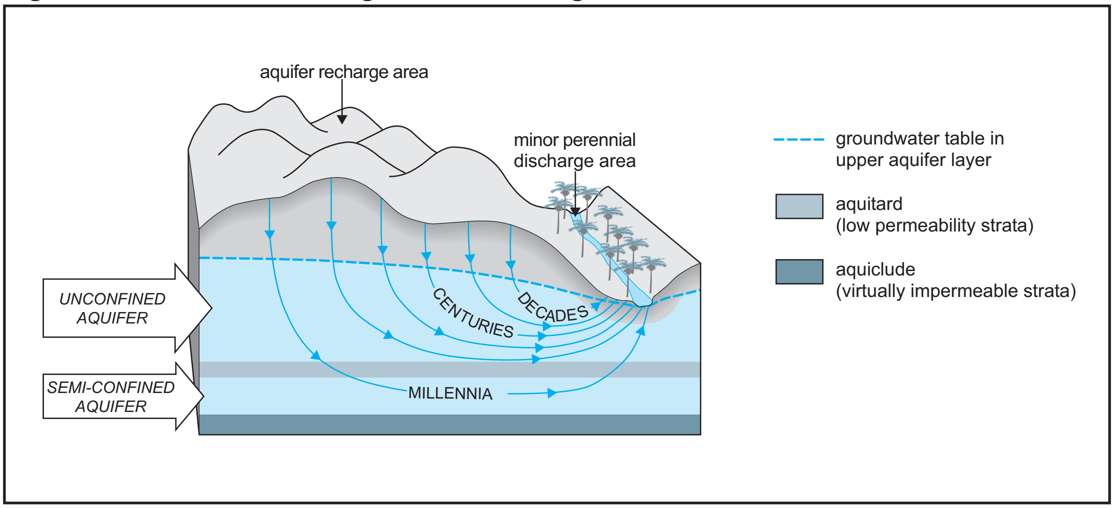
The hydrologic cycle represents the continuous movement of water between the atmosphere, the earth's surface (glaciers, snowpack, streams, wetlands and oceans) and soils and rock. The term groundwater refers to water in soils and geologic formations that are fully saturated. Groundwater flow (see Fig. 10.1) is driven by recharge (through the soil profile or via stream channels and wetlands) and discharge (through evapotranspiration, abstraction, seepage, springflow etc). The difference between recharge and discharge determines the volume of groundwater storage.

Any variations in climate have the potential to affect recharge, discharge and groundwater quality, either directly or indirectly. An example of a direct impact would be reduced recharge due to a decrease in precipitation. Sea water intrusion to coastal aquifers due to increased temperature and sea level rise represents an indirect influence on groundwater quality. Groundwater quantity and quality can also be affected by water and land use change.

1.2 Climate change and hydrologic variability

Climate change is "an altered state of the climate that can be identified by change in the mean and/or variability of its properties and that persists for an extended period, typically decades or longer". It may be due to "natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use" (IPCC, 2007).

Figure 10.1: Groundwater recharge, flow and discharge



Over the past 150 years global mean temperatures have increased with the rate of warming, accelerating in the past 25 to 50 years. This process will continue in the future (IPCC, 2007).

Climate also varies in response to natural phenomena, on seasonal, inter-annual, and inter-decadal scales such as the El Nino Southern

1 The content of this module is largely based on the report prepared for the World Bank Economic and Sector Analysis on Climate Change and Water (World Bank, 2009). For the case study on managed aquifer recharge, use is made of Van Steenbergen, (2009). Both publications are available as background document to this Module. Other important background information is given in the references.

Table 10.1 Projected impact of global warming for primary climate and hydrologic indicators

Variable	Projected future change*
Temperature	Temperatures are projected to increase in the 21st century, with geographical patterns similar to those observed over the last few decades. Warming is expected to be greatest over land and at the highest northern latitudes, and least over the Southern Oceans and parts of the North Atlantic ocean. It is very likely that hot extremes and heat waves will continue to become more frequent.
Precipitation	On a global scale precipitation is projected to increase, but this is expected to vary geographically - some areas are likely to experience an increase and others a decline in annual average precipitation. Increases in the amount of precipitation are likely at high latitudes. At low latitudes, both regional increases and decreases in precipitation over land areas are likely. Many (not all) areas of currently high precipitation are expected to experience precipitation increases, whereas many areas of low precipitation and high evaporation are projected to have precipitation decreases. Drought-affected areas will probably increase and extreme precipitation events are likely to increase in frequency and intensity. The ratio between rain and snow is likely to change due to increased temperatures.
Sea level rise	Global mean sea level is expected to rise due to warming of the oceans and melting of glaciers. The more optimistic projections of global average sea level rise at the end of the 21st century are between 0.18-0.38 m, but an extreme scenario gives a rise up to 0.59 m. In coastal regions, sea levels are likely to also be affected by larger extreme wave events and storm surges.
Evapo-transpiration	Evaporative demand, or potential evaporation, is influenced by atmospheric humidity, net radiation, wind speed and temperature. It is projected generally to increase, as a result of higher temperatures. Transpiration may increase or decrease.
Runoff	Runoff is likely to increase at higher latitudes and in some wet tropics, including populous areas in East and South-East Asia, and decrease over much of the mid-latitudes and dry tropics, which are presently water stressed. Water volumes stored in glaciers and snow cover is likely to decline, resulting in decreases in summer and autumn flows in affected areas. Changes in seasonality of runoff may also be observed due to rapid melting of glaciers and less precipitation falling as snow in alpine areas.
Soil moisture	Annual mean soil moisture content is projected to decrease in many parts of the sub-tropics and generally across the Mediterranean region, and at high latitudes where snow cover diminishes. Soil moisture is likely to increase in East Africa, central Asia, the cone of South America, and other regions with substantial increases in precipitation.

***Relative to 1990 baseline. Source: IPCC (2007), World Bank (2009)**

Oscillation. The presence of, and degree of influence from, these natural phenomena will vary between countries and even watersheds.

Variations in climate will induce hydrologic change. Table 10.1 summarizes the variations in climate and hydrology that are projected to occur due to global warming. The potential impacts of these changes for groundwater resources are discussed in subsequent sections.

2. Impacts of climate change on groundwater

2.1 Recharge

Groundwater recharge can occur locally from surface water bodies or in diffuse form from precipitation via the unsaturated soil zone. Precipitation is the primary climatic driver for groundwater recharge. Temperature and CO_2 concentrations are also important since they affect evapotranspiration and thus the portion of precipitation that may drain through the soil profile to aquifers. Other factors affecting groundwater recharge include land cover, soils, geology, topographic relief and aquifer type.

The only global scale estimates of climate change impacts to groundwater recharge are those developed by Döll & Floerke (2005). According to their results, recharge – when averaged globally for the 2050s – will increase by 2%. This is less than the projected increases of 4% and 9% for annual precipitation and runoff. Geographical variations include:

- significant decreases in groundwater recharge (>70%) for north-eastern Brazil, the western part of southern Africa and areas along the southern rim of the Mediterranean Sea
- increased groundwater recharge (by greater than 30%) across large areas, including the Sahel, Northern China, Western US and Siberia
- potentially significant decreases in groundwater recharge for Australia, USA and Spain, although results vary significantly between climate models in these areas.

These global estimates identify regions where groundwater is potentially vulnerable to climate change. However, they are not appropriate for scaling down to a country or watershed scale. Precipitation and groundwater systems can vary significantly between watersheds and local data and information will be needed to estimate the changes on the country or watershed level.

Recharge is not only influenced by the magnitude of precipitation, but also by its intensity, seasonality, frequency, and type (Fig.10.2). Other factors are the geological setting of the area and changes in soil properties or vegetation type and water use.

2.2 Discharge

The impacts of climate change on groundwater discharge are less well understood. In part this reflects the difficulties in measuring discharge, and thus a lack of data to quantify discharge processes. Historically groundwater assessments have also been focused on understanding how much water enters the groundwater system and if this is suitable for human use. Less consideration has been given to the ecosystems groundwater supports, such as terrestrial vegetation and groundwater flow to springs, streams, wetlands and oceans.

For evapotranspiration, direct climate change impacts include: (1) changes in groundwater use by vegetation due to increased temperature and CO_2 concentrations, and (2) changes in the availability of water to be evaporated or transpired, primarily due to changes in the precipitation regime. Increased duration and frequency of droughts (due to increased temperatures and increased variation in precipitation) is likely to result in greater soil moisture deficits. Where soil water becomes depleted, vegetation may increasingly depend on groundwater for survival (if groundwater occurs in proximity to the root zone). During dry periods this may lead to increased evapotranspiration from groundwater. Indirect impacts associated with land use change may also affect groundwater evapotranspiration.

Groundwater flow to *surface water bodies* will be driven by relative head levels between groundwater and surface water. Consequently

Figure 10.2 Summary of climate change impacts on recharge under different climatic conditions.

