INTEGRATION OF GROUNDWATER MANAGEMENT

into Transboundary Basin Organizations in Africa

TRAINING MANUAL

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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FOREWORD

The topic of groundwater management in basin organizations is not completely new, and it has been discussed at international events such as the Africa Water Week, the Stockholm World Water Week and other similar meetings. The process that led to the production of this training manual was the first time that African transboundary basin organizations were directly involved in a "Groundwater Management Needs Assessment Survey" and in the subsequent development of training materials for transboundary groundwater management. Many international organizations such as AGW-Net, BGR, IGRAC, UNDP-Cap-Net, IWMI, and the former GW-MATE team of the World Bank supported this process and have provided valuable inputs to this manual.

Transboundary water management is of great importance to Africa as has been emphasized in the African Water Vision 2025; almost all Sub-Saharan African countries share at least one international river basin. In Africa there are about eighty transboundary lake and river basins and at least forty transboundary aquifer basins. The African Water Vision 2025 stresses that groundwater is the major, and often only, source of drinking water for more than 75 % of the African population. Groundwater constitutes over 95% of the fresh water resources in Africa, and pollution and salinization of this resource is often irreversible on human timescale. As a result, a broad consensus has developed in AMCOW and in ANBO/INBO, (African (International) Network of Basin Organizations), that groundwater must be included in integrated river basin management.

Although worldwide much progress has been made in river basin management, transboundary groundwater management has often been neglected. Among the many reasons for this, the most important is that the groundwater resource is highly complex and has not been quantified across Africa. Most African basin organizations lack the technical skills and capacity to assess and manage transboundary groundwater resources. This renders the groundwater resource largely "invisible" to the water managers who are required to manage it sustainably.

Given the huge importance of the groundwater resource to Africa, and especially in light of the growing impacts of climate change, it is imperative that wise management of groundwater at every scale begins without any further delay. There are already some promising precedents in Africa that can provide helpful examples and experiences that other African basin organizations can draw on.

The recent 2012 AMCOW status report on “Water Resources Management in Africa” states that groundwater management systems are working satisfactorily in most North African countries, whereas in Central and West Africa, groundwater management systems are less common. The needs assessment survey shows that groundwater governance mechanisms are prioritized in the more arid parts of the continent, where the local population is highly dependent on groundwater as their primary drinking water source. In regions where people depend on groundwater, management systems are implemented.

“Conceptualizing Cooperation for Africa’s Transboundary Aquifers Systems” (German Development Institute - DIE) sums it up by saying: “Africa’s transboundary aquifer basins contain huge volumes of water which are vital for the future’s economic development and social well-being of the riparian countries. Fortunately, negative transboundary effects of national use have been very rare to date. This will almost definitely change if the potential for Africa’s groundwater resources is exploited, and this with international support. Then, cooperation between African nations will become almost imperative in order to prevent the “race to the pump-house”. That’s why we have to act now!

We wish the students and trainers to be inspired by this manual and to disseminate it to all stakeholders in regional basin organizations, national and local governments, civil society and businesses.

Tamiru Abiye (African Groundwater Network, Manager)
Vanessa Vaessen (Policy Advice on Groundwater, Project Management, BGR)

PREFACE

This training manual is the product of two specific policy visions.

The first is derived from one of the pillars of Integrated Water Resources Management (IWRM): that all water should be managed as a unitary resource within hydrological basin boundaries.

The second relates to the obvious transboundary nature of water as rivers flow from one country to the next. International development cooperation in the water sector is therefore increasingly supporting transboundary cooperation mechanisms.

Although groundwater has not been excluded from these policy visions, its integration into river basin management organizations and appreciation of the transboundary nature of groundwater flows have lagged behind. This is a product of both the complexity of the groundwater resource and its ‘invisibility’ to the public eye.

As a result, many African multi-state basin organizations do not even have a mandate to manage transboundary groundwater or coordinate its management between the basin states. Even where such a mandate does exist, many of these basin organizations have limited capacity to do so.

As a result of these conditions, BGR / AGW-Net / IWMI carried out a ‘needs assessment for transboundary groundwater management’ in nine international river basin organizations in Africa[1]. This survey revealed the varying needs in the different basin organizations for effective transboundary groundwater management.

This training manual has been complied in response to the needs expressed and is designed to help develop capacity within the basin organizations to manage their transboundary groundwater issues.

The topics covered range from policy and legislation, through bio-physical resource issues to communication and stakeholder relations. Much of the material in this manual is also relevant for internal national basin organizations.

Editor: Dr. Richard Owen
Africa Groundwater Network.

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[1] ORASECOM, LIMCOM, OKACOM, OMVS, VBA, LCBC, NSAS, NBI, NBA.

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www.agw-net.org

The teacher and the taught together create the teaching.

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FRAMEWORK AND NEEDS ASSESSMENT OF GROUNDWATER MANAGEMENT IN TRANSBOUNDARY BASIN ORGANIZATIONS IN AFRICA

CONTENT

MODULE 1

Framework and Needs Assessment of Groundwater Management in Transboundary Basin Organizations in Africa

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MODULE

1

Framework and Needs Assessment of Groundwater Management in Transboundary Basin Organizations in Africa

FRAMEWORK AND NEEDS ASSESSMENT OF GROUNDWATER MANAGEMENT IN TRANSBOUNDARY BASIN ORGANIZATIONS IN AFRICA

LEARNING OBJECTIVES:

- Provide an overview of groundwater management needs in transboundary African River and Lake Basin Organizations based on a detailed needs assessment carried out in 2011/12. (BGR / AGW-Net, 2013).
- Understand the strengths, weaknesses, opportunities and threats of including transboundary groundwater management into transboundary basin organizations

1.1 Introduction.

This module introduces the rationale and the focus of the training manual. The materials presented in this manual have been informed by a combination of pre-existing materials from the GW-Mate series of briefing notes on groundwater management, from the Cap-Net training manual Groundwater Management in IWRM (2010) and by a specific detailed needs assessment carried out in nine basin organizations in Africa with a view to understanding their needs with regards to groundwater management (BGR / AGW-Net, 2013).

The rationale for a training manual on transboundary groundwater management is two fold:

1. The first relates to the need to manage all water fluxes within a unitary framework, which, in context of Integrated Water Resources Management (IWRM), is the river basin. Hence this manual seeks to not only integrate groundwater management with surface water management, but it also seeks to do it within the framework of hydrological basins.
2. Second is that since the widespread adoption of an integrated approach to water resources management in African countries, many new water management structures have been formed, often called River Basin Organizations (RBO) or Catchment Management Agencies (CMA). Since many river basins are transboundary in natures, international development cooperation in the water sector has increasingly focussed on transboundary cooperation mechanisms.

Groundwater is the major component of available fresh water and attains an increasingly important role in economic development, for water supply and water security and for environmental integrity in Africa. However groundwater management is often neglected and much groundwater development takes place outside any long-term management framework or plan and in fact often without the knowledge or approval of the relevant water management authorities. It is clear that greater emphasis must be placed on groundwater management and that it must be managed within an appropriate and effective framework.

International river and lake basin organizations play an increasingly important role in transboundary water management on the African continent. A recent Africa-wide survey showed implementation of the river basin approach going ahead in 60% of reporting countries and institutions for groundwater management are being implemented in 47% of countries (AMCOW 2012). As most large rivers in Africa are transboundary there is a close linkage between river and lake basin management decisions at national level and the management of shared basins at international level. Water management structures at national level are the primary source of information for decision making at transboundary level and likewise are often the main route through which recommendations from transboundary level can be implemented.

One of the entry points for enhanced groundwater management is through support to the existing or emerging African international lake, river and aquifer basin organizations (TBOs)[1] that have institutionalised mandates on integrated water resources management in areas of shared water resources (AMCOW, SADC, INBO). It is anticipated that enhancing capacities of the transboundary basin organizations to address groundwater management will promote collaboration and coordination of groundwater management internationally as well as nationally, in addition to integrating groundwater management into overall water resources management.

It must be noted that the approaches, skills, mandates, legal and institutional frameworks, stakeholders etc. for international basin organizations to manage transboundary groundwater flow are rather different from the same management components as required by an internal local catchment authority. However there are also many similar management requirements such as resource assessment, monitoring, demand management, effluent control and protection and, as is the case for surface water, the national water management structures are the primary source of information for decision making at transboundary level.

This manual is targeted primarily at International Basin Authorities, or Transboundary Basin Organizations (TBO) in Africa and it focuses on transboundary groundwater management issues. As intimated in the paragraph above, there are many issues that overlap with non-transboundary groundwater management and these are also covered in the manual. Where possible, the manual also provides training exercises that focus on transboundary groundwater management, but in many cases, the exercises will also be valid for local groundwater management authorities.

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[1] Including groundwater bodies as a potential delimiting basis for transboundary water management and denoting these as ‘aquifer basins‘. The term ‘basin‘ has been broadened to not only encompass river and lake basins but also groundwater units.

1.2 Objectives of the Needs Assessment

This module addresses the issue of transboundary groundwater management capacity in international river and lake basin organizations in Africa based on a recent needs assessment survey carried out in nine international river basins (BGR / AGW-Net, 2013).

Nine TBOs in Africa were surveyed on the present status, progress, and limitations to incorporating groundwater management into their mandate and practices (BGR and IWMI, 2012). The primary focus institutions of the needs assessment were the executive secretariats of the TBOs and the national (ground)water authorities in the member states.

The immediate objectives of the needs assessment were to:

1. Assess the present national and international framework (legal, institutional), practices, experiences, and capacity for groundwater management
2. Identify and assess shortcomings and strengths for integrated groundwater management as part of integrated national and transboundary water resources management
3. Based on consultations with the TBOs, recommend immediate and longer term strategic steps for supporting a capacity-enhancing process through which groundwater is gradually and permanently included and integrated into the mandate of existing TBOs
4. Initiate a process and a network of partners (institutions, experts, decision makers, donors, and NGOs) for developing and sustaining capacity for transboundary groundwater management in TBOs in Africa

1.3 Methodology

Nine selected TBOs (Senegal River (OMVS), Niger River (NBA), Volta River (VBA), Lake Chad (LCBC), Nubian Sandstone Aquifer (NSAS), Nile River (NBI), Okavango River (OKACOM), Orange-Senqu River (ORASECOM), and Limpopo River (LIMCOM)) entered into the survey that comprised personal interviews with representatives of the transboundary basin organizations as well as officials from water management institutions in the respective member states (Table 1.1).

The needs assessment consisted of three parts:

1. Desktop studies to develop short individual **basin profiles** for each basin;
2. **Interviews** with key personnel involved in groundwater management in the basins; and
3. **SWOT analyses**[2] based on the outcomes of the first two parts.

In a consultation process, the results of the survey were reviewed by the respective TBOs, AGW-Net, ANBO, and AMCOW in Burkina Faso in February 2013. Their recommendations were used for developing this training manual.

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[2] A SWOT analysis is a tool that identifies the strengths, weaknesses, opportunities and threats of an organization. The method is used to analyse the information from an organizational analysis and separate it into internal (strengths and weaknesses) and external issues (opportunities and threats).

1.4 SWOT Analysis:

Swot analyses were carried out in each TBO and the results from all the SWOT analyses were combined and summarized below.

TBO STRENGTHS - SUMMARY

Governance:

1. TBOs tend to operate within the framework of a multi-state agreement that provides for the possibility of a transboundary water management mandate.
2. TBOs generally have a permanent secretariat that can initiate and manage programs and projects such as transboundary groundwater management and monitoring activities.
3. TBOs can provide a platform for mobilizing basin-wide political support and for bringing groundwater higher on the political agenda.
4. TBOs have a good platform for raising finance to carry out transboundary groundwater actions such as monitoring.

Riparian State Collaboration:

1. TBOs can be a focal point for improved political and technical collaboration between riparian states.

Data Management and Sharing:

1. TBOs can provide a suitable platform for hosting transboundary groundwater data and for the management and use of the data.

Capacity Development:

1. TBOs can optimize groundwater management capacity development as a focal point for basin wide training programs in transboundary groundwater management.
2. TBO’s can optimize capacity utilization by providing a platform for the pooling of scarce technical expertize from the riparian states.

TBO WEAKNESSES - SUMMARY

Governance:

1. Many TBOs are advisory bodies only and do not have a legal mandate to manage transboundary groundwater.
2. Most TBOs have a strong traditional focus on surface water management and hardly consider groundwater.

Riparian State Collaboration:

1. Many TBOs are not well integrated with the groundwater management authorities in the riparian states.
2. There is often insufficient understanding of transboundary groundwater issues in TBOs.
3. Disparities in groundwater challenges and context as well as groundwater development and management give rise to different focus between states.

Data Management and Sharing:

1. Many TBOs have neither groundwater data, nor trained staff, nor a suitable computer platform for a groundwater database at present.
2. Agreements on data sharing are often limited and ill defined. Data sharing protocols are often non-existent and riparian states may be reluctant to share their data under such circumstances.
3. Most TBO agreements do not include any legal requirement for states to share their groundwater data, even in transboundary aquifer situations.

Capacity Building:

1. Many TBOs do not have the skills, personnel, or the equipment to carry out transboundary groundwater management.
2. There is often a lack of interest to develop groundwater technical capacity in TBOs, due to their focus on surface water resources.

TBO OPPORTUNITIES - SUMMARY

Governance:

1. TBOs can promote the philosophy that groundwater should be managed within the river basin catchment management framework.
2. TBOs are well placed to take the lead in transboundary groundwater management and transboundary groundwater monitoring.
3. There is a very strong international interest to bring groundwater management into the ambit of TBOs.
4. TBOs are well placed to identify important transboundary groundwater impacts on river flow, water quality and aquifer degradation.

Riparian State Collaboration:

1. TBOs generally have very good relationships with the riparian states and can introduce the need for transboundary groundwater management.
2. TBOs can establish multi-state taskforces from the riparian states to deal with transboundary groundwater management and monitoring.
3. TBOs can promote transboundary groundwater management on the political agenda in the riparian states.
4. TBOs can link transboundary groundwater management to existing or proposed groundwater projects in the riparian states.