High Altitude Regions	Temperate Regions	Arid and Semi-Arid Regions
Recharge may occur earlier due to warmer winter temperatures, shifting the spring melt from spring toward winter. In areas where permafrost thaws due to increased temperatures, increased recharge is likely to occur.	Changes to annual recharge will vary depending on climate and other local conditions. In some cases little change may be observed in annual recharge, however, the difference between summer and winter recharge may increase.	In many already water-stressed arid and semi-arid areas, groundwater recharge is likely to decrease. However, where heavy rainfall and floods are major sources of recharge, an increase in recharge may be expected. In many already water-stressed arid and semi-arid areas, groundwater recharge is likely to decrease. However, where heavy rainfall and floods are major sources of recharge, an increase in recharge may be expected. Eg. Alluvial aquifers where recharge occurs via stream channels or bedrock aquifers where recharge occurs via direct infiltration of rainfall through fractures or dissolution channels.

the effects of climate change are indirect; through alterations to recharge and other discharge mechanisms (e.g. evapotranspiration). If groundwater falls below surface water levels, groundwater discharge may no longer occur (and vice versa). In semi-arid and arid regions, the dependence on groundwater to maintain baseflow in permanent streams is likely to be greater during periods of extended drought.

Groundwater pumping also forms a mechanism for groundwater discharge. Projected increases in precipitation variability are likely to result in more intense droughts and floods, affecting the reliability of surface water supplies. Human demand for groundwater is therefore likely to increase to offset this declining surface water availability and, where available, will become a critical facet for communities to adapt to climate change.

2.3 Groundwater storage

Groundwater storage is the difference between recharge and discharge over the time frames that these processes occur, ranging between days to thousands of years. Storage is influenced by specific aquifer properties, size and type. Deeper aquifers react, with delay, to large-scale climate change but not to short-term climate variability. Shallow groundwater systems (especially unconsolidated sediment or fractured bedrock aquifers) are more responsive to smaller scale climate variability. The impacts of climate change on storage will also depend on whether or not groundwater is renewable (contemporary recharge) or comprises a fossil resource. For shallow groundwater storage the vulnerability to climate change can partly be solved by artificial recharge. This is further discussed below.

2.4 Water quality

In many areas, aquifers provide an important source of freshwater supply. Maintaining water quality in these aquifers is essential for the communities and farming activities dependent on them. Both thermal and chemical properties of groundwater may be affected by climate change. In shallow aquifers, groundwater temperatures may increase due to increasing air temperatures. In arid and semi-arid areas increased evapotranspiration may lead to groundwater salinisation. In coastal aquifers, sea level rise and storm surges are likely to lead to sea water intrusion and salinisation of groundwater resources. Changes in recharge and discharge (see above) are likely to change the vulnerability of aquifers to diffuse pollution.

In areas where rainfall intensity is expected to increase, pollutants (pesticides, organic matter, heavy metals, etc.) will be increasingly washed from soils to water bodies. Where recharge to aquifers occurs via these surface water bodies, groundwater quality is likely to decline. Where recharge is projected to decrease, water quality may also decrease due to lower dilution and in some cases may also lead to intrusion of poorer quality water from neighboring aquifers.

3. Impacts of non-climatic factors

Whilst climate change is likely to have adverse impacts on the quantity and quality of groundwater resources, in many areas this will be dwarfed by the non-climatic impacts including growth in the global population, food demand (which drives irrigated agriculture), land use change, and socio-economic factors that influence the capacity to appropriately manage the groundwater resource.

Historically, in both developed and developing nations, groundwater demand has been poorly managed. Low investment in groundwater investigations and management during the 20th century, a time of intensive groundwater use for agricultural crop production, has placed groundwater under stress. Increased groundwater use associated with population growth has also been a factor, particularly in arid and semi-arid areas where water is scarce. Future global population growth is expected to place groundwater resources under greater stress.

Land use change also affects groundwater resources. The degree and magnitude of impact will depend on local conditions. In a small Sahelian catchment in Niger, Seguis et al. (2004) found that the transition from a wet period under a 'natural' land cover (1950) to a dry period under cultivated land cover (1992) resulted in a 30 to 70% increase in runoff. Recharge in this catchment occurred preferentially through ponds, and thus the increased runoff caused a significant and continuous water table rise over the same period.

In a south-western Uganda catchment, clearing of vegetation has led to a 90% reduction in yields from local groundwater springs (Mutiibwa, 2008). The clearing has been driven by population growth and the need to cultivate and settle land. Loss of vegetation cover has resulted in less interception and infiltration of rainfall, and increased runoff. The dominant recharge mechanism is direct infiltration of rainfall and therefore changes in the rainfall-runoff relationship have resulted in a significant reduction in groundwater recharge.

A range of technical and socio-economic factors have contributed to the current condition of groundwater resources, and these will influence their management in the future also. Inadequate information to inform groundwater allocation; lack of qualified personnel; increasing contamination of water resources from agriculture, industries and mining; uncontrolled groundwater abstraction; lack of land use planning; inadequate financial capacity and a lack of education and awareness amongst stakeholders are just some of the challenges that must be overcome. Mutiibwa (2008) concluded that the appropriate management of groundwater resources required not only a technical and financial capacity, but also 'political goodwill'.

4. Implications for groundwater dependent systems and sectors

Groundwater dependent systems comprise those communities, industries and environments that rely on groundwater for water supply. Dependence on groundwater in developing countries is high, due to either water scarcity or a lack of safe drinking water from surface water supplies. Climate change and other pressures may compromise the availability and quality of groundwater resources with significant implications for human and environmental health, livelihoods, food security and social and economic stability.

4.1 Rural and urban communities

Shallow wells often provide an important source of drinking water for rural populations in developing nations. Increased demand and potentially increased severity of droughts may cause these shallow wells to dry up. With limited alternatives for safe drinking water supplies (surface water may be absent or contaminated and deeper wells may not be economically feasible), loss of groundwater would force people to use unsafe water resources or walk long distances for water. This has associated impacts for human health and the capacity (time) to earn an income or gain education.

The livelihoods of rural populations are largely dependent on land, water and the environment with limited alternatives compared to their urban counterparts. Reduced water availability can cause severe hardships. Drying up of pasture and drinking water to livestock can wipe out herds of livestock that are sources of income, family security and food. Small scale irrigation enterprises, usually reliant on shallow groundwater, may also fail.

Where increases in heavy rainfall events are projected, floods can wash away sanitation facilities, spreading waste water and potentially contaminating groundwater resources. This may lead to increased risk of diarrhoeal disease. The risk of such contamination is likely to be greater in urban areas due to higher population density and concentration of source pollutants. In coastal regions, sea water intrusion may limit the capacity of groundwater to serve already large and rapidly expanding populations.

4.2 Agriculture

Globally, irrigated agriculture is the largest water use sector. In areas where the availability of groundwater is reduced, irrigation may become unviable, particularly if demand for drinking water supply in the area (a higher priority) cannot be met. Alternatively, irrigation may need to occur on an opportunistic basis during periods of water availability or adopt alternative water resources (such as recycled waste water), or technologies and methods for increased water use efficiency. In areas where groundwater availability increases, agriculture may benefit. However shallow rising water tables may also cause problems such as soil salinisation and water logging.

4.3 Ecosystems

The impact of climate change is likely to accentuate the competition between human and ecological water uses, particularly during periods of protracted drought. Environmental implications include the reduction or elimination of stream baseflow and refugia for aquatic plants and animals, dieback of groundwater dependent vegetation, and reduced water supply for terrestrial fauna. In areas where salinisation occurs, e.g. coastal regions, salt sensitive species may be lost. Other sources of groundwater contamination may also adversely affect ecosystems.

4.4 Uncertainties and knowledge gaps

Quantifying impacts of climate change on groundwater is difficult and is subject to uncertainties in future climate projections (particularly precipitation) and the relative influence of other factors, eg. vegetation response to change in carbon dioxide. Studies of climate change impacts on groundwater recharge have largely focused on quantifying the direct impacts of changing precipitation and temperature patterns, assuming other parameters remain constant. Few studies have addressed indirect climate effects such as change in land use, vegetation cover and soil properties.

Natural climate variability is also often ignored with the focus typically being on anthropogenic climate change impacts only (Figure 10.3).

Current understanding of climate change impacts is poor. However there are a number of organizations beginning to enhance the understanding of climate change impacts on groundwater resources. This includes UNESCO's initiative Groundwater Resources Assessment under the Pressures of Humanity and Climate Changes (GRAPHIC), with which the International Groundwater Resource Assessment Centre (IGRAC) and the International Association of Hydrogeologists (IAH) Commission on Climate Change are partners. Whilst knowledge of climate change impacts for groundwater is advancing, there does not appear to be any coordinated approach for developing responses (adaptation).