Data Management and Sharing:

1. TBOs have an opportunity to develop a protocol on groundwater data sharing for transboundary aquifers within their river basins.
2. TBOs have an opportunity to stimulate the creation of a basin wide groundwater database and to encourage the riparian states to share groundwater data.
3. TBOs have an opportunity to support regional groundwater initiatives.
4. TBOs are directly interested and well placed to establish the importance of the linkage between groundwater abstractions and flow and water quality variations in international rivers.

Capacity Building:

1. There is an opportunity to use experts from riparian states' groundwater departments to support the TBOs capacity.
2. TBOs can work with AMCOW to promote institutionalisation of groundwater management by river basin organizations.
3. TBOs have an opportunity to link to regional and donor supported groundwater capacity development initiatives.
4. TBOs can identify the capacity needs within the riparian states for transboundary groundwater management.
5. TBOs have an opportunity to host / implement training courses and other capacity development activities in the field of transboundary groundwater management.

TBO THREATS – SUMMARY

Governance:

1. TBOs often lack the finances to carry out transboundary groundwater management and monitoring programs.
2. Many TBOs are advisory organizations and lack the legal mandate to carry out transboundary groundwater programs.
3. Many TBOs lack strategies and procedures for the integration of groundwater into river basin water resources management structures.
4. There are often mismatched resources and political power between the riparian states that can hinder smooth agreement on transboundary groundwater management.

Riparian State Collaboration:

1. Riparian states may reject the TBOs role in managing transboundary groundwater.
2. Technical complexities may make it difficult to fully understand transboundary groundwater movements and therefore to get support from the riparian states, especially in conflict situations.
3. Many TBOs do not have a legal mandate to enforce transboundary groundwater decisions.
4. There may be a lack of common interest, or conflicting interests, from member states on groundwater issues.

Data Management and Sharing:

1. Some riparian states may be unwilling to share groundwater data.
2. Riparian states have different data archive systems that may be incompatible
3. Lack of knowledge of groundwater resources.
4. Lack of credible/ accurate information on the major uses of groundwater within the basin
5. Sustainability of mechanism of data collecting & sharing is not assured.

Capacity Building:

1. Limited capacity in the basin for undertaking groundwater management activities
2. Riparian states may not accept the need for capacity development with regards to transboundary groundwater management.
3. Funding for capacity development may be unavailable.

1.5 Overall Results

The survey showed that despite incipient awareness, adoption of international legal frameworks and international promotion, transboundary groundwater management in the TBOs has not yet been fully addressed. Encouraging factors, such as international advocacy, and financial and technical support, need to be backed up by an emphasis on political commitment and capacity development at all levels. Because TBOs are still struggling with their present mandates, primarily related to surface water management, the added challenges of groundwater management will need to be incorporated gradually.

It is clear that surface water and groundwater must be managed coherently. There are some inherent structural challenges to such an approach. The areal extent of surface water basins and the underlying groundwater systems often differ radically (BGR et al., 2012, see Fig. 1.1), making groundwater management by river basin organizations complex. Furthermore, in arid regions, due to the lack of surface water, it is more rational to use aquifers in discrete groundwater basins as the basis for water management organizations in such areas. In addition, there is a lack of adequate information on the distribution and extent of groundwater resources in many parts of the world and there is a distinct need for investment to improve capacity for groundwater assessment and monitoring. Despite these factors, the strong global support and progress towards IWRM in international river basins is such that they are still considered to be the appropriate organizations to manage transboundary aquifers.

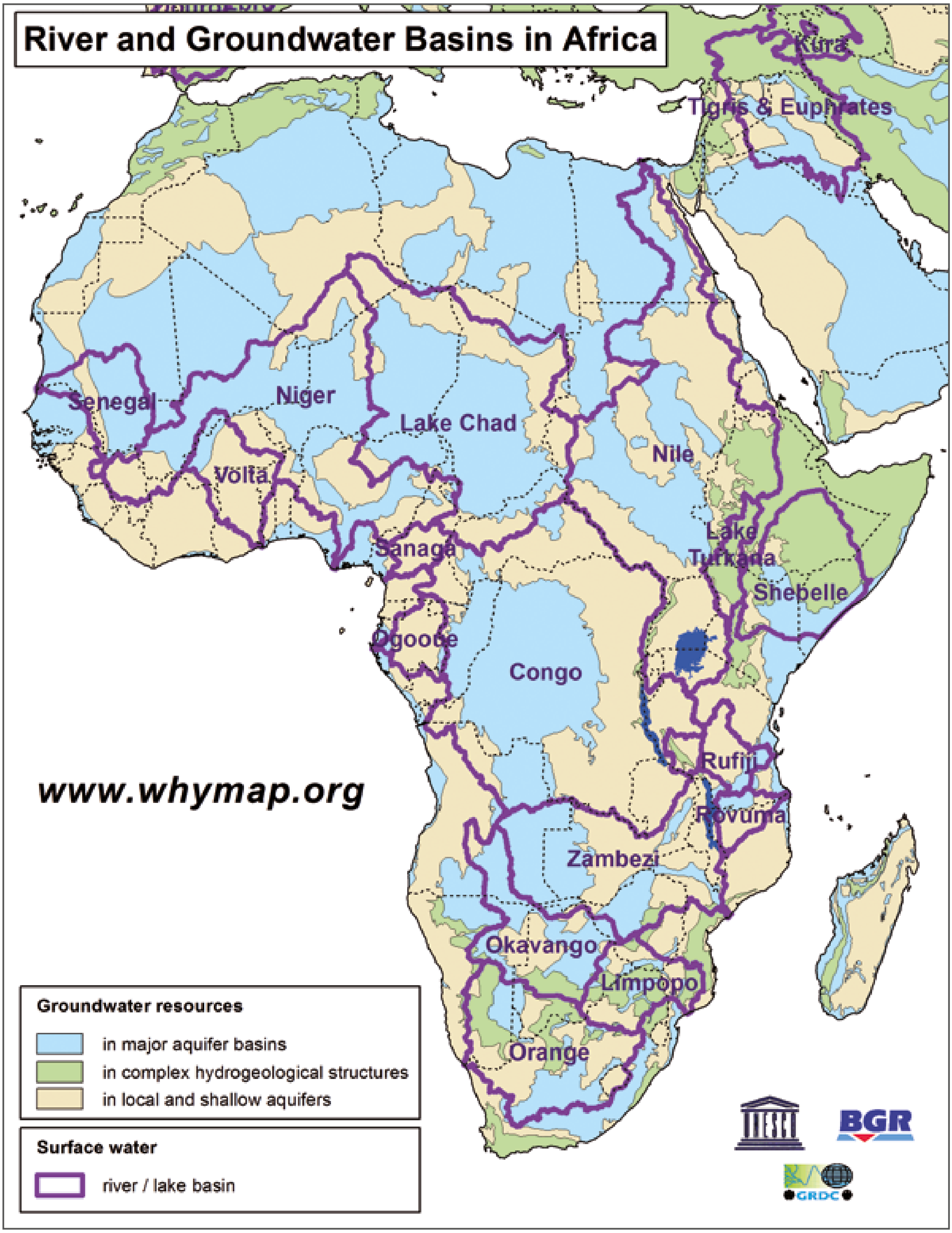

Figure 1.1 Transboundary Aquifers and International River Basins in Africa.

All TBOs surveyed are different in terms of their geography, size and mandate (see Table 1.1).

Table 1.1 Key data on the basins and their organizations

Basin	Riparian countries	Area (km2)	Population (mill.)	TBO (created)	Mandate[a]	Associated TBAs[b]	Ref. to basin profile reports[c]
Oange-Senqu	Botswana, Lesotho, Namibia, South Africa	896,000	19	ORASECOM (2000)	Cons, A, Coo, I	4	Abiye, 2012
Limpopo	Botswana, Mozambique, Zimbabwe, South Africa	410.000	14	LIMCOM (2003	Cons, A	3	Owen, 2012
Okavango	Angola, Botswana, Namibia, (Zimbabwe)[d]	430,000	0.7	OKACOM (1994)	Cons, A, Coo, R	2-5	Mapani, 2012
Nile	Burundi, Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, Uganda	3,100,000	160	NBI (1999)	Cons, A, Coo, I	7	Mirghani and Tindimugaya, 2012
Nubian	Chad, Egypt, Libya, Sudan	2,200,000	0.14	NSAS (1999)	Cons, A	-	Mirghani, 2012
Senegal	(Guinea)[e], Mali, Mauritania, Senegal	300,000	5	OMVS (1972)	Cons, A, Coo, I, R, Conf, P	2	Diene, 2012
Niger	(Algeria)[f], Benin, Burkina Faso, Cameroon, Chad, Guinea, Ivory Coast, Mali, Niger, Nigeria	2,000,000	109	NBA (1980)	Cons, A, Coo, I, R	3	Menge and Jäger, 2012
Volta	Benin, Burkina Faso, Mali Ghana, Ivory Coast, Togo	400,000	19	VBA (2006)	Cons, A, Coo, I, R	1	Jäger, 2012
Chad	(Algeria), Cameroon, Chad, Central African Republic, (Libya)[g], Niger, Nigeria, (Sudan)[h]	2,300,000	30	LCBC (1964)	Cons, A, Coo, R	2	Vassolo, 2012

Individual reports for the nine TBOs have been produced as part of the survey These are available at: http://www.splash-era.net/search_outputs2.php

[a] Cons: consultative, A: advisory, Coo: coordinating, P: policy-making, I: implementing, R: regulatory, Conf: conflict arbitration, TBAs: transboundary aquifers

[b] Acc. to WHYMAP (BGR, UNESCO, 2006). Reservations exist, due to uncertainty of extent of TBAs (e.g. Okavango)

[c] See Annex 1 THESE SHOULD JUST BE LISTED IN THE REFERENCES AND DON'T NEED A SEPARATE ANNEX

[d] Zimbabwe is part of the inactive part of the basin, not member of OKACOM

[e] Guinea is now full member of OMVS, but was not signatory of the treaty creating TBO

[f] Algeria is not a full member of NBA, but does have observer status

[g] Libya is now full member of the LCBC, but was not signatory of the treaty creating TBO

[h] Nations in parenthesis are not signatories to the LCBC treaty

1.6 Recommendations

Based on the needs assessment, the following generic recommendations for improving groundwater management in the international TBOs can be put forward.

With regard to the legal basis:

1. The UN draft articles on the United Nations International Law Commission (UNILC) Law of Transboundary Aquifers and the 1997 Convention on the Non-Navigational Use of Watercourses can be used as guidance for TBOs for transboundary groundwater management.
2. The particular properties of groundwater resources need to be specifically addressed in the legal frameworks, e.g. the relative delay in response, the relative vulnerability of the aquifers, and the distributed access and use of the resource.

With regard to the institutional framework and decision making:

1. Groundwater committees of the TBOs should be created (with at least one groundwater / hydrogeological expert) to give emphasis to groundwater issues in the organizations.
2. Centralised databases of transboundary aquifers (TBA) should be maintained at the TBOs and in the riparian states and clear data sharing protocols that include groundwater should be put in place.
3. All TBOs should develop strategic groundwater action and investment plans for their basin.
4. Apply inter-disciplinary and cross-sectoral assessment approaches for water supply, food security, climate change adaptation, environmental integrity involving groundwater, as well as socio-economic and cost-benefit analysis of groundwater development to prioritize use and valuation of groundwater resources.

With regard to financial viability:

1. Regional development communities (SADC, ECOWAS, IGAD) should be further engaged in transboundary groundwater management, enhancing groundwater focus and facilitating multilateral donor support and support from international water organizations. (e.g. UNESCO-IHP, UNECE, IAH, IAHS, IAEA)
2. Advocacy should be focussed on political decision makers in order to promote political interest and commitment for groundwater management, which should facilitate financial support to the TBOs.

With regard to capacity development (CD) and awareness raising:

1. Use existing CD organizations and programmes in Africa to strengthen the capacity among the TBOs. (GWP, WaterNet, AGW-Net, Cap-Net, WRC, CoE on Water, NEPAD Water CoE, and IW:LEARN)
2. Increase staff with hydrogeological background in the TBOs. It is also essential to improve groundwater knowledge and skills of existing personnel.
3. Enhance liaison between TBOs and groundwater expertise existing in the riparian countries and in academia.
4. Rather than starting from scratch, TBO’s should use, replicate, and expand existing frameworks for enhancing public participation and awareness raising to address groundwater issues in the basins. (as done in e.g. NBI and ORASECOM)
5. Increase visibility of benefits (to politicians and public) of managing groundwater in river basin organizations by packaging information on groundwater issues so that non groundwater-experts are able to understand it.

1.7 The Training Manual.

This training manual has been prepared as a response to the needs expressed by the TBOs participating in the survey. The manual aims to provide specific guidance on groundwater management to transboundary basin organizations in Africa.

During the preparation of this manual, it became clear that much of the available training material on groundwater management is directed towards general groundwater management and less towards specific transboundary situations. This manual attempts to provide some balance to that with insights into transboundary aspects of groundwater management. Nevertheless, the general principles of groundwater management are included because they are, in many cases, relevant to transboundary situations.

Although this manual is directed to groundwater management by TBOs, it must be appreciated that there are many issues that TBOs face that impact on groundwater management, but which fall outside the scope and ambit of a training manual on groundwater management in TBOs. Financial viability is perhaps one such area.

The major purpose of the manual is to provide TBO technical and professional staff with the requisite understanding and skills to improve their ability to manage transboundary groundwater. However the manual also highlights the legal and institutional limitations that TBOs face with regards to their mandate and their professional capacity.

Where possible, the exercises in the manual focus on transboundary situations and provide an opportunity for TBO staff to work through these with the course facilitators and compare them to conditions that they face in their own work environment.

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1.9 Exercise

- Regarding your TBO, can you identify the Strengths, Weaknesses, Opportunities and Threats?
- What are your key concerns with regards to transboundary groundwater issues?

For example

Title: Needs assessment for groundwater management in transboundary basin organizations.

Purpose: To explore how groundwater is managed in national and transboundary water management structures.

Activity: 1.5 – 2 hrs

1. **Work in groups, either by basin organization or by country.**
2. **Discuss the following questions:**

- What are the key water management structures at basin level?
- How are surface water and groundwater management integrated in these structures?
- What are the strong points of the management system?
- What are the weak points?
- What action would you recommend to improve integrated ground and surface water management?

Report back

Each group to report back on each question 10-15 mins each then 20 mins general discussion.

Notes to Facilitator: Try to keep the focus on the operational level of management. Remember that there are many different kinds of structures in place and groundwater may have a entirely separate structure. For transboundary basin organizations, try to find out how they link down to national level structures of participating countries.

Finally consider how the points raised by the participants may be addressed by the course.

MODULE

INTEGRATED WATER RESOURCES MANAGEMENT AND THE GROUNDWATER MANAGEMENT FRAMEWORK

CONTENT

MODULE 2

Integrated Water Resources Management and the Groundwater Management Framework

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

Editorial Staff: *Vanessa Vaessen, Ramon Brentführer – BGR*
Layout: *ff.mediengestaltung GmbH, Hannover, Germany*
Picture: *IWMI*

INTEGRATED WATER RESOURCES MANAGEMENT AND THE GROUNDWATER MANAGEMENT FRAMEWORK

LEARNING OBJECTIVES

This module emphasises the need for managing groundwater in the context of Integrated Water Resources Management. The module will contribute to the following learning objectives:

- Appreciate the characteristics of groundwater in the context of all available freshwater resources
- Understand the challenges facing groundwater management and the need for improved approaches to address the resource management problems
- Understand key principles and themes in IWRM with respect to joint surface-groundwater management
- Emphasize key advantages of incorporating groundwater management into national and river basin water resource planning

2.1 Introduction

One of the cornerstones of the IWRM philosophy is that the fundamental management unit for water should be a ‘river basin’ or ‘surface water catchment’. A river basin is a naturally occurring physical entity that has a contiguous integrated surface water system with a unique outlet. Water management by river basin is therefore based on physical ecological reality. Due to this guiding philosophy, many nations now manage their water by river basin, and many River Basin Organizations (RBOs) and other catchment water management authorities have been created.

The conjunctive management of groundwater and surface water is also a guiding principle of IWRM. However the integrated management of surface and groundwater has lagged behind in many RBOs for various reasons. These include traditional institutional separation of groundwater and surface water management, the different knowledge and skill systems required for surface and groundwater management, and the fact that aquifer systems may not coincide with river basin boundaries. Aquifers may be transboundary between adjacent river basins, and / or shared between two or more states. (See Module 4: Management of transboundary aquifers)

Given their overarching prominence in regional transboundary water management in Africa, RBOs have a unique opportunity to fully integrate groundwater and surface water management and thereby manage their catchment water supplies in an optimal and sustainable manner.

A fundamental purpose of this short course is to promote this objective by providing an overall understanding of groundwater management within IWRM and by providing tools for river basin water managers to manage their groundwater resources conjunctively with their surface water resources.

2.2 Groundwater in the hydrologic cycle

- The hydrologic cycle is the continuous circular process by which water evaporates from the oceans, condenses and falls to the Earth as rain or snow, becomes run-off and groundwater recharge and eventually returns to the oceans through river flow and groundwater discharge. (Figure 2.1).
- The implications of the hydrologic cycle are that surface water and groundwater cannot be sustainably managed separately since they are inextricably bound together in the water cycle.

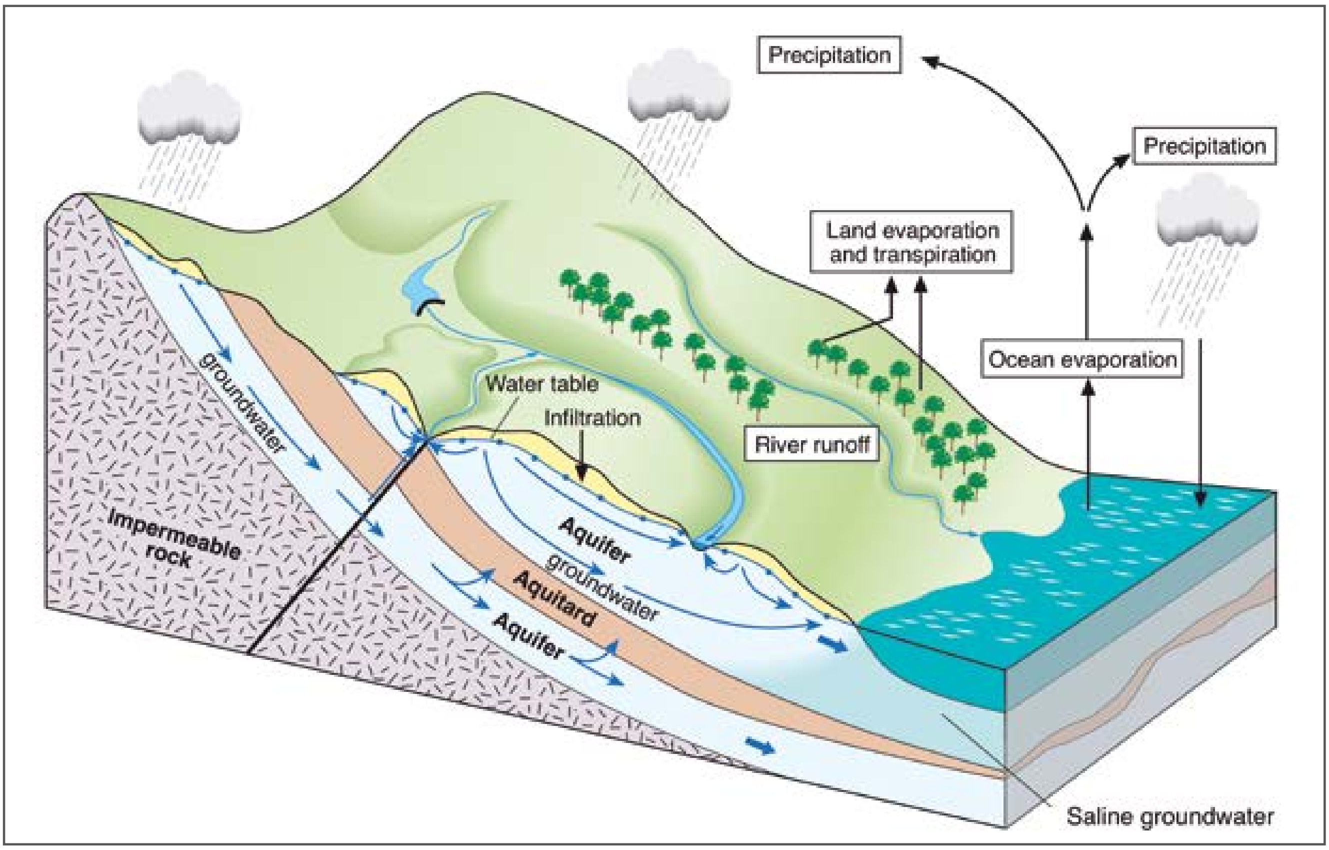


Figure 2.1 Hydrologic cycle: linkages between surface and groundwater.

Importance of groundwater

- Although groundwater is the hidden part of the hydrologic cycle, it represents a much larger volume than surface water. Groundwater makes up 97% of the available unfrozen freshwater on our planet (Figure 2.2)
- The surface water / groundwater ratio in Africa is similar (Fig 2.3), with groundwater at (5,500,000 km3) dominating the available freshwater resources (31,776 km3).
- Africa is blessed with abundant groundwater resources, although perversely most of the largest aquifers are located either in the humid and water rich Congo basin or in the sparsely populated Sahara / Sahel areas (Fig 2.4)
- Groundwater is the main source of water for domestic use for more than 2 billion people in the world – that is almost 30% of the estimated 7 billion global population. It is often the only source of water for all uses for dispersed rural communities in semi-arid regions
- The acccelerated global development over the past few decades has been significantly supported by groundwater, as a low-cost, drought-resistant and (mainly) high-quality water supply for urban and rural populations and for irrigation (Module 9: Groundwater for food production.)
- It is the major source of water for many mega cities (Mexico City, Dhaka, Dar es Salaam, etc.)
- Groundwater is under-developed in many parts of the continent
- Additional and sustainable use of groundwater will be vital for the achievement of the 'UN Sustainable Development Goals' and for adaptation to climate change (Module 11: Groundwater and Climate Change)