5. Adaptation to climate change

5.1 What is adaptation?

Groundwater dependent systems have the capacity to cope with some level of hydrological variability (in quality and quantity of water) without impairment (Figure 10.4). This 'coping range' varies with the sensitivity of the groundwater dependent system to changes in various groundwater attributes (e.g. water quality, depth, pressure, discharge flux). Extremes of natural climatic variability (e.g. prolonged climatic drought) may mean that some groundwater attributes fall outside the coping range of the system, resulting in socio-economic and/or environmental harm. In some areas, human-

Figure 10.3 Rainfall records from the early 1900s to mid-1980s show the natural rainfall variability but also that Africa's average annual rainfall has decreased since 1968, and has been fluctuating around a notably lower mean level (figure; source: UNEP 1985). There is also some evidence that natural disasters have increased in frequency and severity over the past 30 years, particularly in the Sahel.

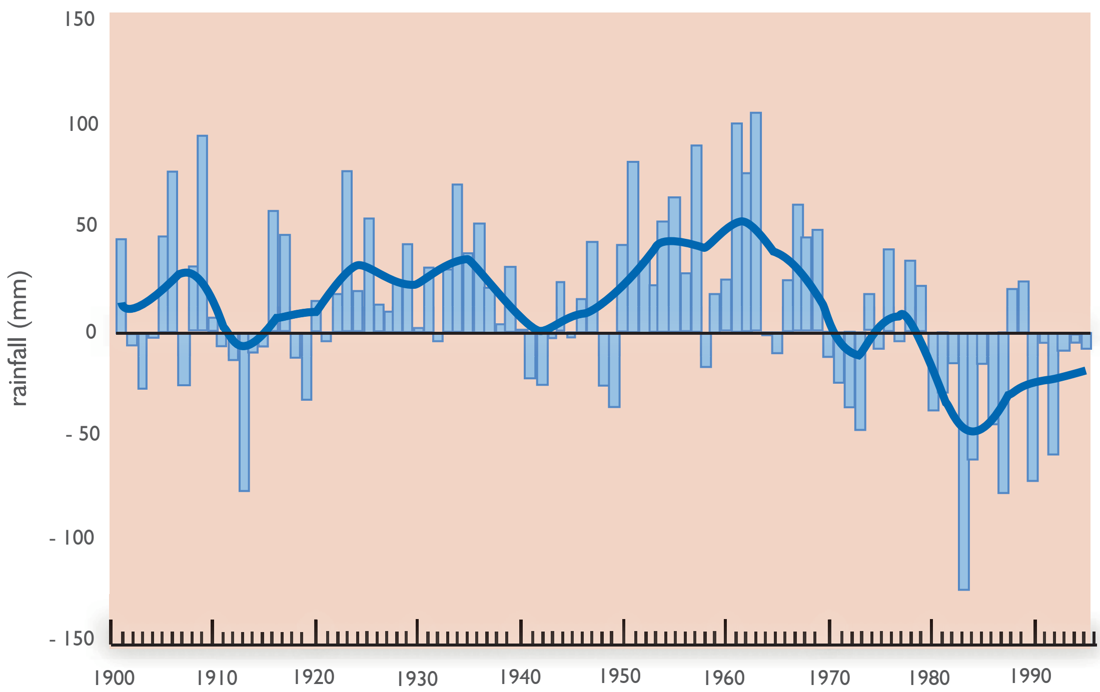
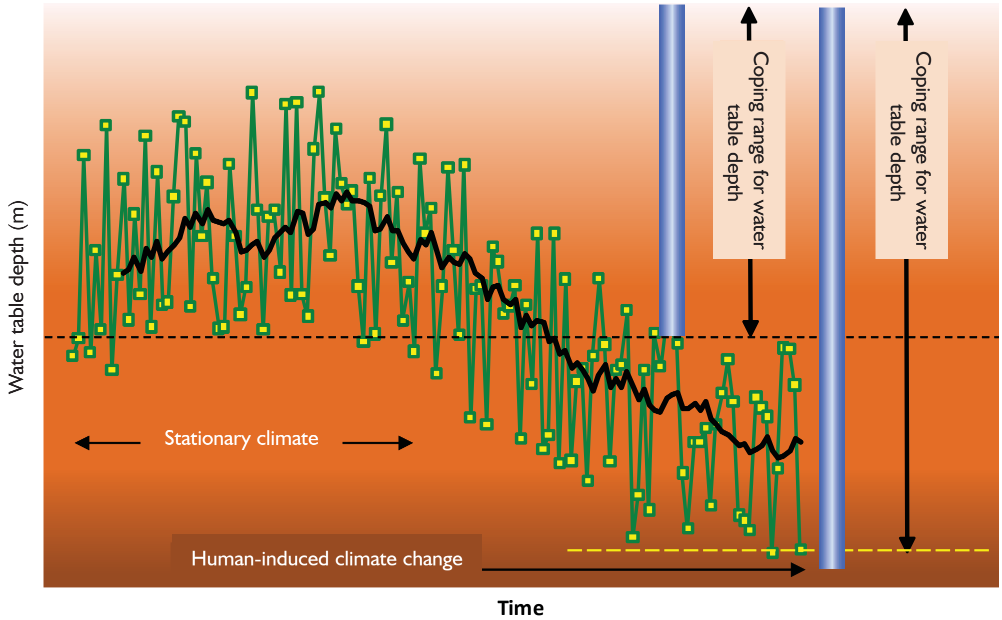


Figure 10.4 Coping range and adaptation to human-induced climate change (redrawn from Willows and Connell, 2003).

The graph shows variation in a hypothetical hydrological parameter (e.g. water level in shallow aquifer) under stationary conditions and human-induced climate change (the solid black line shows the mean state). In sequences of dry years, water levels may fall below the depth of a well or bore (which would define the system's coping range) and some form of harm is experienced. In this example, human-induced climate change is projected to initially result in increased frequency of years during which water levels fall below the level from which water can be extracted. As change progresses, this state becomes permanent. With adaptation (e.g. extending the well or sinking a deeper bore) the system's coping range is extended so that permanent harm is avoided. Note that adaptations are rarely required to respond to a single stimulus, such as in this example.



induced climate change threatens to change the hydrological environment such that its state is outside the system's coping range more frequently, potentially perpetuating that harm (Fig. 10.4).

Adaptations are adjustments made in natural or human systems in response to experienced or projected climatic conditions or their beneficial or adverse effects or impacts. In the context of this report (and Figure 10.4) they are concerned with reducing the vulnerability of groundwater dependent systems to climate change and hydrological variability. Adaptations are essentially management responses to risks associated with climate variability and climate change.

5.2 Adaptive groundwater management

This section contains a review of adaptation options for risks to groundwater dependent systems from climate change and hydrological variability. It is structured around the five groups of options discussed in the previous section, where they are appropriate, and five main groundwater process themes

- Managing groundwater recharge
- Protection of groundwater quality
- Management of groundwater storage
- Managing demand for groundwater
- Managing groundwater discharge.

The background report (World Bank, 2009) gives a detailed overview of adaptation options for these themes in tabular form. Below is a short description of the issues:

Managing groundwater recharge: Groundwater recharge areas may be managed to protect or enhance water resources and to maintain or improve water quality. While the latter is also covered in section 6, it is relevant here as activities in groundwater recharge areas that lead to groundwater contamination also reduce resource availability.

Protecting groundwater quality: Climate change and hydrological variability may affect the quality of groundwater available for use in a groundwater dependent system. This is particularly true of groundwater resources on small islands and coastal areas that are projected to be subject to sea level rise. It is also true where reduced security of supply leads water resource managers to include lower quality water in the supply stream (e.g. through aquifer recharge) or where increased pressure on groundwater resources leads to increased use and greater risk of contamination of a high quality aquifer by any overlying or underlying poorer quality aquifers.

Managing groundwater storage: While aquifers are recognized as underground water storages, they are rarely operated with the same level of precision and control as major surface water storages. Opportunities exist to manage groundwater storages more effectively, and reduce the vulnerability of systems that depend on them to climate change and hydrological variability.

Managing demand for groundwater: Climate change adaptations for water resources most frequently operate on demand management. In many cases, the adaptations for groundwater dependent and surface water dependent systems will be identical.

In areas where climate change reduces supply security for surface water resources, it is likely that there will be increased focus on utilization of groundwater resources as an adaptation to climate change. This will require greater attention to management of demand for groundwater and for conjunctive management with surface water. It may also be possible to use groundwater as a store for surplus surface water flows during periods of abundant supply for use during periods of surface water scarcity.

Management of groundwater discharge: Aquifer systems discharge water to the land surface, rivers, lakes, wetlands or to near or off-shore marine environments. Discharge, recharge and

Table 10.2. Adaptation options: building adaptive capacity

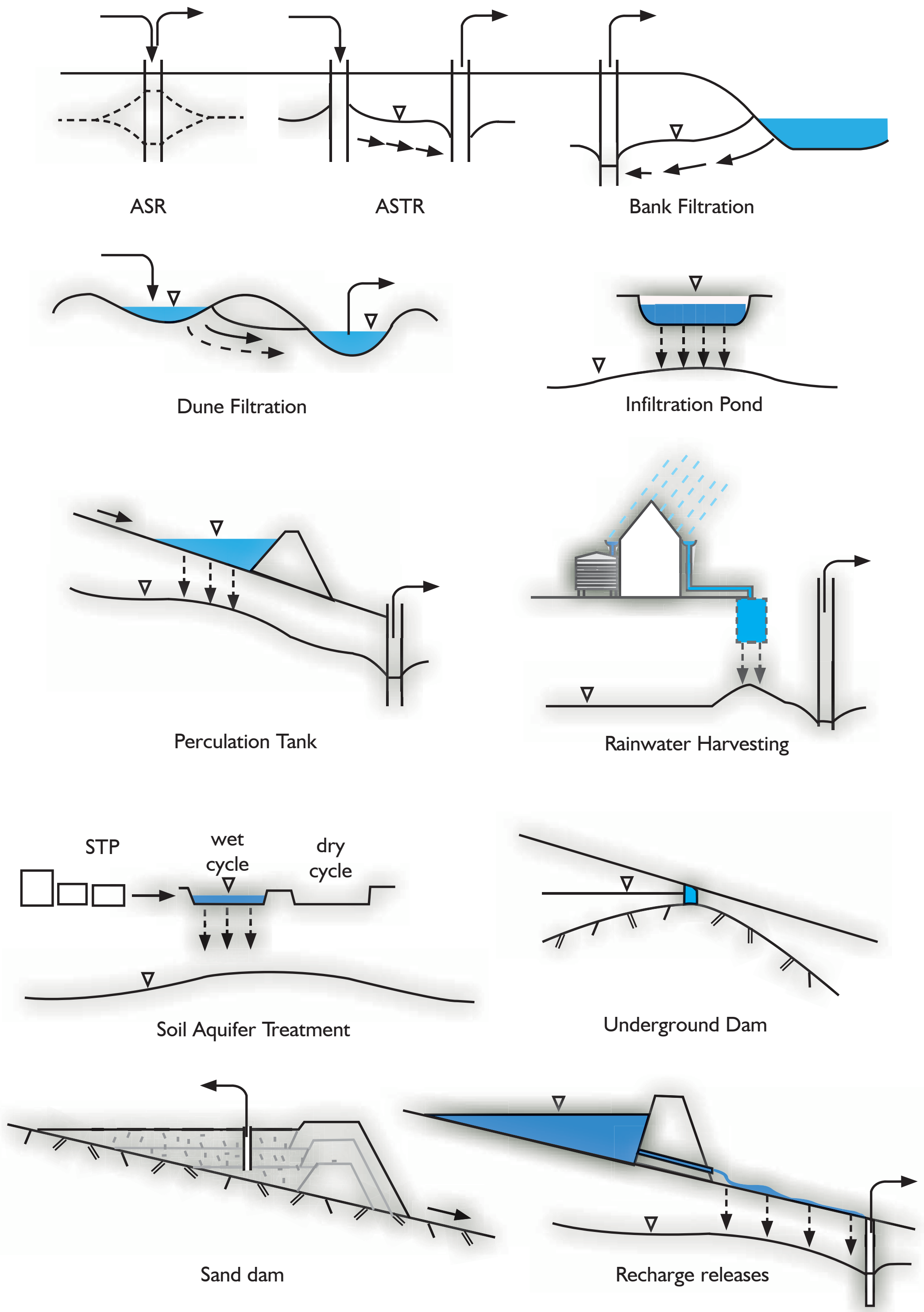
Adaptation option group	Adaptations
Social capital These options are concerned with enabling communities to understand climate and hydrological risks and actively participate in management responses.	• Education and training – to improve community and stakeholder understanding of climate risks and their capacity to participate in management responses and/or generate, modify or apply adaptations. • Governance – devolve some level of responsibility for planning and management of groundwater to local communities to increase local 'ownership' of problems and responses • Sharing information – instigate processes for sharing of information regarding climate risks and responses within and between vulnerable communities.
Resource information Gathering and providing information on climate risks and the groundwater system being managed.	• Understanding climate – analysis of historical and palaeoclimate information to understand the natural drivers of climate variability. • Climate change projections – developing downscaled climate change projections for the area of interest • Quantify the groundwater system – understand the scale and characteristics of the aquifer(s); recharge, transmission and discharge processes; water balance (including use); water quality, etc. • Monitoring, evaluation and reporting – of the state of the groundwater resource.
Research & development Research and development activities to improve the effectiveness of adaptive responses to climate change and hydrological variability.	• Climate impact assessments – studies to better define the nature of projected climate change impacts on the groundwater system and the associated climate and hydrological risks. • Management of groundwater recharge – methods. • Management of groundwater storage – technologies, water management and other practices to maximize groundwater storage capacity and resource availability. • Protection of water quality – technologies and management systems to enable treatment and reuse of contaminated water and avoid contamination of higher quality water by water of lesser quality. Protection of island and coastal aquifers from effects of sea level rise. • Managing demand for groundwater – technologies and management practices that: improve the efficiency of urban and agricultural uses of water; reduce water quality requirements of non-potable uses; or reduce the need for water.
Governance & institutions Improving governance and institutional arrangements for groundwater resource management. Improved planning regimes for groundwater and associated human and natural systems.	• Conjunctive management of surface water and groundwater in rural areas. Integrated water cycle management (including various potable and non-potable sources in urban areas). • Multi-jurisdictional planning and resource management arrangements for large scale aquifer systems that cross jurisdictional boundaries. • Defining water allocations based on resource share rather than volume. • Set and regulate standards for (eg.) groundwater resource and land use planning, water governance, environmental management. • Drought response planning.
Markets Establishment and operation of markets for water and associated environmental services.	• Markets – establishment and operation of markets for and trading of water within a groundwater system. Market to determine the price for water. • Property rights – establish clear title and property rights to groundwater.

utilization are in a state of dynamic equilibrium, such that changes in recharge or utilization ultimately result in a change in discharge. In some settings, it is possible to increase resource availability (for use by human systems) by reducing groundwater discharge.

5.3 Building adaptive capacity for groundwater management

Building adaptive capacity is a crucial cross- cutting theme or does at least partially apply to multiple themes. Adaptive capacity building

Figure 10.5 Examples of managed aquifer recharge (MAR) approaches.ASR: aquifer storage and recovery; ASTR: aquifer storage, treatment and recovery, STP: sewage treatment plant. Source: Peter Dillon (pers. comm., 2008)



options are generally concerned with providing the necessary conditions for other forms of adaptation to be implemented successfully, rather than managing or avoiding climate or hydrological risks directly. Some adaptation options from World Bank (2009) are given below to illustrate the importance of the theme (Table 10.2).

6. Example of adaptation: management of aquifer recharge and storage

6.1 Managed aquifer recharge

Managed aquifer recharge (MAR) involves building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge (Fig. 10.5) It forms one of the 'managing aquifer recharge' adaptation responses and is increasingly being considered as an option for improving the security of water supplies in areas where they are scarce (Gale, 2005).

MAR is among the most significant adaptation opportunities for developing countries seeking to reduce vulnerability to climate change and hydrological variability. It has several potential benefits, including: storing water for future use, stabilising or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water.

Implementation of MAR requires suitable groundwater storage opportunities. Falling water levels or pressures in aquifers in many regions throughout the world are creating such opportunities, either as unsaturated conditions in unconfined aquifers or as a pressure reduction in confined aquifers. However, MAR is not a remedy for water scarcity in all areas. Aquifer conditions must be appropriate and suitable water sources (eg. excess wet season surface water flows or treated waste water) are also required. MAR potential should be determined in any particular country or region before activities commence.

Detailed planning and assessment are required to determine whether MAR is a viable adaptation option. This may be carried out at national and watershed scale considering:

- Water availability;
- The hydrogeological suitability: and
- Feasibility.

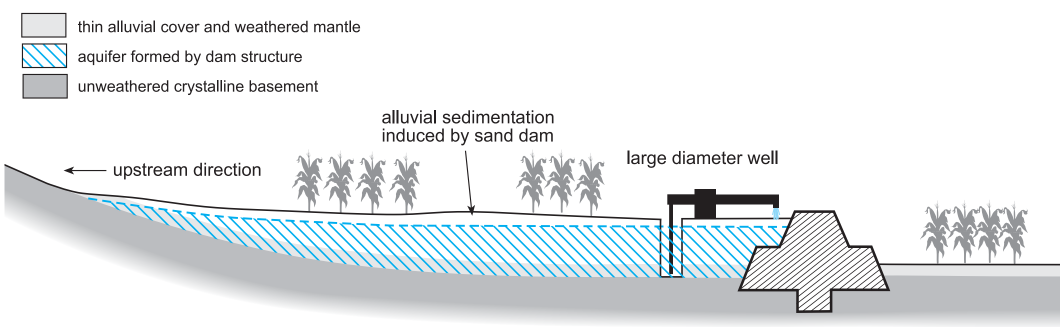
6.2 MAR example: sand dams in Kenya

Sand dams are made by constructing a wall across a riverbed, which slows flash floods/ephemeral flow and allows coarser sediment to settle out and accumulate behind the dam wall. The sedimentation creates a shallow artificial aquifer which is recharged both laterally and vertically by stream flow (Gale, 2005).