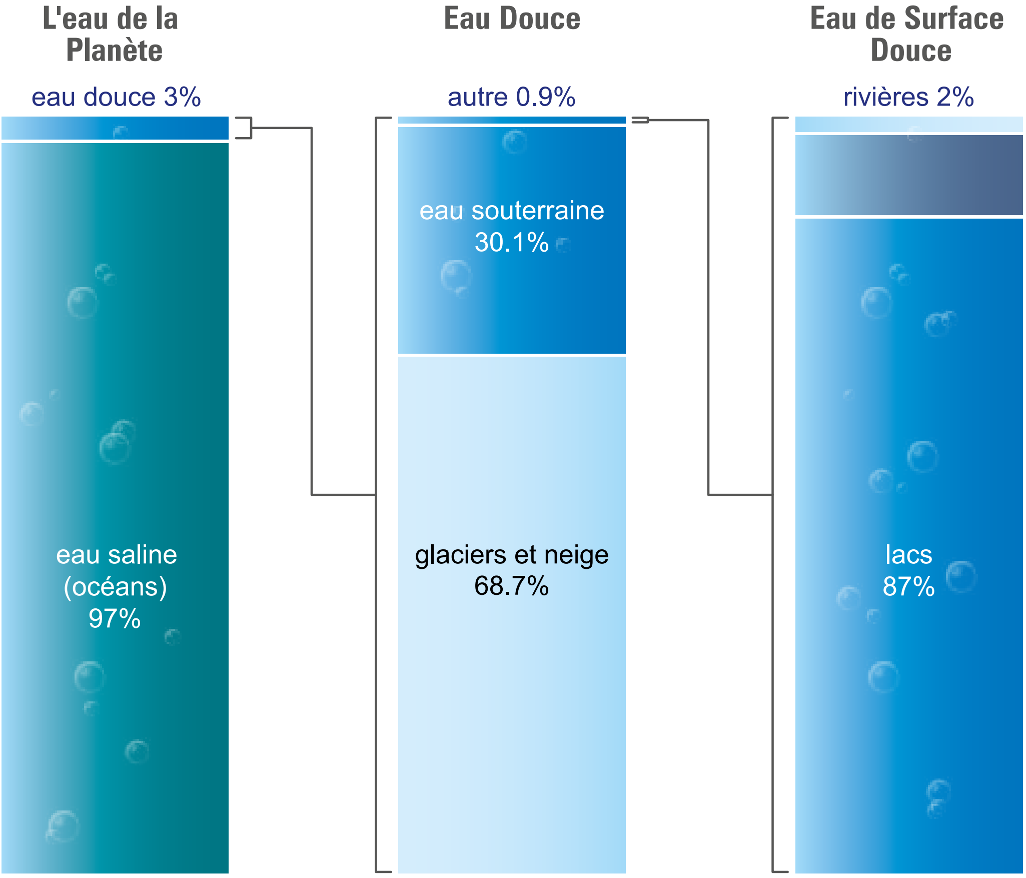


Figure 2.2 Distribution of earth's freshwater resources

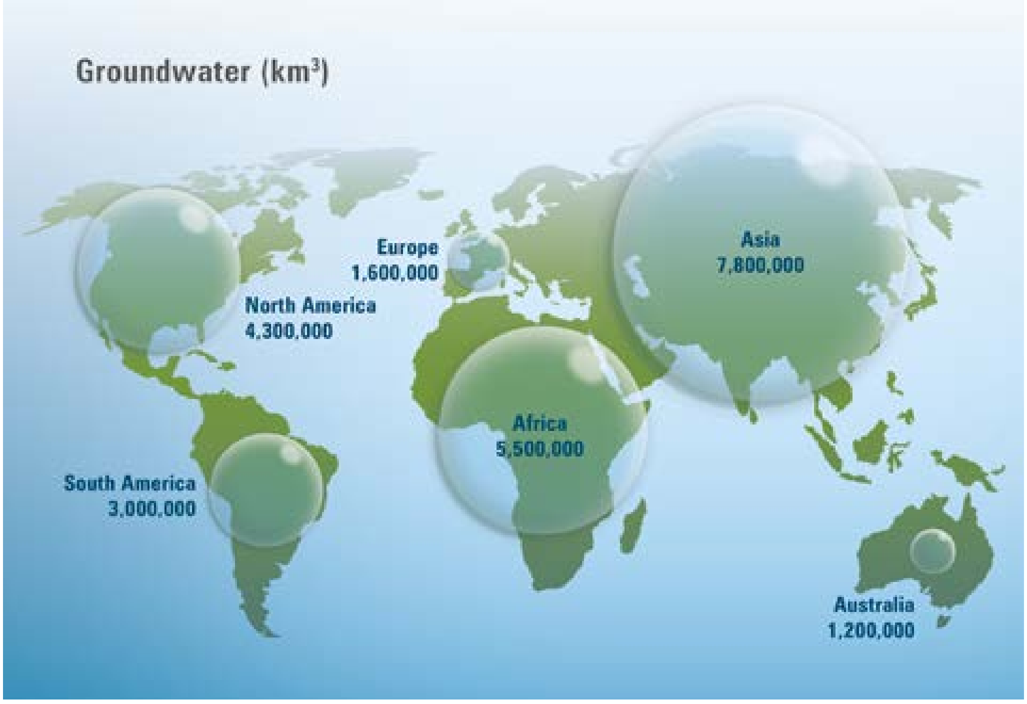


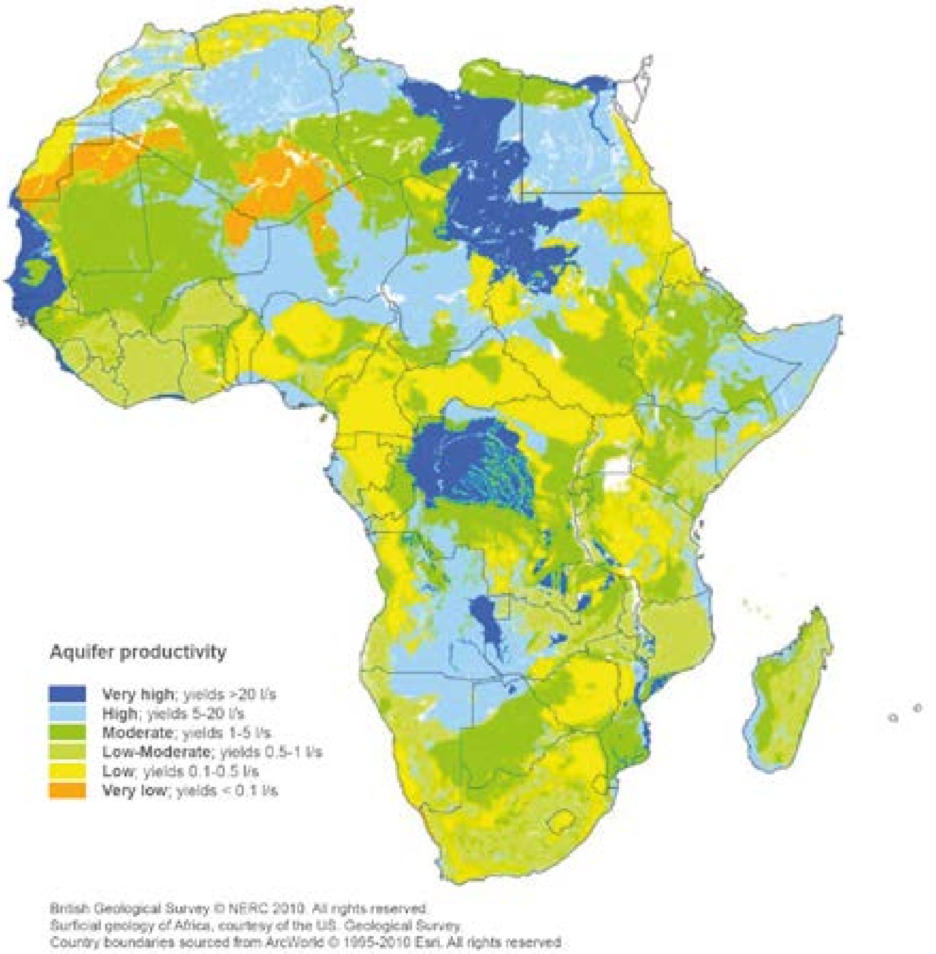
Figure 2.3 Regional distribution of global groundwater resources.
Source: UNEP, 2008. http://www.unep.org/dewa/vitalwater/article32.html

2.3 Characteristics of groundwater

Besides its importance in terms of quantity, groundwater has a number of other natural and physical characteristics that makes it an important resource for economic and social development. (Table 2.1)

However although groundwater has many positive characteristics, there are some critical issues that make groundwater management complex and difficult

- Groundwater is invisible and often there is very limited data available on its physical distribution and aquifer characteristics
- Groundwater flow within the aquifer systems is difficult to ascertain and can vary over time due to pumping, natural discharge and recharge, climate change, etc.
- There are usually many independent users pumping groundwater, thus making monitoring abstraction and managing users complicated
- The interaction between surface water and groundwater is often little understood but can have great implications for management decisions



British Geological Survey © NERC 2010. All rights reserved.
Surficial geology of Africa, courtesy of the US. Geological Survey
Country boundaries sourced from ArcWorld © 1995-2010 Esri. All rights reserved

Figure 2.4 Aquifer productivity map of Africa. Source: British Geological Survey, 2011.
http://www.bgs.ac.uk/research/groundwater/international/africangroundwater/mapsDownload.html

Table 2.1 Beneficial characteristics of groundwater resources

Characteristics	Explanation
Available where needed	Groundwater can be found almost everywhere (not neccesarily in the quantities desired)
Naturally protected	Groundwater is protected against direct pollution and evaporation, and often provides potable water without treatment
Our largest reservoir	Global groundwater storage is vast, providing a water buffer that can be used to mitigate droughts and water scarcity
Untapped resource	There are many untapped aquifers that can provide water for future needs if managed sustainably. This is particularly true in Africa (e.g. Addis Ababa and Dar es Salaam)
Stable temperature	Groundwater is becoming increasingly used as an important and safe source of renewable energy for heating and cooling, although this use is still minor in Africa.
Environmental function	Dry season river baseflow is maintained by groundwater discharge. Groundwater dependent ecosystems (GDE) such as wetlands provide vital environmental services.
Natural treatment	Soils and aquifers have the capacity to improve water quality by degradation and sorption of biological and some chemical contaminants.

2.4 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 global challenges in natural resource management.

Whilst groundwater storage is vast (more than 97% of freshwater reserves) its replenishment by recharge is finite and mainly limited to shallower aquifers, which can also be seriously degraded by pollution. Groundwater is the invisible part of the hydrologic cycle and a clear understanding of its physical environment in space and time (quality, depth, recharge, productivity) is required to take decisions on cost-effective and sustainable exploitation (Module 3: Aquifer systems characterization for groundwater management). However such information about groundwater is not routinely obtained in most countries.

Investment in the assessment, 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 socioeconomic 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.

For example, in Harare (2014), the water distribution network based on surface water and the water treatment plant, due to aging, lack of investment and lack of maintenance, lacks the capacity to serve the needs of the expanding population. Water supplies are erratic, insufficient and have not reached some parts of the city for several years. The result has been an explosion of borehole drilling, mushrooming of bulk water sellers, and uncontrolled private pumping of groundwater, particularly in parts of the city where people can afford private boreholes. Over the past decade, groundwater levels have declined by more than 10 m and many boreholes have already dried up. Water level and compliance monitoring are hampered by lack of investment into the catchment authorities, and the situation continues to deteriorate. Many other cities in Africa face similar problems, e.g. Lusaka, Accra, Nairobi.

Traditional institutional separation of surface water from groundwater has created fundamental communication barriers that now extend from technical experts to policy developers, operational managers and water users (Module 7: The role of stakeholder participation and communication in groundwater management). These barriers impede the understanding of the processes and consequences of groundwater-surface water interactions.

Ultimately sustainable groundwater use requires a comprehensive understanding of the multiple factors that impact on the resource. These may include:

- The impact of land use / land management which has a direct impact on both groundwater recharge and on groundwater pollution.
- The protection of the groundwater resource though separation of important water supply wells and groundwater recharge areas from polluting activities such as waste disposal sites, sewage treatment plants etc.
- In water scarce areas, managed aquifer recharge (MAR), from e.g. occasional flood waters or irrigation excess water, can be introduced to promote sustainability of the groundwater resource
- In all circumstances where possible, conjunctive use of surface and groundwater can be used to ensure the optimum sustainable use of the total water resource.

2.5 What is IWRM?

Integrated Water Resources Management (IWRM) 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.

IWRM is not just about managing physical resources, it is also about reforming human systems to enable people, women as well as men, to benefit from those resources and to protect and manage them. Integrated water resources management is a comprehensive process for the sustainable development, allocation and monitoring of water resources and their use in the context of social, economic and environmental objectives. The integration of groundwater into the IWRM paradigm can provide important benefits for both the water managers and the societies that they serve.

2.6 IWRM principles and framework

There are three key 'pillars' that provide a framework for the implementation of IWRM (Figure 2.5). These are: economic efficiency; environmental sustainability; and social equity. All IWRM plans need to operate with these three fundamental objectives in mind.

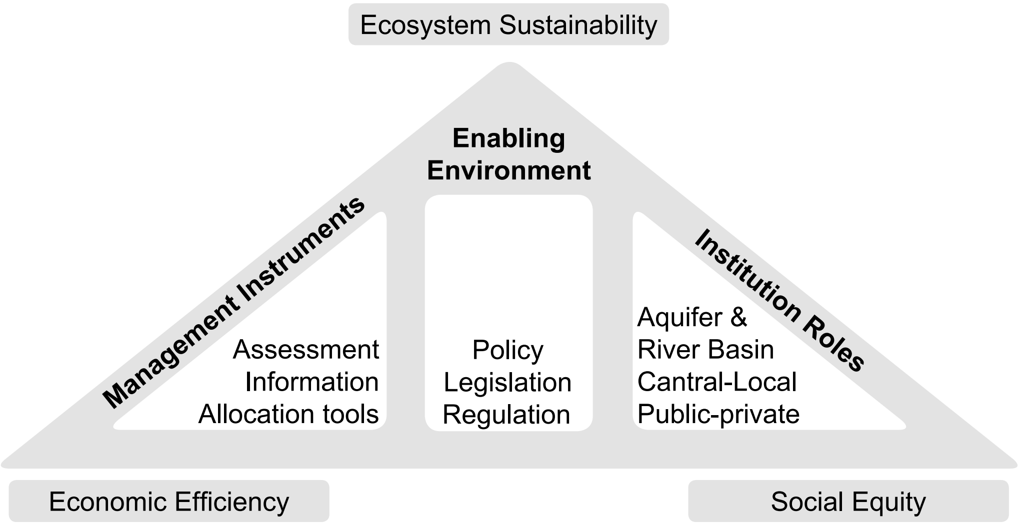


Figure 2.5 The IWRM Implementation Triangle

To enhance IWRM, there are three key areas for IWRM reforms:

- Enabling Environment – water policy; water laws and regulations; financial and economic instruments (Module 6: Groundwater regulation, licensing, allocation and institutions)
- Institutional Roles – organizational frameworks; institutional capacity development
- Management Instruments – assessment and monitoring of (ground)water resources; water demand information; allocation tools, predictive models (Module 5: Groundwater Monitoring and Information Management).

These three action areas are known to be essential for implementing IWRM and are presently driving country level reform at all stages in water planning and management in Africa. This usually begins with a new water policy to reflect the principles of sustainable management. 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 iterative process, with some changes taking place immediately and others requiring several years of planning and capacity building.

When beginning the process of change, consider:

- What changes **must** happen to achieve agreed-upon goals?
- Where and when is change possible given the current social, political, economic and institutional 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 Tool Box in table 2.2

Table 2.2: IWRM Tool Box: Change Areas (http://www.gwp.org/en/ToolBox/)

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.

There are many courses and manuals (IWRM for River Basin Organizations; IWRM Plans, etc. at www.cap-net.org) that expand on the principles and implementation of IWRM more broadly. This manual focuses on the specific issues associated with groundwater management for basin organizations.

2.7 Groundwater management for river basins

Although the principles of IWRM emphasize that groundwater and surface water must be managed as a single resource, how to achieve this may not be immediately obvious to RBO professional and technical staff, who tend to be more skilled in managing surface waters. There are certain distinct features about groundwater that water managers need to take into account in order to achieve an optimum level of conjunctive management of surface and groundwater.

Table 2.3 Comperative features of groundwater and surface water

Feature	**Groundwater Resources & Aquifers**	**Surface Water Resources & Reservoirs**
Hydrological Characteristics		
Storage	Very large	Small to moderate
Resource Areas	Relativity unrestricted	Restricted to water bodies
Recharge	Restricted to unconfined aquifers	Takes place everywhere with rainfall
Response to changes	Very slow	Rapid
Flow velocities	Low	Moderate to high
Residence time	Generally decades / centuries	Mainly weeks / months
Drought vulnerability	Generally low	Generally high
Evaporation losses	Low and localised	High for reservoirs
Resource evaluation	High cost and significant uncertainty	Lower cost and often less uncertainty
Abstraction impacts	Delayed and dispersed	Immediate
Natural quality	Generally (but not always) high	Variable
Pollution vulnerability	Variable natural protection	Largely unprotected
Pollution persistent	Often extreme	Mainly transitory
Socio-Economic Factors		
Public perseption of the resource	Mythical, unpredictable	Aesthetic, predictable
Development cost	Generally modest	Often high
Development risk	Less than often perceived	More than often assumed
Style of development	Mixed public and private, often by individuals	Largely public

Table 2.3 compares the hydrological characteristics of groundwater and surface water as well as the socio-economic factors that are important in terms of management and provide insight into how management strategies may be adjusted when managing groundwater resources.

While no specific ‘toolbox’ for groundwater management in river basins has been created, water resources managers will find that as their understanding of the groundwater resource grows, their appreciation of how groundwater can be integrated into river basin water resources management will increase too. The aim is to conjunctively manage surface and groundwater for optimum sustainable water resources management.

A focus on conjunctive management will require that the basin authority develop capacity in groundwater management. Groundwater management often entails significant uncertainty, for example in the extent of the resource, the recharge rate and the discharge and abstraction. These complexities require an adequate level of professional groundwater skill to be retained in-house by the basin authority.

A key issue for sustainable groundwater management is balancing the increasing demands of water users with the available resources by:

a. balancing groundwater abstraction against long term average annual groundwater recharge
b. protecting groundwater from all forms of pollution, but especially from pollution by persistent toxic chemicals

A schematized illustration of sustainable management of the groundwater balance is shown in Fig 2.6. This supply vs demand illustration captures all sources of supply from both recharge and from storage as well as considering the range of demand for groundwater including subsistence, economic and environmental demands.

Although figure 2.6 focuses on groundwater management, the direct interaction between surface water and groundwater is a critical reason to manage these resources conjunctively. Some of the direct interactions are given below:

- Groundwater recharge is impacted by surface water use. Damming rivers and abstracting water reduces downstream flow for indirect groundwater recharge through riverbed infiltration. This is often the major component of groundwater recharge in arid and semi-arid environments. Irrigation excess and wastewater discharge are also sources of groundwater recharge.
- Similarly groundwater use, particularly from shallow unconfined aquifers, delays the timing and reduces the amount of surface run-off in the rainy season and decreases baseflow in the dry season. Such baseflow may be of critical importance especially during the periods of low flow and in semi-arid climates.
- Groundwater may provide perennial water to groundwater dependent ecosystems and the communities that survive from these resources.
- Interaction between surface and groundwater can cause pollution to be transferred from one to the other. Groundwater pollution can persist for centuries thereby reducing water resources availability for generations to come.