Since 1995, over 400 sand dams have been constructed in the Kitui District of Kenya, supported by the SASOL Foundation (Fig. 10.6; Foster and Tuinhof, 2004). Each of these dams provides at least 2,000 m3 of storage and has been constructed by local communities using locally available material. The benefits identified through this program include: water supplies more readily available in the dry season, enhanced food security during drought periods, and less travel time to obtain water supply.

Sand dams are not appropriate for all locations. They require unweathered and relatively impermeable bedrock at shallow depth; the dominant rock formation in the area should weather to

Figure 10.6. Cross section of sand dam structure (from Foster and Tuinhof, 2004)



coarse, sandy sediments; sufficient overflow is required for fine sediments to be washed away; and risk of buildup of soil and groundwater salinity needs to be low. Cooperative effort, ownership and ongoing maintenance by the local community are also necessary for the success of these schemes (Foster and Tuinhof, 2004).

6.3 The integrated approach: managing the water buffer - the 3R approach

Climate change is expected to bring more highs and lows in water availability as well as increasingly erratic rainy seasons. With this larger uncertainty the management of the water buffer assumes a central place.

To manage water buffers at scale the 3R initiative has been developed. The vision of 3R is to help people - even those that live in fragile times and difficult places - to have the confidence and cushion that their livelihood will not unduly suffer under changes in climate - but can even improve by managing the local water buffer.

3R stands for the three subsequent steps in buffer management: recharge, retention and reuse. The water buffer is the storage that is provided especially in the upper meters of the soil, in shallow aquifers and in local surface storage. Managing the overall water buffer is of vital importance – it determines how people live and what economies are sustained. The larger idea is that tackling a local water crisis is not so much about allocating scarce water, but to catch water and extend the chain of water use and its reuse as much as possible within a basin, taking account of all people and the environment across entire basins.

3R can be applied in humid and arid areas, in rural and urban areas. 3R needs to be part and parcel of local land use planning and regional development. It concerns the upscaling of local water storage techniques (subsurface dams, sand dams, surface storage), large scale infiltration, the creation of water banks, groundwater retention in very humid areas, the conjunctive management of large irrigated areas, controlled drainage, the dovetailing of road planning to water recharge and retention, etc. Many of these techniques will have a business case of their own.

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Module 11: Information Management and Communication

Learning Objectives:

- To appreciate how information management supports effective groundwater management
- To understand the information management process and learn some of the tools used in information management.
- To identify important information management outputs for groundwater and how they can be disseminated.
- To understand the importance of communication amongst stakeholders in effective groundwater management
- To become acquainted with typical concepts and tools for communication of groundwater management

1. Introduction

Information Management.

Sound decision making on how to allocate groundwater now and in the future requires comprehensive, accurate and timely information. There is therefore a need to identify the key issues for groundwater management within a defined pragmatic management unit such as a river basin and to prioritise the information (essential and non-essential) required to address these issues. Deciding on what and to whom to report, and how to communicate the report is the final most important step. Thus, for effective implementation of groundwater management, there is a need for an information management function to be carried out – preferably by an Information Management Unit (IMU) as part of its normal activities within a relevant management institution such as a River Basin Organization (RBO). For this module, it is assumed that groundwater management is undertaken by an RBO (or at least nested within a larger water resources management institution), and that the information management process is carried out for the whole river basin and for both surface and groundwater. This section of the module is largely based on the Module 8 on Information Management in the IWRM for River Basin Organisation Training Manual (Cap-Net, 2008).

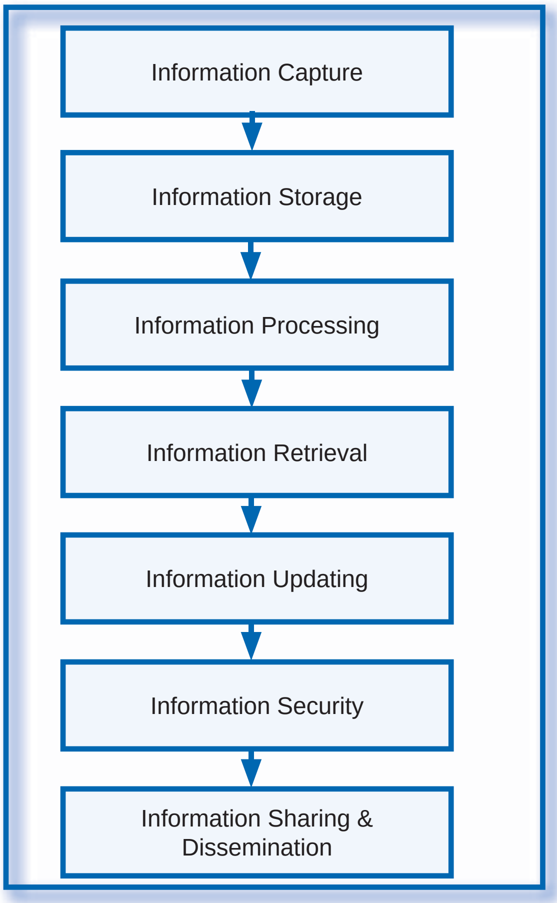
Communication.

Communication is closely linked to information and information management. Information management deals with the more technical process of collecting, storing and disseminating information based on identified management issues and on the information needs of the different stakeholders. Communication focuses more on the human dimension of information management. Effective communication ensures that all stakeholders are involved in defining the water resources management issues and in deciding on their (often different) information needs during management. In this sense, communication is at the basis of successful information management. In this module four aspects of communication are presented: (i) some principles of communication, (ii) the broader context and relevance of communication in groundwater management, (iii) communication tools are discussed and (iv) some words are devoted to our personal role and opportunities in communication.

2. Information Management Process

The generic information management process steps that can be used to manage and derive any

Figure 11.1 Information Management Process Steps



desired information for decision-making and informing stakeholders within a RBO is given in Fig. 11.1. For the purposes of groundwater management only the information capture, processing, updating, and sharing and dissemination are explained below. The rest of the processes are dictated by the overall information management process for the basin.

Information Capture

The first step is to decide "what" and "how" to capture the desired information. The "what" will be defined by the priority information needs of the users, in accordance with the groundwater management objectives in a river basin. A list of the required information will then be produced.

For the groundwater quality management issue, information on the background and current quality parameters, groundwater flow and water users/uses is required. Some of the required information will most probably be processed information. For example the direction of flow is determined by groundwater level measurements. This will mean that there is a need to collect the resulting raw information data on water table levels from observation or abstraction wells.

Once the raw information needs are defined, one must define the methods to be used to capture the data. These can be simple or complex, depending on the desired levels of accuracy and timeliness of information, and the technical and resource constraints. The chapter on monitoring gives details of the various methods available for capturing raw data, associated limitations and trade-offs that have to be made in view of resource constraints (human and material).

Information Processing

The desired information will normally be processed from raw data or other lower level information. Thus, there is a need to decide on the level of processing and the quality control required to produce the desired information, and also to define the processing methods to be used. The chapter on monitoring discusses the techniques for monitoring groundwater levels and quality.

Information Sharing and Dissemination

There is a need to decide what information to share, how to disseminate the information and in what form, to support decision-making and keep stakeholders informed. The choice of methods will depend on the resources available and the target audience. The RBO will need to decide the methods of transmitting such information to the users and also how to respond to queries on the published information. Table 11.1 gives examples of different audiences and their corresponding information requirements and appropriate disseminations methods and channels.

All stakeholders should be able to access an annual report of the state of the water resources in the basin. They may also need to have access to a system to make complaints and to make queries on the water management and water allocation in the river basin. This may take the form of complaint or query forms, in hardcopy or electronic forms on the Internet. The IMU may not be responsible for maintaining all the databases to produce the above outputs.

Table 11.1 Examples of information products for different stakeholders

Target Audience	Information outputs required	Dissemination methods and channels
Water Managers	• Quantity and quality of groundwater available for allocation; • List of non-compliance by water permit users and actions taken • List of groundwater users and permit holders • List of complaints by groundwater users and actions taken.	Shared Database (e.g. intranet or CMS)
Civil society including the media and NGOs	• General trends in water use and quality	News features on a website
Water Users including those that discharge wastes into the water	• Water allocation decisions • Consumption patterns by all the users • Revenue raised from permits and how its used	Regular quarterly status reports such as a leaflet or newsletter
Political stakeholders such as government officials	Summarised information on the status of the groundwater water management and allocation	Half-yearly or annual report

However, the IMU needs to co-ordinate with the relevant agencies maintaining the databases to ensure that the required outputs are produced and delivered to the water managers for decision-making

Information Management Plan

The reality of human resources and financial constraints will limit an RBO's ability to collect, analyse, interpret, use and share information. Thus, the RBO has to prioritise its information collection and processing to derive the necessary information outputs to address the pressing IWRM issues in a river basin. Together with surface water, groundwater management information requirements must be prioritised and incorporated into an overall basin Information Management Plan that meets the immediate IWRM needs of the basin and which can be implemented within the resource limitations of the RBO. The above systematic exercise may also help RBO define the information management capacity building needs and also the possible areas where investments in technical improvements and systems can be made.

3. Information Management Tools

Information Management is commonly defined as "the collection and management of information from one or more sources and the distribution of that information to one or more audiences". To facilitate the organisation and classification of information it will be useful to know what the generic information types and their characteristics are. It is also useful for the IMU to be exposed to the range of possible information management tools available to them. The IMU then need to work with information and communication (ICT) specialists in developing and customising such tools to support its operations.

Information Types and Their Characteristics

There is a wide range of different information types which can be selected for different information purposes (see Table 11.2 below).

Examples of Some Information Management Tools

Rapid advances in ICT have enabled a number of new information management tools to be developed and thus assist an RBO in its information management tasks. These enable better information generation, processing and dissemination than in the past.

- *Dedicated data processing systems and databases* can be developed to process raw data for storage in databases. The systems are normally developed based on the specific information needs of the users and follow a very clear set of information processing procedures.

- *Geographical Information Systems (GIS)* use the powers of a computer to display and analyse spatial data that are linked to databases. When a specific database is updated, the associated map will be updated as well. Thus by continually updating data captured from monitoring, updated maps are available for stakeholders to view. GIS databases can include a wide variety of information such as population and borehole sites, pollution hotspots etcetera.

Table 11.2. Information types and their characteristics

Information Type	Characteristics
1. Static Info	Static information does not change with time. They are typically information used to identify an object and those relatively time-invariant characteristics of an object, such as geology, aquifer type, aquifer properties, etc.
2. Dynamic Info	Dynamic information varies with time, e.g. abstraction data, water quality data, water levels, and base flow, recharge rate etc.
3. Raw data	Raw data are information recorded by measuring equipment or derived from a survey.
4. Processed Info	Processed information is information that meets a defined need and is processed from raw data.
5. Report-type Info	Report-type information is a combination of text, figures and tables, organised within a set of narrative text.
6. Spatial-type Info	Spatial-type information is information stored in the form of maps and is geo-referenced to a map.

- *"Google Earth" Program* combines the power of the Google Search engine with satellite imagery, maps, terrain and 3D buildings and makes available a bird's eye view of the world's geographic information for any area of interest. Most of the satellite imagery used is one to three years old. For example, from Google earth maps a water manager can identify geological boundaries using surface features to infer tectonic structures.

- *Content Management Systems (CMS)* use the Internet standard of presenting linked webpages to organise and present report-type information. There are several types of CMS available, many of which are free. Report-type information is the most common type used by stakeholders in making decisions. Therefore the use of a CMS to store and publish report-type information electronically, either on the Internet or in the form of a CD/DVD, will enable a RBO to disseminate and share information in an effective way. The CMS also has the advantage that it allows for a central information repository for data and information that is posted by different people.

Guidelines for the Development of ICT Systems

There are numerous reported failures and bad experiences of water managers in the application and use of ICT tools and ICT systems to support their operations. The following guidelines will assist the IMU in the development of ICT systems:

- *Develop the Information Management Plan*
  The IMU must first develop its Information Management Plan for its river basin, as described in Section 2. By working through the series of steps in the information management process to arrive at the plan the IMU will gain an in-depth understanding and appreciation of the information management needs of the water managers including those for groundwater and stakeholders in a river basin. The IMU will then be able to provide guidance to the ICT specialists on what it needs to support its operations. The plan will also assist the ICT specialists in advising the IMU on the possible areas where ICT tools may be applied to increase its effectiveness.

- *Employ a Multi-disciplinary Project Manager*
  A frequent cause of failure of the application of ICT tools is due to the lack of technical leadership in the ICT project. The project manager of an ICT project must have a multi-disciplinary background, with knowledge/experience in both water resources management and ICT. This will ensure that the project manager can appreciate and understand the information management needs of groundwater managers, incorporate them into the Information Management Plan and communicate them to ICT specialists.

- *Aim for ICT systems that match existing capacity of IMU*
  Another frequent cause of failure of ICT projects is the lack of capacity in the IMU to operate the developed ICT systems. Thus, it is very important to aim for ICT systems that are "simple" enough to be operated by the IMU. If new ICT systems for groundwater are introduced, then there is a need to ensure that staff in the IMU are trained to operate them.

- *Adopt staged development of ICT systems*
  The IMU should resist the development of complex, integrated systems and choose to adopt a staged approach in the development of ICT systems. The groundwater manager should help to ensure that staff at an IMU have mastered operations relevant for their information management need before integrating it with other information, for example from surface water.

4. IM and monitoring, modelling and Decision Support Systems (DSS)

Information management is strongly related to monitoring. Monitoring of groundwater quality and quantity is designed on the basis of information needs and data collected in monitoring programs has to be translated back into information for management.

The use of computer simulation to model water quality, base flow, etc. is quite common. ICT tools have been developed to support the linking and integration of the simulation models with the decision-making process, so as to provide decision-makers with the simulation modelling tools to conduct "what-if" scenarios, while making decisions.

In view of the comments highlighted in Section 3, it is advisable that groundwater specialists adopt a cautious approach in the development and promotion of the use of DSS.

5. What is communication and why is it important?

Definition

Communication is a learned skill. Most people are born with the physical ability to talk and to hear but we must learn to speak and listen well and communicate effectively. Speaking, listening and our ability to understand verbal and non-verbal communication are skills we develop in various ways. We learn basic communication skills by observing other people and modelling our behaviours based on what we see. We are also taught some communication skills directly by education and practising those skills and having them evaluated.

Communication goes beyond information management and deals with all the necessary interactions between the stakeholders in groundwater resources management at the different stages of resource development.

Groundwater communication

The specific communication role for groundwater experts is to interact effectively with the broad array of other stakeholders who play a role in the development and management of groundwater (Figure 11.2).

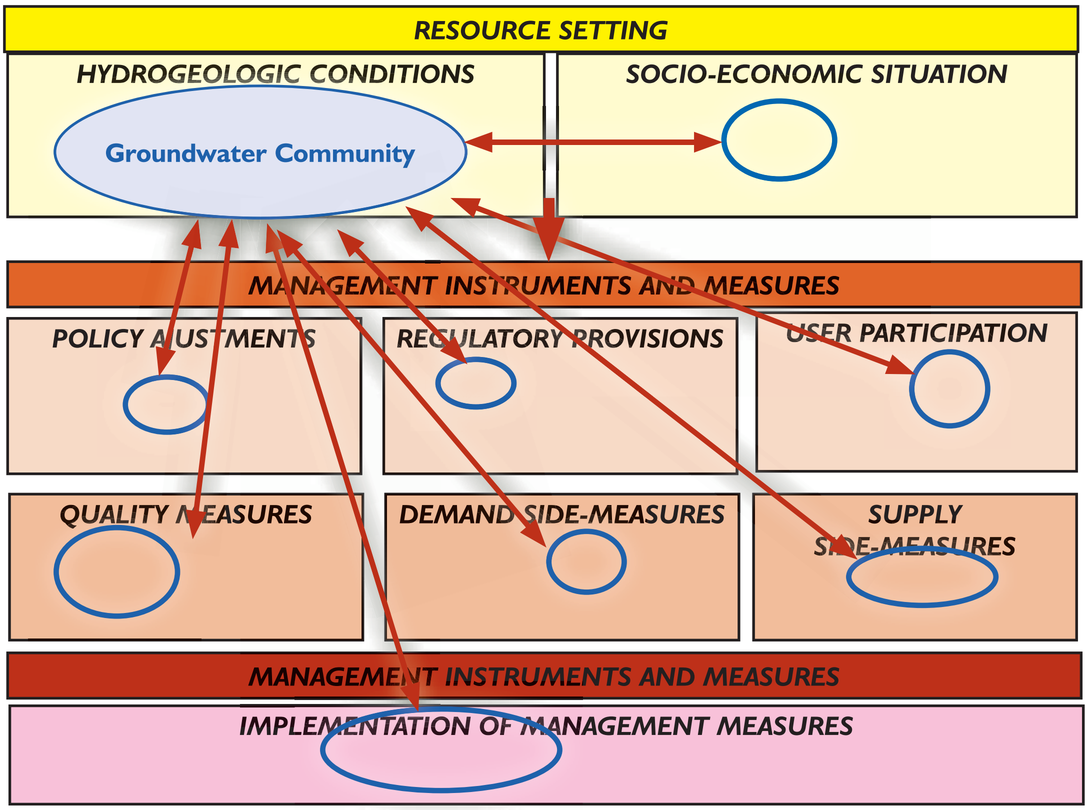
The challenge is to convey the key concepts of groundwater, realising the frequent misconceptions that exist with stakeholders who have no background in groundwater and hydrogeology. Typical "myths" on groundwater are described in GWMATE Briefing note no. 2 and include misunderstandings such as "groundwater resource is infinite compared to its abstraction" and "the pumping of groundwater has no downstream effect". The groundwater community has to communicate an invisible resource ("out of public sight, out of political mind") to the policy level and other stakeholders.