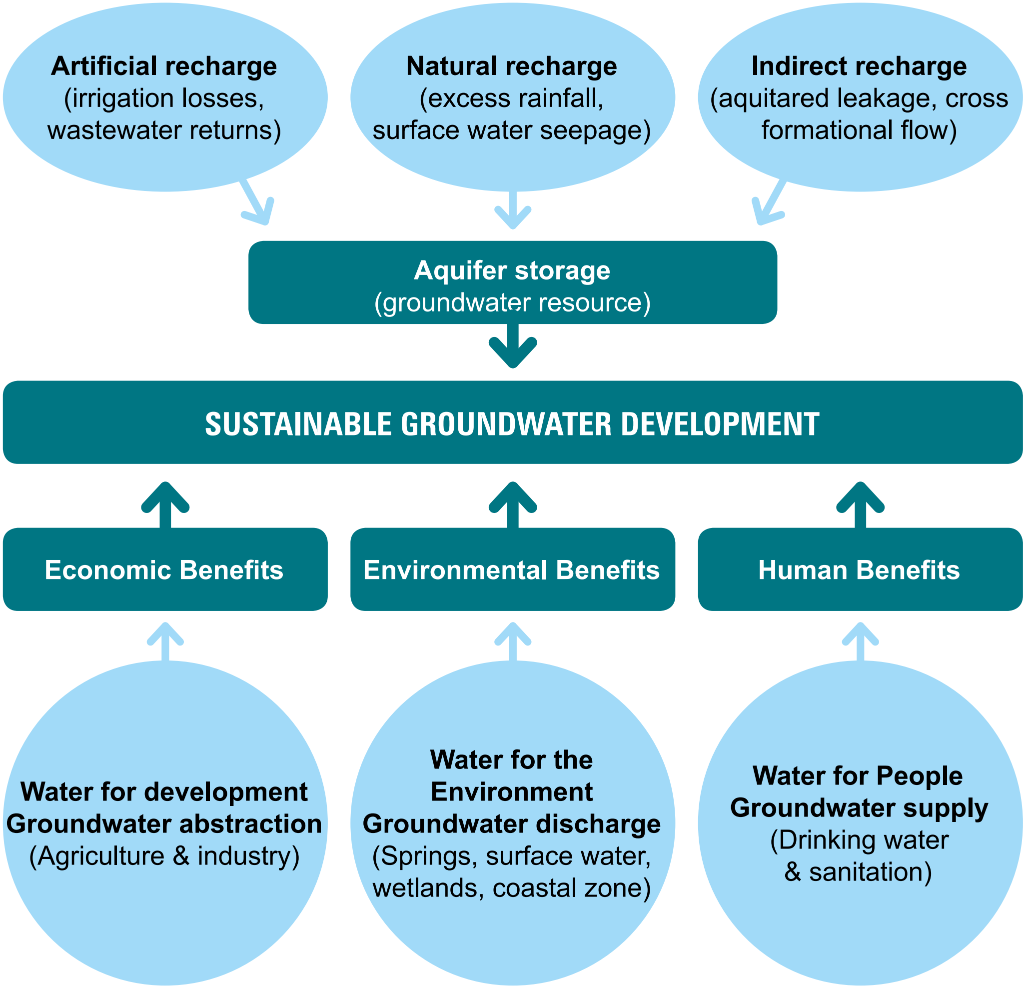


Figure 2.6 The elements of sustainable groundwater management: supply (above) and demand (below)

Once RBO water managers embrace the groundwater resource as a component of their available water resources and part of their management responsibilities, they soon begin to appreciate the opportunities and advantages of conjunctive management strategies. Examples of opportunities for conjunctive management may include:

- Groundwater holds large volumes of water in storage, while surface water storage is moderate or small and often ephemeral. Conjunctive management strategy would suggest that surface water be allocated during the rainy season before it runs off and evaporates, and groundwater use be increased in the dry season to offset the shortfall from surface water. Groundwater volumes in storage can provide a buffer in times of drought and water scarcity.
- Managed aquifer recharge (MAR) of sandy aquifers may be done with surplus surface water during the wet season if there is excess flow. Recharging aquifers in this way will not only provide additional dry season water resources but will also allow for natural purification of any bacterial contamination in the surface water.
- Groundwater may be developed where demand is dispersed and moderate, while development of surface water may focus on large-scale demand and irrigation development.
- Upstream and downstream interests: by considering the entire suite of water resources, both surface and groundwater, along the length of a catchment, managers are better able to provide for equitable upstream and downstream demands.

- Financing of groundwater development is a key area for flexibility. In many instances, private and individual development of the resource takes place, particularly if the basin authority establishes a positive enabling environment such as, for example, subsidies for electricity or borehole drilling.
- Public development of groundwater may be incremental as demand rises, thus avoiding high financing charges and interest payments. The funds saved can provide the basin authority with financial flexibility to manage its expenditure for surface water infrastructure and other development in an optimal manner.
- Many sectors depend on water:- agriculture, energy, water supply, and environment. By integrating the entire suite of available water resources, water managers are better able to balance the different competing needs in the catchment.

Water resources management includes many opportunities and threats. The wise water manager looks beyond the direct and the obvious and considers distant and indirect events in order to enhance and protect the catchment water resources. Some of these issues are listed below:

- *Land and water*. Land management plays a fundamental role in a number of groundwater related factors such as recharge and non-point source pollution, as well as being linked to baseflow, overland flow and run-off.
- *The river basin and its adjacent coastal and marine environment*. The salinization of coastal groundwater resources has become a major issue for many coastal cities. Overpumping of coastal aquifers is the major cause of this.
- *Rural water supply*. Groundwater may often be used as a potable source of water without treatment, providing water managers with useful options for dispersed smaller communities.
- *Groundwater pollution.* Polluted groundwater may take a very long time to remediate, and precautionary protection from pollution is strongly recommended. This may include oversight of waste management practices in the catchment. (Module 8: Groundwater hazards)
- *Groundwater often developed privately*. Unlike surface water which is usually developed and managed by an external authority, groundwater may be developed by users for their own needs. This requires a different management paradigm to ensure the sustainability and protection of groundwater resources. (Module 7: The role of stakeholder participation and communication in groundwater management)
- *Water as a free human right and a chargeable, tradeable commodity or service.* Groundwater resources may be traded just as surface water is, but knowledge is needed about the impact of groundwater abstraction when engaging in such transactions.

These examples and other conjunctive use strategies provide the basin authority, whether transboundary or not, with a variety of diverse challenges but also significant flexibility for water management under a variety of climatic and socio-economic challenges.

Table 2.4 suggests that the approach taken to groundwater management at any moment in time will depend on information about, and interaction between, the following factors:

- The depth, size and complexity of the groundwater resource
- The climate and the rate of aquifer recharge and resource renewal
- The scale of groundwater abstraction and the number and types of groundwater users
- The ecosytems and environmental services dependent upon groundwater (Module 10: Groundwater and environment)
- The susceptibility and vulnerability of the aquifer system to degradation (Module 8: Groundwater hazards)
- Natural groundwater quality concerns
- Present degradation of the groundwater resource (from depletion or pollution)
- Other available water resources

Table 2.4 Typical aquifer types and their appropriate management strategies

Hydrogeological Setting	Main Feature	Recommendation	African Examples
Significant aquifers but 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 into account that groundwater recharge may be dependent upon upstream river flow and downstream river flow may be dependent upon aquifer discharge	Stampreit aquifer. Orange-Senqu river basin. South Africa, Namibia, Botswana.
River basins extensively underlain by shallow aquifers	Management of surface water-groundwater interactions critical to avoid problems such as salt mobilization on land clearance, water logging, salinization from irrigated agriculture	Fully integrated ground and surface water resource planning and management is essential	The Limpopo River alluvials Limpopo basin. Botswana, South Africa, Zimbabwe Mozambique
Extensive deep aquifer systems occurring in arid regions	Groundwater flow system dominates, there is little permanent surface water	It may not be helpful to establish a 'river basin organization', but more valid to define a groundwater resource management plan and to manage at 'aquifer level'	Nubian Sandstone Libya, Egypt, Sudan. Nile Basin
Minor aquifers predominant, characterized by shallow depth, patchy distribution and low potential	Such aquifer systems occur in many parts of the Sub-Sahara African continental shield – these will have limited interaction with the overlying river basin	Storage not sufficient to justify comprehensive groundwater resource planning and administration. Social importance in rural water supply makes it appropriate to put effort into design of water-wells to maximize their yield and reliability, and to identify any geogenic groundwater quality problems	Crystalline basement aquifers in eg: Tanzania, Ghana, Zambia etc.
Transboundary aquifers	May be of different types; local or extensive. Requires legal and political oversight	Need to assess the degree of transboundary interaction and the strategies required	Kalahari aquifer: Zambezi / Limpopo basins. Zambia, Botswana Zimbabwe

2.8 Summary

Groundwater management for river basin organizations is essential as part of IWRM to ensure the long-term sustainability of the overall basin water resources and to optimize the water use in the basin by conjunctive management of the surface and groundwater resources and associated land uses. The importance and potential benefits of such management become clearer as water scarcity and groundwater quality degradation increases. Transboundary aquifer systems are a special case that requires a political and legal framework as well as transboundary institutional cooperation.

Important questions that water managers may ask themselves are:

- What is the RBO already doing on GW management?
- What they see as the most important GW management issues to take up next?
- Why (political, technical economic, social reasons) do you consider these to be the most important next steps?

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2.10 Exercise

Limpopo transboundary basin

Alluvial aquifers and large-scale irrigation along the banks of the Limpopo River.

**** Answers are in red and must be removed before providing exercise to course participants.***

The Issues: The Limpopo River is an international river and the Limpopo Basin Commission (LIMCOM), a transboundary basin organization, manages the water flows.

River flows are gauged at a number of gauging stations and weirs along the main stem of the Limpopo River and also along some of the major tributaries.

Just upstream of the towns of Messina and Beit Bridge (Figure 1 – Map / Satellite image of area), there is large-scale commercial irrigation development, growing principally citrus and cotton, on both the South African and the Zimbabwean sides of the stream (figure 2).

A total area of 6500 ha are irrigated from alluvial groundwater. Assume an irrigation demand of 1 litre/sec per ha. continuously for 300 days per year. The 65 days without irrigation occur between December and February during the rainy season. Assume that the irrigation water is pumped from the alluvial sands in the active river channel, and that this water is at the expense of river flow. Table 1 provides a water balance data and figure 3 is a graphic chart that shows the water balance components; nb. River flow blue line is the Limpopo flow prior to irrigation development. Assume that the alluvial aquifer must be fully recharged before the onset of any surface flow.

What is the delay (months) in the onset of surface flow at the start of the annual hydrological year due to the irrigation? ***3 months***.
Identify the months during which aquifer recharge takes place. ***Dec, Jan, Feb***
In which month does the aquifer first become fully saturated? ***Jan***
In which month does river flow start again? and in which month does river flow end? ***Jan and Feb***
How many months earlier will surface flow in the Limpopo end at the end of the rainy season due to the irrigation? ***6 months***
What is the difference between river flow without groundwater abstraction and river flow with groundwater abstraction? ***63.4 m^3/s***

- Draw a new Limpopo river flow hydrograph taking into account the irrigation abstraction.
- Discuss the potential impacts of these flow reductions on downstream communities and downstream countries.
- Discuss the possible impacts on the environment, and on water quality.
- Propose a monitoring strategy to identify the impacts of the irrigation on the river flow, the groundwater and the local ecosystems.
- Suggest methods for integrating the irrigation abstraction into the surface water management planning.

Methodology:

The solution to this problem lies in developing a simple water balance for inflows to and outflows from the alluvial aquifer linked to the river. For simplicity, it is convenient to start the water balance at a time when there are no surface river flows ie. in September each year, but also note that we bring forward the deficit in the alluvial aquifer for the year to date.

1. All abstractions of groundwater from the alluvial aquifer result in a decline in the water level in the aquifer … part of the aquifer becomes "desaturated".
2. The degree of desaturation is cumulative if the abstraction is higher than recharge, so that the aquifer becomes progressively more empty as groundwater abstraction for irrigation continues. The amount of groundwater in storage becomes progressively less.
3. When the rainy season begins run-off / river flow is generated. When the run-off / river flow is greater than the groundwater abstraction and there is a positive value for the water balance*. This first goes to refilling the empty aquifer.
4. The positive balance between run-off (positive) and abstraction (negative) accumulates as groundwater in storage until the aquifer becomes fully saturated again (i.e. no deficit).
5. Once the aquifer is fully saturated, the positive balance between abstraction and runoff becomes river flow.
6. Note that river flow is not cumulative – it is not stored anywhere; it flows downstream and is no longer available for recharge to the aquifer.
7. Note also that we assume that there is no delay between groundwater abstraction and impact on the river. This may not be entirely realistic.
8. Once the rains stop, river flow declines and then ceases when run-off becomes less than aquifer abstraction.
9. As the dry season progresses, groundwater abstraction continues and the aquifer again become progressively depleted.
10. The cycle continues when the next rains begin.

It should be noted that the river flow hydrographs from the Limpopo are already disturbed due to the fact that irrigation and groundwater abstraction are already taking place. It will be necessary to go back in time and look at Limpopo hydrographs from times prior to the establishment of the irrigations to be able to assess the impact of groundwater abstractions on river flows. This can also be achieved by comparing old pre-irrigation hydrographs with post irrigation hydrographs. Another simple strategy is to simply calculate the volume of abstracted groundwater in any year, and equate this to the amount of river flow that is diverted to irrigation.

Table 1: LIMPOPO Water Balance:

The impact of alluvial groundwater abstraction on river flow.

Month	a) Rainfall mm	b) River flow: no GW abstraction m^3/sec	c) GW abstraction m^3/sec	d) Monthly water balance m^3/sec	e) Alluvial aquifer deficit m3/sec nb: max < 0 e (previous) + d		f) River flow with GW abstraction m^3/s
Previous dry season					Brought Forward	= -28	
September	0	0	-6.5	***-6.5***	***-28 - 6.5***	***= -34.5***	***0***
October	17	0.2	-6.5	***-6.3***	***-34.5 - 6.3***	***= -40.8***	***0***
November	39	5.3	-6.5	***-1.2***	***-40.8 - 1.2***	***= -42.0***	***0***
December	73	27.5	-3.2	***+24.3***	***-42 + 24.3***	***= -17.7***	***0***
January	129	88.7	0	***+88.7***	***-17.7 + 88.7 = 71.0***	***= 0***	***71.0***
February	108	42.1	-1.7	***+40.4***	***0 + 40.4 = 40.4***	***= 0***	***40.4***
March	19	5.4	-6.5	***-1.1***		***-1.1***	***0***
April	0	1.9	-6.5	***-4.6***		***-5.7***	***0***
May	0	1.4	-6.5	***-5.1***		***-10.8***	***0***
June	0	1.1	-6.5	***-5.4***		***-16.2***	***0***
July	0	0.7	-6.5	***-5.8***		***-22***	***0***
August	0	0.5	-6.5	***-6***		***-28***	***0***
Annual Totals	***385***	***174.8***	***63.4***	***111.4***	***Monthly total is the deficit at that time.***		***111.4***

Calculate the monthly water balance for each month.
Calculate the monthly water deficit in the alluvial aquifer.
Calculate the monthly river flow with groundwater abstraction.
Calculate the annual totals for all columns.