6. What are key concepts in "groundwater communication?"

The receiver is not a groundwater expert

In communicating the groundwater message we have to realize that there are different perspectives, different interests and different views amongst the stakeholders (Figure 11.3) and this should be kept in mind when designing our communication strategy and material.

Figure 11.2 . Communication lines in groundwater management

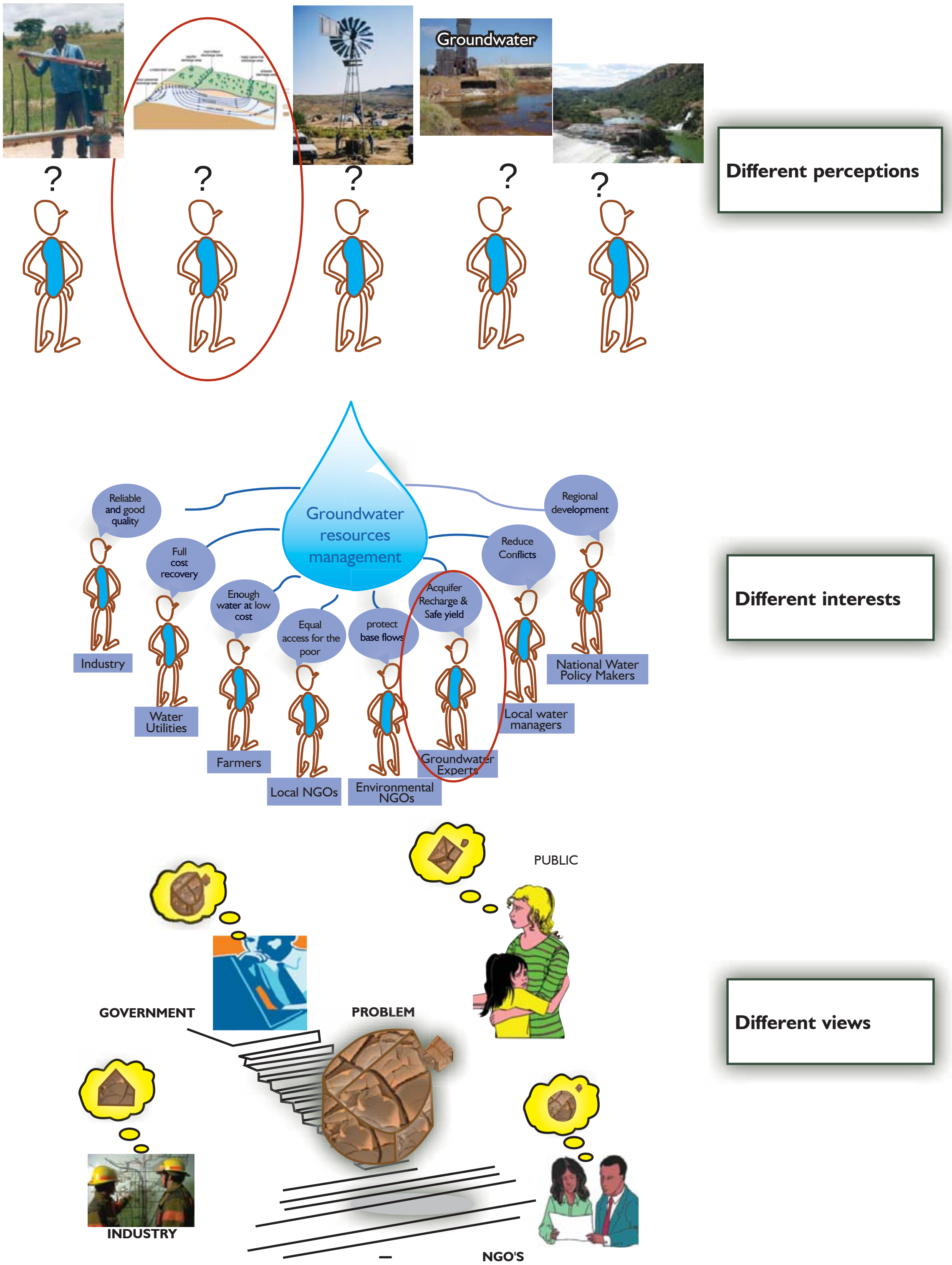


The image of groundwater

Another characteristic of groundwater to be taken into account in communication is the often negative image of groundwater. In early stages of development, the resource seems to be infinite and there is little or no incentive for management. Management needs arise usually when stress on the resource increases and conflicts arise between users. If management and regulation is not introduced effectively (or only partially) the stress on the resource remains. Since the resource is invisible and the physical processes not understood, the water managers and users develop a negative perception in which groundwater is linked to problems and constraints. Groundwater experts are usually called in to evaluate the resource when management becomes inevitable and to assess the technical and hydrological feasibility of management options (Figure 11.4)

This can be addressed through communication by presenting the key concepts of groundwater

Figure 11.3. Different perceptions, interests and views

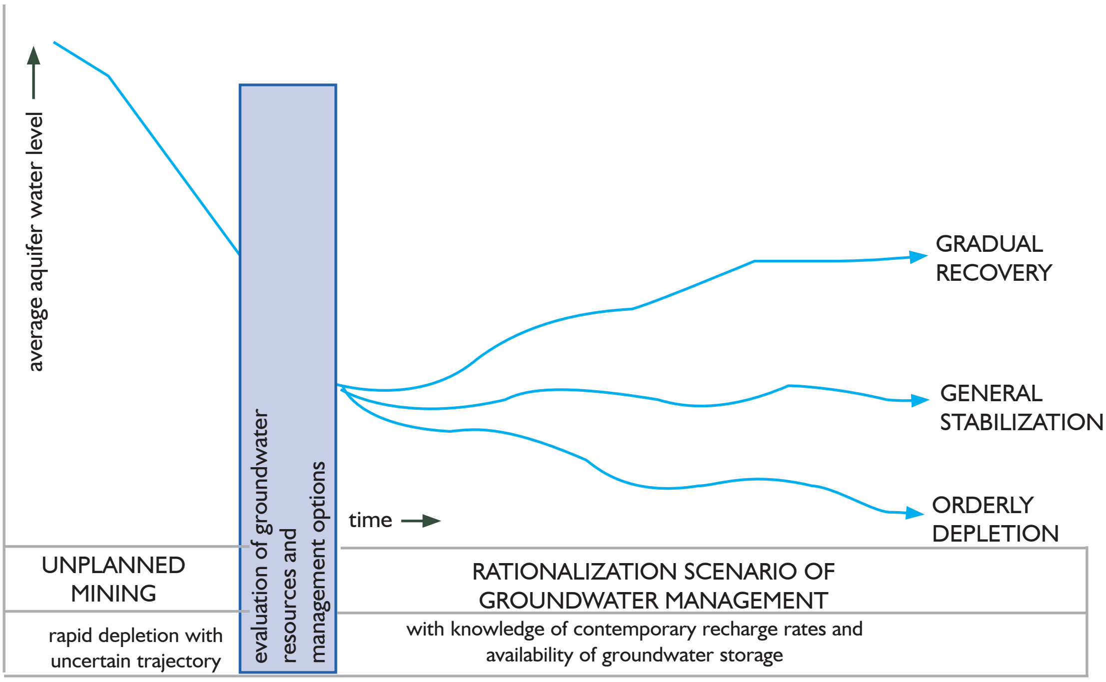


recharge, flow and discharge in a simple way using graphics and/or model simulations which can be understood by non-groundwater professionals.

It is also important to communicate the selling points of groundwater such as:

- Available where needed: universal access
- Naturally protected: safe and stable quality
- Storage capacity: our largest reservoir
- Brackish groundwater: the untapped resource
- Deep groundwater: vertical resource extension
- Environmental flows: wetland and river base-flow

Figure 11.4. Stages of groundwater development and management strategies



- Stable temperature: sustainable energy source
- Natural treatment: pollution abatement

Highlighting the selling points of groundwater is in fact a form of marketing and making use of appropriate marketing tools/methods may be useful to raise the profile of groundwater.

7. Communication methods, materials and skills

Communication is generic topic and there is a wealth of literature, textbooks and courses on communication methods, materials and skills. Information and examples are widely available on the internet. In this section only a few remarks and examples are given.

Communication methods

We are constantly in communication (both in our private and professional life) when interacting with other people, ranging from personal communication to addressing a conference.

The different communication methods reflect these settings:

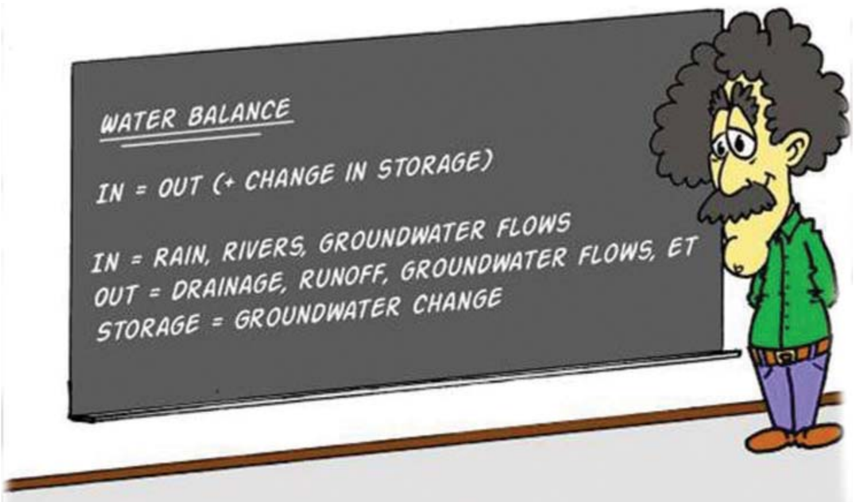
- person to person - face to face, reading a letter, making a phone call
- in a small group - planning, problem solving, decision making, written reports, memos, notice boards
- in a meeting - presenting, bargaining, negotiating agreements
- using mass media - speaking in public, on radio or television, writing for print media such as newspapers and journals, books, advertising
- others - training, teaching, entertaining.

Communication material

There is wide range of materials available for the different methods of communication ranging from books, papers, reports to flyers, brochures, films or animations and other audiovisual material. It is beyond the purpose of this module to discuss communication material and communication strategies in detail. Since groundwater experts are generally not trained in communication, it is strongly advised to consult an information specialist for the design of a communication plan and to select the most suitable material given the type of communication needed. A few general recommendations with respect to the selection of communication materials are:

- A picture/simple diagram tells more than a 1000 words
- Cartoons are an effective way to address key concepts and misconceptions
- Animations and videos: such as The Water Channel which contains a large number of videos on water management, including over 20 on groundwater http://www.thewaterchannel.tv/

Figure 11.5 : Cartoon from website Know With the Flow: http://www.knowwiththeflow.org/



1. Why using cartoons
2. Example of cartoon strip
3. How to create cartoons
4. Tips for creating cartoons
5. Interesting links

Some examples of useful communication material are given below:

Communication skills

Communication skills are the final step in the process and are concerned with how we act and behave in our communication. Communication skills include oral presentation, written presentation and non-verbal communication (Figure 11.6)

The material of your presentation should be concise, to the point and tell an interesting story. In addition to the obvious things like content and visual aids, the following are just as important as the audience will be subconsciously taking them in:

- Your voice - how you say it is as important as what you say
- Body language - a subject in its own right and something about which much has been written and said. In essence, your body movements express what your attitudes and thoughts really are.
- Appearance - first impressions influence the audience's attitudes to you. Dress appropriately for the occasion.

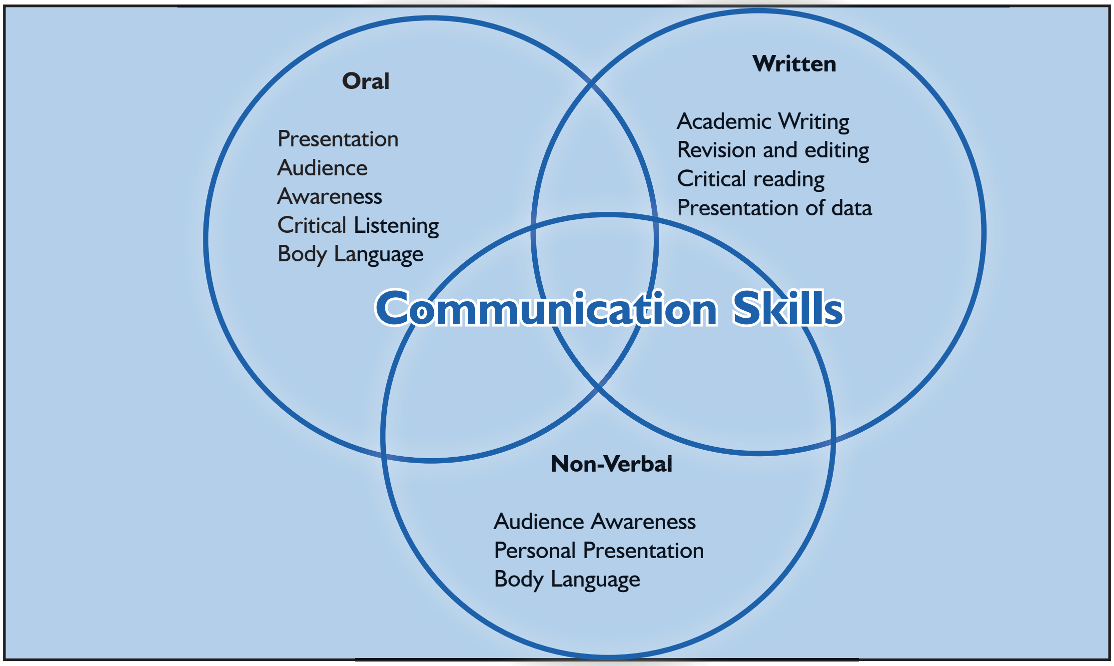
As with most personal skills oral communication cannot be taught. Instructors can only point the way. So as always, practice is essential, both to improve your skills generally and also to make the best of each individual presentation you make.

8. Lessons

From experience of information management systems and the information presented above the lessons to take away are:

- Good information management is essential for effective groundwater and general water management in a river basin;
- Information management systems should be realistic and work within available resources;
- Information management tools and ICT systems should be adopted in a staged process, matching the skills available and reliability of the information data base; and
- The effectiveness of the information man-

Figure 11.6. Communication skills



agement system is demonstrated by information outputs that meet the needs of water managers and stakeholders.

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Cap-Net, 2008. Module 8, Information Management in Integrated Water Resources Management for River Basin Organisation Training Manual. http://www.cap-net.org/node/1494

Tilak Raj Kapoor (2007); Role of Information and Communication Technology in Adaptive Integrated Water Resources Management ; American Society of Civil Engineering Publication. http://cedb.asce.org/cgi/WWWdisplay.cgi?0603740

- Information Management (http://en.wikipedia.org/wiki/Information_management)
- What is GIS and how does it work? (http://www.mapcruzin.com/what-is-gis.htm)
- Google Earth (http://earth.google.com)
- Know With the Flow: http://www.knowwith-theflow.org/
- The Water Channel: http://www.thewaterchannel.tv/

EXERCISE
Information Management

Purpose: An RBO recently established a groundwater management plan and awarded the Information Management Unit (IMU) a limited budget to incorporate groundwater management in the information management plan. The budget will be adequate for the IMU to meet some of the information needs of the water users.

The Players and their Roles

There shall be 5 groups of players. They are:

(a) IMU Team
(b) The Groundwater Management Team within the RBO
(c) A Community Based Organisation representing rural communities that use boreholes for drinking water
(d) An Environmental NGO
(e) A Mining Company

The participants shall be divided into the above 5 groups. They shall spend 30 minutes in their respective Individual Group Session before coming together in the 30-minute Plenary Session. In the Plenary Session the IMU Group shall conduct the forum and the other groups shall make their respective requests for the information outputs they need from the IMU Group.

The roles of the 5 Groups are as follows:

(a) IMU – You need to identify and prioritise all the information management outputs that the water manager and water user stakeholders may need. Subsequently, you will be required in the Plenary Session to explain why you cannot meet all the information management needs of the stakeholders in the river basin due to your limited budget. Note that some of the information requested is already produced for surface water management,
(b) Groundwater Management Team – You need to identify all the information management outputs that you need the IMU to provide to you to enable you to perform your groundwater management responsibility in the basin.
(c) Community Based Organisation – You need to identify all the information management outputs that you want from the IMU to make decisions on domestic water use
(d) Environmental NGO – You need to identify all the information management outputs that you want from the IMU to enable you to fulfil your objective of protecting the wetland ecosystem in the basin
(e) Mining Company-You need to identify all the information management outputs that you want from the IMU to enable you to conduct business in the most cost effective manner

Facilitator

Highlight how decisions are made on the essential non essential information management by the IMU, the strategies that groundwater Management Team and different stakeholders will take in the absence of their information wish list and finally if the stakeholders perceive the proposal by the IMU as being better off than when the meeting started.

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