NB – this is the answer sheet – for the participants, we will leave last row & last three columns blank for them to complete

EXERCICE

Figure 1: Beit Bridge / Musina area with alluvial irrigation development along Limpopo main-stem river.

Figure 2: Detail showing the irrigated areas with Centre Pivots (2000 ha) and rectangular field (4500 ha) layouts. Rectangular fields are largely Citrus, and centre pivots are for cotton. Limpopo river runs west to east through the middle of the image.

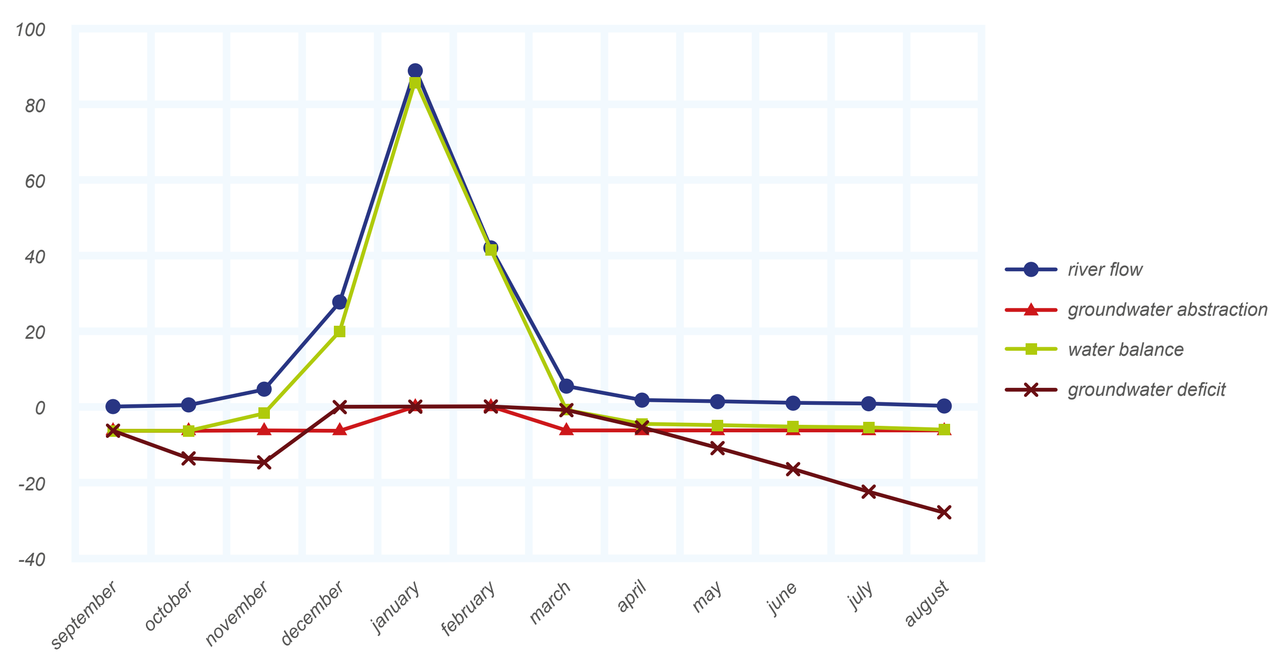

Figure 3: Limpopo chart showing water balance components. Vertical axis is m3/sec. River flow line is prior to gw abstraction.

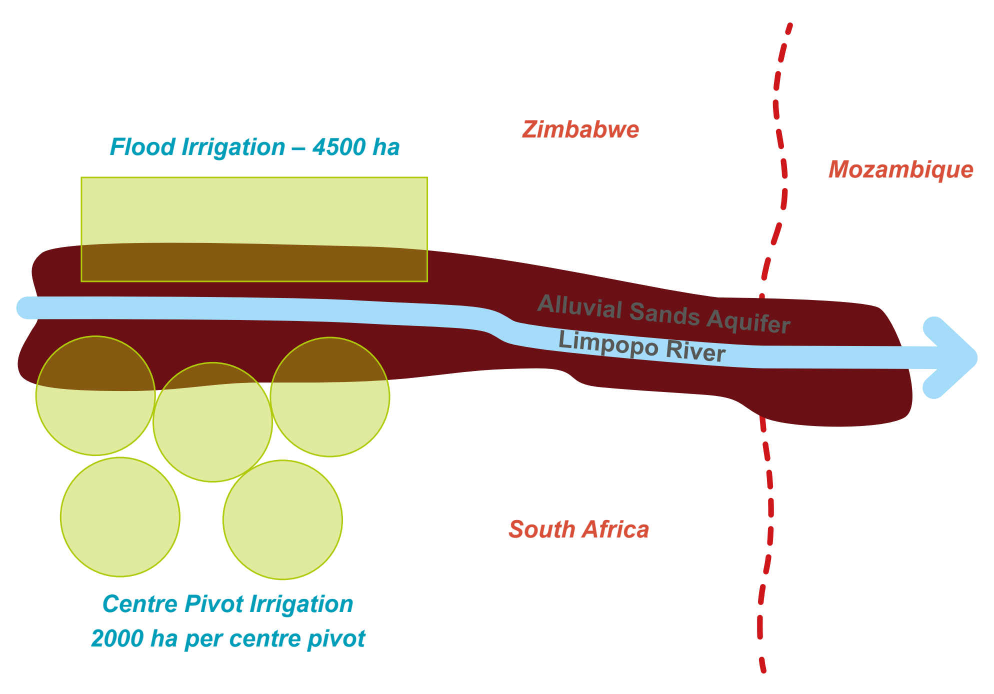

Figure 4: Schematic illustration of the Limpopo alluvial aquifer irrigation.

MODULE

AQUIFER SYSTEMS CHARACTERIZATION FOR GROUNDWATER MANAGEMENT

CONTENT

MODULE 3

Aquifer Systems Characterization for Groundwater Management

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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AQUIFER SYSTEMS CHARACTERIZATION FOR GROUNDWATER MANAGEMENT

LEARNING OBJECTIVES

This course module will provide an introduction to groundwater system characterisation for water resource managers who are not groundwater specialists, with special emphasis on understanding of:

- Importance of aquifer characterization in groundwater resources management
- Key properties of aquifers for better groundwater management
- The different hydrogeological environments in relation to groundwater development
- Groundwater occurrence, and interactions between groundwater and surface water

3.1 Introduction

Groundwater differs from surface water as a result of the different physical and chemical environment in which it is found. Some groundwater occurs in most geological formations with sediments and rocks in effect forming a subsurface reservoir or aquifer in which groundwater can be accumulated and transmitted.

The hydrogeological properties, porosity and permeability, of geological layers and their spatial distribution vary for many reasons, including the tectonic structure, the position in the depositional basin, the type of sedimentary basin, the depth of burial and the lithology. The availability of groundwater depends on hydrogeological setting, which may be very variable, even within a single lithology.

Because groundwater is usually an important source of surface water, particularly baseflow, these two water sources, surface and groundwater, and the services they both provide should be considered in an integrated and holistic way within the planning framework of RBOs.

Groundwater management in river and lake basins has to be based on a good understanding of the characteristics of the groundwater system, including its interaction with surface water bodies such as rivers, lakes and wetlands.

3.2 Groundwater occurrence

Diversity in groundwater occurrence

Groundwater occurs in openings in rock materials in the form of pores, or voids, or fractures that constitute the **porosity** of the material. Nearly all rocks, whatever type, origin or age, possess some degree of porosity. Therefore groundwater can be found in all geological environments. If ‘useful’ groundwater occurs a rock material, then this rock is called an **aquifer**. An aquifer is defined as a geological formation (or sometimes part of a formation or a group of formations) that contains saturated material of sufficient permeability to yield ‘useful’ quantities of water to wells and/or springs. Aquifer units may be combined into aquifer systems.

A framework for assessing groundwater occurrence.

Porosity:

A rock material may exhibit ‘primary’ or inter-granular porosity. These unconsolidated sediments are made up from individual grains that have been deposited at the surface of the earth by various sedimentary processes. Porosity in primary porosity materials is normally high.

Alternately a rock material may be impermeable and have close to zero porosity. Typically crystalline rocks that have crystallized from a molten magma form such materials. In these igneous rocks, porosity is related to fractures through the rock mass, rather than pore spaces in the intact rock material. This type of porosity is known as secondary porosity, or fracture porosity, and it usually much lower that primary porosity.

Unconsolidated sediments become sedimentary rocks by burial, compaction and cementation processes. During these processes, the porosity of sedimentary rocks decreases, the rock mass decreases in volume and becomes fractured. These fractured sedimentary rocks now exhibit dual porosity.

Permeability:

For a rock mass to be considered an aquifer, water has to be able to flow through the rock mass at an appreciable rate such that useful quantities can be pumped from water wells. The rate at which water flows through a rock mass is its permeability.

For granular primary porosity rocks, water flows by seepage or matrix flow between the grains that constitute the rock mass. This type of seepage flow is governed by the size of the pore spaces between the grains, which in turn is governed by the size of the grains. Coarse materials such as sand and gravel have high permeability, while fine-grained materials such as clays have very low permeability.

Crystalline rocks that do not have primary porosity exhibit fracture flow, with water flowing through the fractures. This type of fracture permeability, or fracture flow, is usually more rapid that seepage flow, but because it only takes place through a small volume of the rock mass, it may be less productive the seepage flow in some cases.

Unconfined and confined aquifers.

Aquifers may be open to the atmosphere through a permeable soil cover, and in this condition they are know as unconfined. Unconfined aquifer can receive direct recharge from rainfall infiltrating and percolating through the unsaturated (or vadose) zone down to the water table. These aquifers are also known as water table or phreatic aquifers. The water in them is at atmospheric pressure and when these aquifers are pumped, the water table is lowered. Crystalline rocks tend to weather at and near the surface to become unconfined aquifers, but they are impermeable at depth where they are un-weathered and the fractures are closed due to overburden pressure.

Alternately aquifers may be buried beneath impermeable materials. This typically occurs in sedimentary basins where permeable and porous sedimentary strata dip beneath impermeable strata to become cut off from the land surface. These aquifers are known as confined aquifers. Confined aquifers do not receive direct recharge from rainfall because they are separated from the surface by an impermeable layer. They may receive recharge from a distant point where the aquifer strata outcrop at the surface, and at this point the aquifer is locally unconfined. They may be entirely confined under impermeable strata and receive no recharge at all. Since confined aquifers are not open to the atmosphere, the water in them is usually held under pressure derived from the water level in the recharge area. This pressure is known as the piezometric pressure, or piezometric head. If a well is drilled into a confined aquifer, the water usually rises up in the well bore to a level above the aquifer top as a result of the piezometric pressure. When water is pumped from a confined aquifer, the piezometric pressure is reduced, but the aquifer remains fully saturated.

Aquifer productivity.

The 'productivity' of an aquifer depends a combination of the porosity and the permeability of the aquifer materials and the 'size' of the aquifer. The most significant elements of natural hydrogeological diversity are:

- Major variation of aquifer storage capacity (porosity / storativity), ranging between unconsolidated granular sediments and highly-consolidated fractured rocks;
- Major variation in the ability to transmit groundwater flow (permeability) ranging between cavernous limestone and dense clays and solid intact crystalline rocks;
- Wide variation in aquifer areal extent and saturated thickness based on geological environments ranging from eg. weathered regolith in crystalline rocks, to shallow alluvial sediments to deep tectonic basins, resulting in a wide range of both groundwater in storage and aquifer flow potential (transmissivity).

Unconsolidated sedimentary aquifers are composed mainly of loose materials: sands, gravels, silts, clayey sand, sandy clays and clays. They constitute a porous and continuous medium. Groundwater is stored and transmitted through pore spaces.

Sedimentary basins generally 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 limestone.

They are spatially extensive and possess large thicknesses, ensuring great volumes of groundwater storage with regional flow. These constitute the major transboundary aquifers.

What type(s) of aquifer occur in your catchment and at what depths below the land surface?

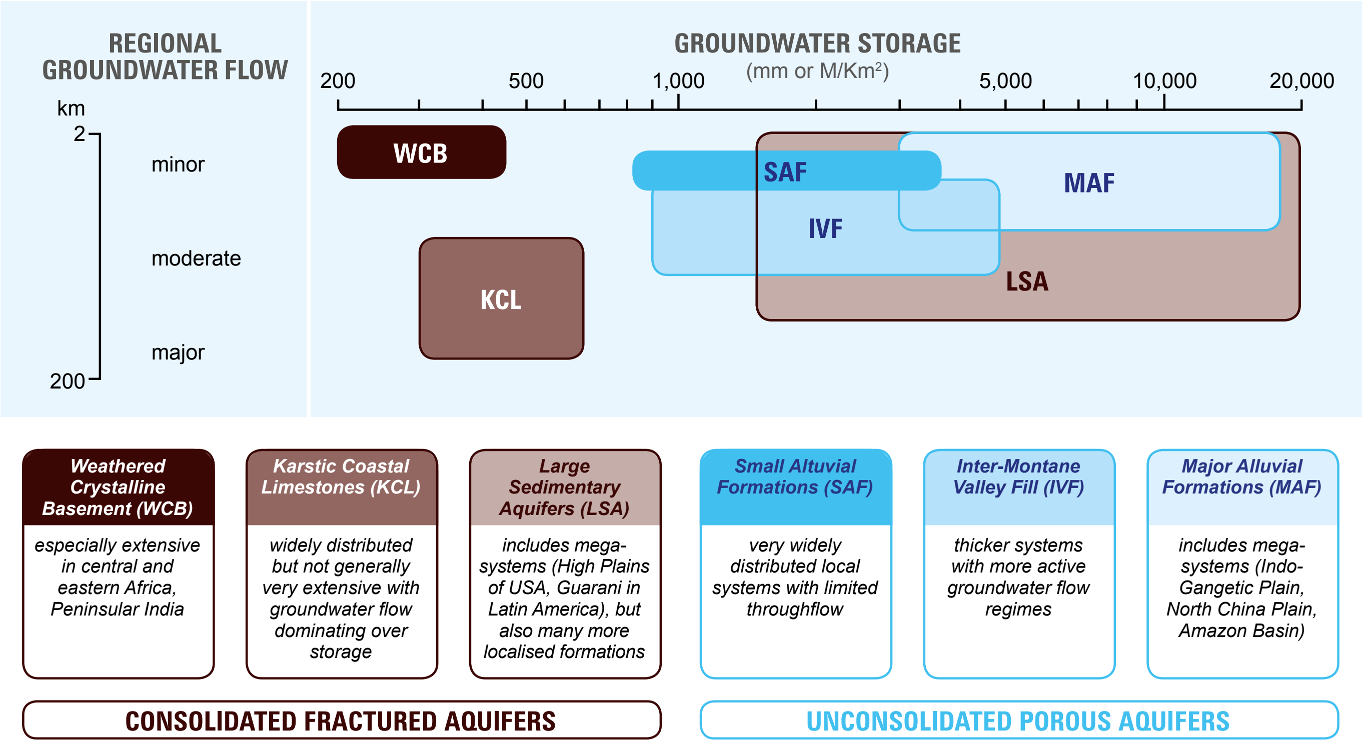
Compact and fractured rocks or consolidated formations have openings that are mainly composed of fractures; they usually constitute a discontinuous medium. Generally one can identify two major types of formations:

- Carbonated rocks, like limestone, that are slightly soluble in rainwater and therefore fractures can be enlarged to form karsts (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 (regolith) that may be a few tens of meters thick.

The characterisation of groundwater occurrence may occur at a variety of scales of investigation, and the characterization is usually related to the type of geology.

- Hydrogeological basins that correspond closely to the topographic boundaries of river basins; these typically occur in crystalline rock terrains and may be comprised of several sub-basins.
- Groundwater basins that are smaller than and contained entirely within a hydrological basin; these are usually local sedimentary basins, or alluvial systems related to the present day hydrology.
- Aquifer or hydrogeological units that extend beyond the borders of the hydrogeological basin; typically these are large depositional basins that pre-date the present day drainage and the present day climate.

This hydrogeological diversity can be summarised into key elements that identify most aquifer types (figure 3.1). The groundwater storage capacity and the scale (length and travel time) of the flow paths are the two elements used here for groundwater characterization for management purposes.



Weathered Crystalline Basement (WCB)	Karstic Coastal Limestones (KCL)	Large Sedimentary Aquifers (LSA)	Small Altuvial Formations (SAF)	Inter-Montane Valley Fill (IVF)	Major Alluvial Formations (MAF)
especially extensive in central and eastern Africa, Peninsular India	widely distributed but not generally very extensive with groundwater flow dominating over storage	includes mega-systems (High Plains of USA, Guarani in Latin America), but also many more localised formations	very widely distributed local systems with limited throughflow	thicker systems with more active groundwater flow regimes	includes mega-systems (Indo-Gangetic Plain, North China Plain, Amazon Basin)

Figure 3.1: Summary of key properties of the most widely occurring aquifer types. (GW- Mate Briefing note 2)

In general terms the so-called **'minor aquifers'** provide smaller and less predictable water wells yields than those constructed in **'major aquifers'**; they possess much less drainable storage and can be rather patchy in extension. In areas underlain only by minor aquifers, the siting of boreholes providing a reliable supply of acceptable quality and adequate quantity can be a significant hydrogeological challenge, but 'minor aquifers' are often the only feasible prospect in this regard over extremely large land areas.

What are the key functions of aquifers?

An aquifer as a hydrogeological unit is made up of two main phases that interact: a reservoir comprising one or many geological formations and the groundwater stored in the reservoir.

The reservoir has two important functions:

- capacity for groundwater storage expressed through storativity (storage coefficient) or specific yield;
- capacity to transmit groundwater flow by gravity or pressure, which can be expressed as transmissivity;

One or more of these functions may dominate, depending on the rock types and hydrogeological environments. For instance a river side aquifer has a predominantly transfer capacity, whereas a deep confined aquifer presents mainly storage capacity but only limited groundwater flow, and an unconfined aquifer may play both roles.

The vast storage of groundwater systems (whose magnitude varies significantly with geological setting) is usually their most valuable asset. This storage asset includes not only groundwater already stored in aquifer systems, but also the potential storage capacity of their void spaces to receive recharge.

3.3 Groundwater flow

How does groundwater flow?

Groundwater flows down gradient from areas of high hydraulic head to areas of lower hydraulic head. The rate of flow is governed by the gradient and by the aquifer properties. Most groundwater is in continuous slow movement (Figure 3.2) from areas of natural aquifer recharge from rainfall to areas of aquifer discharge as springs, and seepages to rivers/lakes, wetlands and coastal zones. Groundwater flow is governed by Darcy’s Law (Box. 3.1).

The natural flow of groundwater occurs, generally at low velocities, through the pore spaces and fractures in rock materials. For groundwater a flow velocity of 1 meter per day is high, and it can be as low as 1 meter per year or 1 meter per decade. In contrast, velocities of rivers flow generally are measured in meter per second.

Can you identify the recharge and discharge zones, and flow regime, of an aquifer in your catchment?

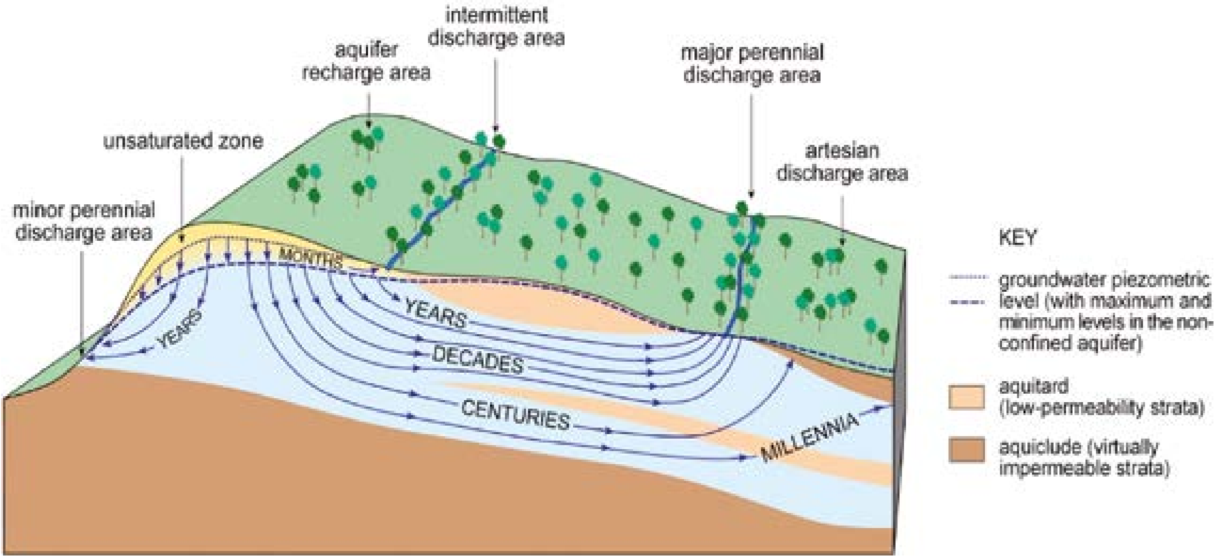


Figure 3.2: Typical groundwater flow regime and residence times in semiarid regions (after Foster and Hirata, 1988)

BOX 3.1: THE DARCY LAW AND PERMEABILITY

The principle that governs how fluids move through sediments and rocks is Darcy's Law – the flow being proportional to the length of the flow path, the fluid pressure difference at the start and end of the flow path and the permeability of aquifer medium between the two points under consideration.

Darcy's Law is usually written as: $Q = -KA\, dh/dl$ where:

Q = rate of groundwater flow,
K = permeability (or hydraulic conductivity)
A = cross-sectional area of flow
dh/dl = hydraulic pressure gradient.

In the subsurface, sediments are usually deposited in horizontal layers. Inter-bedded clay and shale layers have very much lower permeability (especially in the vertical direction) than the main group of aquifer materials, and thus groundwater flow tends to be preferentially confined within aquifer layers and predominantly horizontal, with only a small component of vertical leakage across confining clay or shale beds.

3.4 Groundwater Balance and Recharge

What is involved in the estimation of contemporary recharge rates?

The estimation of contemporary recharge rates to aquifers is of fundamental significance when considering the sustainability of groundwater resource development. Furthermore, understanding aquifer recharge mechanisms and their linkages with land-use is essential for integrated water resources management.

Unfortunately groundwater recharge is both highly complex and uncertain. There are numerous methods including: groundwater level measurements; unsaturated zone flux measurement; isotopic techniques to measure groundwater age; groundwater flow measurement; modelling and many others.

What is the rainfall on your aquifer recharge zone? Is groundwater replenished by annual rainfall?

All these methods suffer from substantial scientific uncertainty (Figure 3.3) in the quantification of individual recharge components due to:

- The vast heterogeneity, irregularity and inherent complexity of natural hydrogeological systems
- The wide spatial and temporal variability of hydrologic events such as rainfall and runoff, including climatic cycles
- The variety and complexity of different recharge processes that range from direct infiltration and percolation of precipitation, seepage through stream and lake beds, to return flows from anthropogenic impacts.
- The inherent uncertainties involved for most of the methodological procedures used for recharge estimation.

These factors, coupled with limited groundwater level monitoring data in many regions, mean that available recharge estimates always have to be treated with some caution.

Nevertheless, for most practical purposes, it is sufficient to make approximate estimates, 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 frequency and rate of recharge;
- Confined and semi-confined aquifer systems are usually only recharge is specific recharge areas where the aquifer outcrops, while unconfined aquifers tend to receive recharge over their entire surface area.
- Indirect recharge from surface runoff and incidental artificial recharge arising from human activity generally are becoming progressively more significant than direct rainfall recharge.

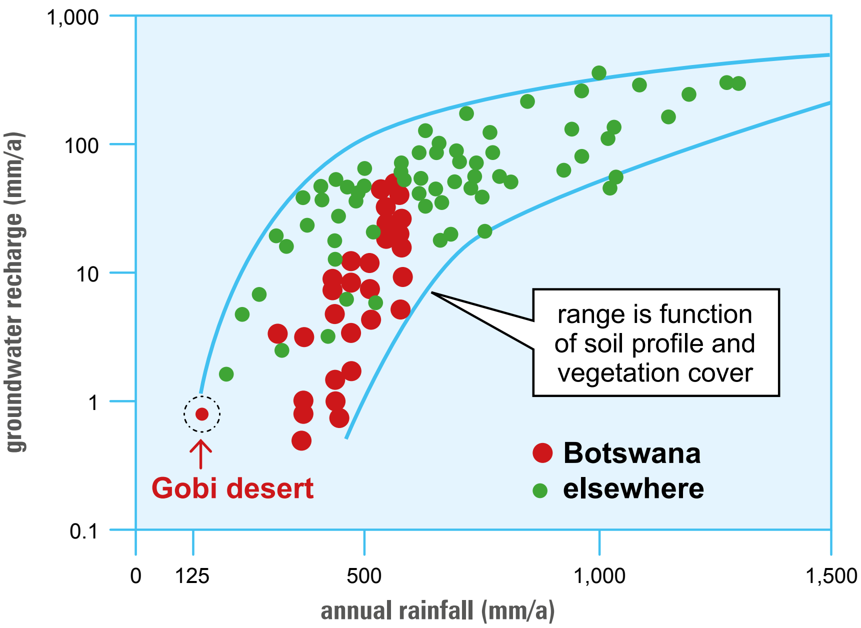


Figure 3.3: Field estimates of diffuse recharge in Southern Africa and their relation with annual rainfall

When attempting to evaluate contemporary groundwater recharge rates it is essential to appreciate fully the significance of the intimate linkages between land-use and groundwater recharge, which is also an essential input for the practice of integrated water resources management. The commonly used paradigm of 'constant average rates of present-day aquifer recharge' is false. In reality the contemporary rate of aquifer recharge varies considerably with:

- Changes in land use and vegetation cover, notably the introduction of irrigated agriculture, but also vegetation clearance and soil compaction;
- Urbanisation processes, and in particular the level of water supply network leakage, the proportion of non-sewer (in-situ) sanitation and the degree of land-surface sealing due to tarmac, concrete etc.;
- Widespread water-table lowering by groundwater abstraction and/or land drainage, which leads to increased areas and/or rates of infiltration in some aquifer systems;
- Changes in surface water regime, especially the diversion of river flow.

Why is it necessary to undertake a groundwater balance?

For management purposes, what is important is the amount of groundwater that is available in the aquifer that can be abstracted on a sustainable basis. This will be a balance between the amount of recharge to the aquifer and the amount of discharge from the aquifer.

In most natural climatic settings, water is regularly added to an aquifer system by the 'natural recharge' processes described above, and continuously leaves the system as 'natural discharge' to springs, seepages and phreatic vegetation. Each aquifer system is unique in as much as the amount of groundwater flow will be dependent upon 'external' factors such as precipitation rates in the recharge area and the location and behaviour of streams and evapotranspiration rates. But putting aside for the moment climate-change and major land-use change considerations, a 'healthy groundwater system' should be in balance (or a quasi-equilibrium state) when viewed over a time-scale of 5-25 years, with the longer time periods required in the more arid climates. Accounting for all the different inflows and outflows of a groundwater system, including changes in storage, is called undertaking a groundwater balance. Evaluation of the groundwater balance is an essential tool for groundwater resource management, and may include the following:

- Estimating recharge to the aquifer system, which is a complex and uncertain suite of processes as described above   and
- Assessing the natural discharge from the aquifer system by baseflow, spring discharge, and evapotranspiration, which is equally complex   and
- Measuring or estimating the amount of groundwater withdrawn from boreholes and used consumptively or exported from the local catchment

There are numerous analytical tools and GIS systems that can greatly help this process. Groundwater balances should be established for a well-defined aquifer system or groundwater body, within a river basin or in some cases an entire sub-catchment of such a river basin. Understanding the groundwater balance and how it changes in response to human activities is a central and critical aspect of groundwater system characterisation.

All groundwater flow must be discharging somewhere, and continuous abstraction will sooner-or-later reduce these discharges. But the sources of pumped groundwater can be complex, and may include an increment of recharge induced as a result of water-table lowering. The question of continuous long-term depletion of aquifers arises and the term **'aquifer overexploitation'** has been introduced in this connection.

In practice, when speaking of aquifer overexploitation we are invariably much more concerned about the consequences of intensive groundwater abstraction than about its absolute level. Thus the most appropriate definition is probably that the 'overall cost of the negative impacts of groundwater exploitation exceed the net benefits of groundwater use', but of course these impacts are not always easy to predict and/or to cost.

Therefore, it is crucial for water resource managers to estimate the 'acceptable abstraction' (or 'safe yield') of a groundwater system. In reality such expressions can also be misleading, because in order to estimate them, it is necessary to make value judgments about the term 'acceptable', which may not be acceptable to some stakeholders, especially to natural ecosystems that are dependent upon aquifer discharge.

Groundwater in confined aquifers is usually older, less oxygenated, more mineralized, and normally under pressure. 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 with leakage downwards and upwards between layers according to local conditions.

Aquifer storage transforms highly variable natural recharge regimes into more stable natural discharge regimes. It also results in groundwater residence times that are usually measured in decades or centuries (Figure 3.2), and often even in millennia, with large volumes of so-called ‘fossil groundwater’, a relic of past episodes with different climate, still being held in storage (Box 3.2).

BOX 3.2: ‘FOSSIL GROUNDWATER AND NON-RENEWABLE RESOURCES’

Isotopic techniques reveal that most groundwater stored (and sometimes still flowing) in large sedimentary formations was recharged by late Pleistocene and early Holocene rainfall (>5,000 yrs BP), when the climate in the areas concerned was cooler and wetter. It is thus commonly referred to as **‘fossil groundwater’**.

If hydrochemical evidence suggests that very little contemporary rainfall is infiltrating (say < 10 mm/a), current groundwater recharge will be responsible for (at most) only a tiny fraction of the groundwater stored in such aquifers. This groundwater storage is thus sensibly treated as a **‘non-renewable resource’**, since it will not be replenished fully in the time-frame of current development.

3.5 Groundwater and Surface water interaction

Nearly all surface water bodies (rivers, lakes, reservoirs, and wetlands) interact with groundwater. These interactions take many forms, in some cases surface water bodies gain water or/and solutes from groundwater systems and in others they may be a source of groundwater recharge and may affect groundwater quality.

As concerns for water resources and the environment increase, it is important to consider groundwater and surface water as a single resource. Therefore understanding their interaction is crucial for water resource management in river and lake basins, even if it is difficult to observe or to measure these exchanges.

The contribution of groundwater to total water surface flow varies widely among streams, but hydrologists estimate the average contribution is somewhere between 40 and 50 % in small and medium-sized streams (USGS, 1999). Correspondingly, the contribution of surface water via stream and lake bed infiltration to groundwater is equally significant, especially in arid and semi-arid climates. Some of these surface water – groundwater interactions are described below.

The interaction of surface water and groundwater is frequently a major concern for RBOs since they are strongly focused on surface water management and such interactions impact directly on the surface water resources that they have quantified and allocated.

Alluvial groundwater occurrence in river valleys.
Groundwater in the river valley environment tends to occur as alluvial deposits associated with the river channel (Figure 3.4) and this groundwater is usually shallow and easily accessible in the vicinity of the river. Such aquifers are generally of limited lateral extent and depth.

In many areas in Africa (Northern Cameroon, Lake Chad basin, Botswana) thick sediments underlying rivers channel contain significant quantities of groundwater. The favourable permeability and porosity features of alluvial channel sands and the regular recharge from river flow combine to make these aquifers highly productive.

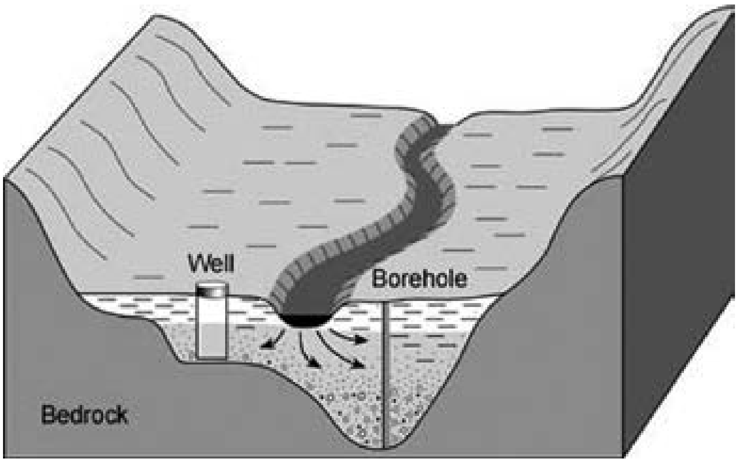


Figure 3.4: Groundwater occurrence in alluvial deposits of river (from MacDonald, 2005)

After the rainy season has ended, these ‘sand rivers’ or ‘wadis’ are usually are dry on the surface, but the coarse sediments underlying the river channel and floodplain are in fact the important sources of domestic and irrigation water for local communities (Figure 3.5). In major alluvial basins, as in the Nile valley, groundwater is stored in more extensive and thicker sedimentary sequences that form important regional aquifers. They are made of unconsolidated layers of alternating strata of sand, clayey sand or sandy clay.

Due to the immediate proximity between alluvial aquifers and river channels, there is continuous and rapid interaction between alluvial groundwater and river flow. Abstraction of groundwater from such alluvial systems will impact on river flow, and this has been cited as a growing concern by many river basin authorities (Villholth, 2011).

Figure 3.5: River channel with coarse deposits (Northern Cameroon)

Do you have sand rivers in your catchment? How is groundwater developed from these?

How can groundwater interact with rivers and streams?

The interactions between rivers and groundwater take place in three ways:

- Rivers gain water from inflow of groundwater through the riverbed (Figure 3.6), or;
- Rivers lose water to groundwater by outflow through the riverbed (Figure 3.7), or;
- In some environments, rivers might at times gain water from groundwater, and at other times, rivers might lose water to groundwater.
- Similarly, some river reaches may be gaining, while other reaches of the same river system may be losing.

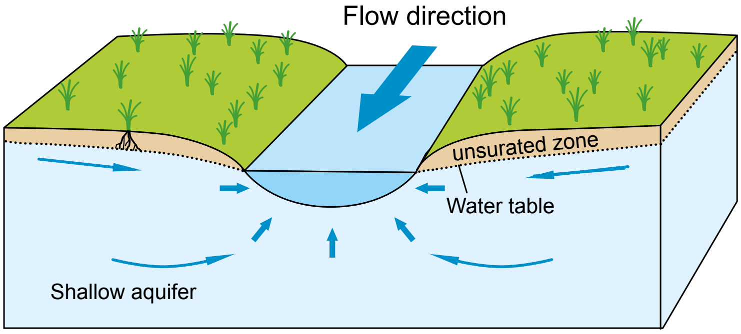


Figure 3.6 : Gaining rivers receive water from groundwater (USGS, 1998)

In the first case, the altitude of water table near the river must be higher than the altitude of the river. In contrast for the second case (losing rivers), the level of water table in the vicinity of river must be lower than the level of the river.

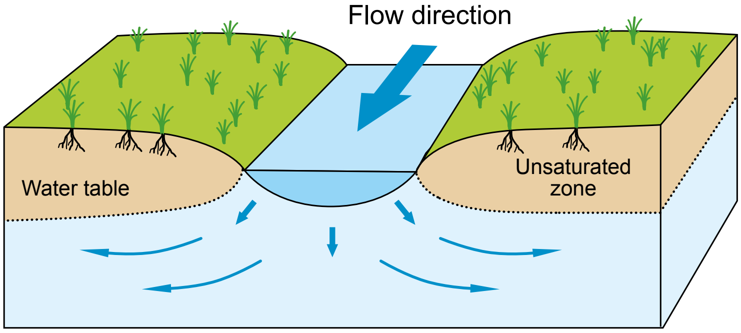


Figure 3.7: Losing rivers provide water to the groundwater system (USGS, 1998)

Losing streams can be connected to groundwater system by a continuous saturated zone (Figure 3.7) or can be disconnected from it by an unsaturated zone (figure 3.8). A type of interaction between groundwater and rivers that takes place often at one time or another is a rapid rise in river stage that causes water to move from the riverbed into the banks. This process, termed bank storage, usually is caused by storm rainfall, or rapid release of water (e.g. from hydroelectric dams).

Is there major groundwater abstraction along river channels in your basin?

Developing shallow aquifers that are directly connected to surface-water bodies can have a significant effect on the relationship between these two water bodies. The effects of pumping a single borehole or a small group of boreholes on the hydrologic regime are local in scale. However, the effects of many wells withdrawing water from an aquifer over large areas may be regional in scale.

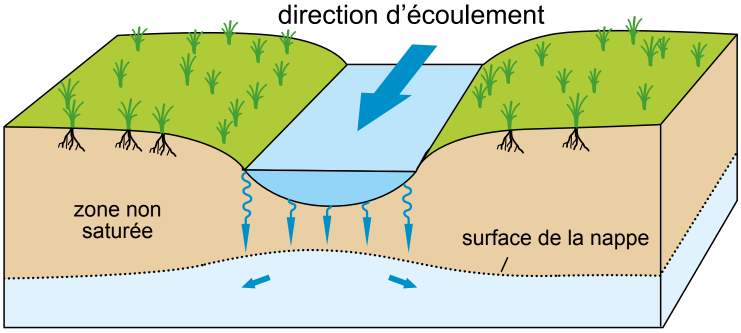


Figure 3.8: River separated from groundwater by an unsaturated zone (USGS, 1998)

How can groundwater interact with lakes?

Lakes also interact with ground water, although these basic interactions are the same as for the rivers, they differ in several ways. Some lakes receive groundwater inflow throughout their entire bed; others have seepage loss to groundwater throughout their entire bed; but perhaps most lakes receive groundwater inflow through part of their bed and have seepage loss to groundwater through other parts (Figure 3.9).

Generally water levels in natural lakes do not change rapidly compared to rivers; therefore bank storage is relatively less important in lakes than it is in streams. Furthermore evaporation has a greater effect on lakes surface than on rivers because the surface area of lakes is generally larger, and because lake water is not replenished as readily as for rivers. Lake sediments commonly are thick and have more organic deposits. These poorly permeable organic materials can affect the distribution of seepage more in lakes than in rivers.

Reservoirs that are designed primarily to control the flow and distribution of surface water are constructed in stream valleys; they have some characteristics both of rivers and lakes; they can have widely fluctuating levels, and significant bank storage. Moreover, like lakes, reservoirs can have significant loss of water by evaporation.

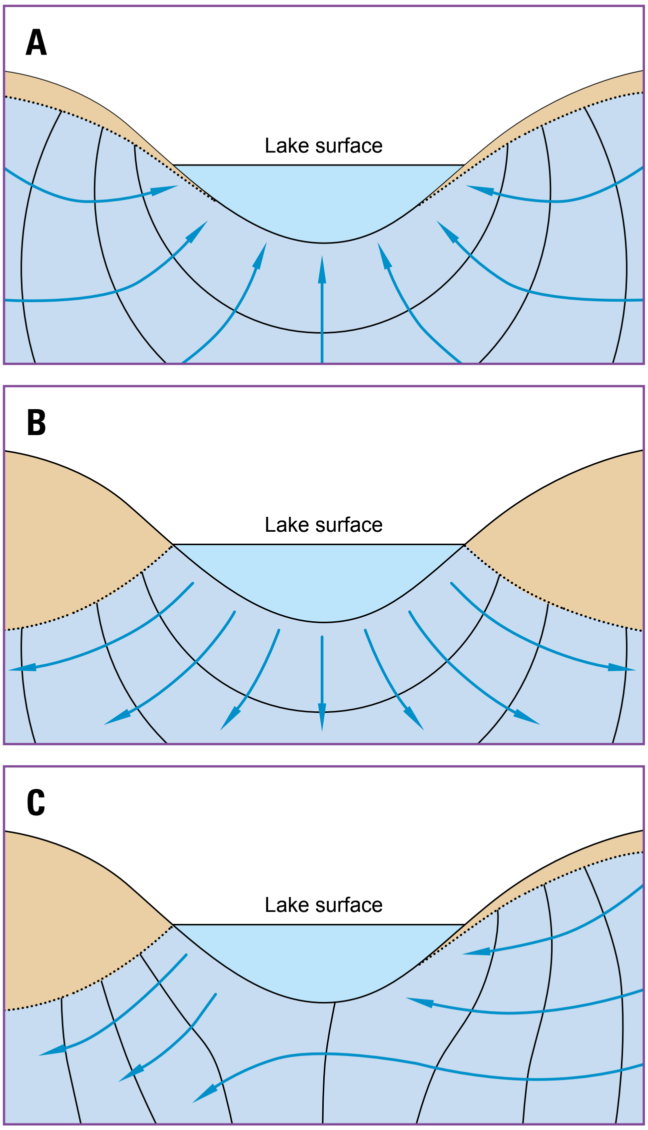


Figure 3.9: Lakes interaction with groundwater (inflow (A), lose water as seepage to groundwater (B), or both (C))

How can groundwater interact with wetlands and other groundwater related ecosystems?

Similar to streams and lakes, wetlands can receive groundwater inflow, recharge groundwater, or do both (Figure 3.10). Wetlands that occupy depressions in the land surface have interactions with groundwater similar to lakes and rivers. However wetlands do not always occupy low points and depressions; they also can be present on slopes or even on drainage divides. Water tables sometimes intersect the land surface, causing groundwater discharge directly to the land surface, which permits the growth of wetland plants.

Does your L/RBO assess interactions between surface water and shallow aquifers?

Many wetlands exist along streams, especially slow flowing ones. Although these riverside wetlands commonly receive groundwater discharge, they are dependent primarily on these streams for their water need. Wetlands in riverside areas have especially complex hydrological interactions because they are subject to periodic water level changes.

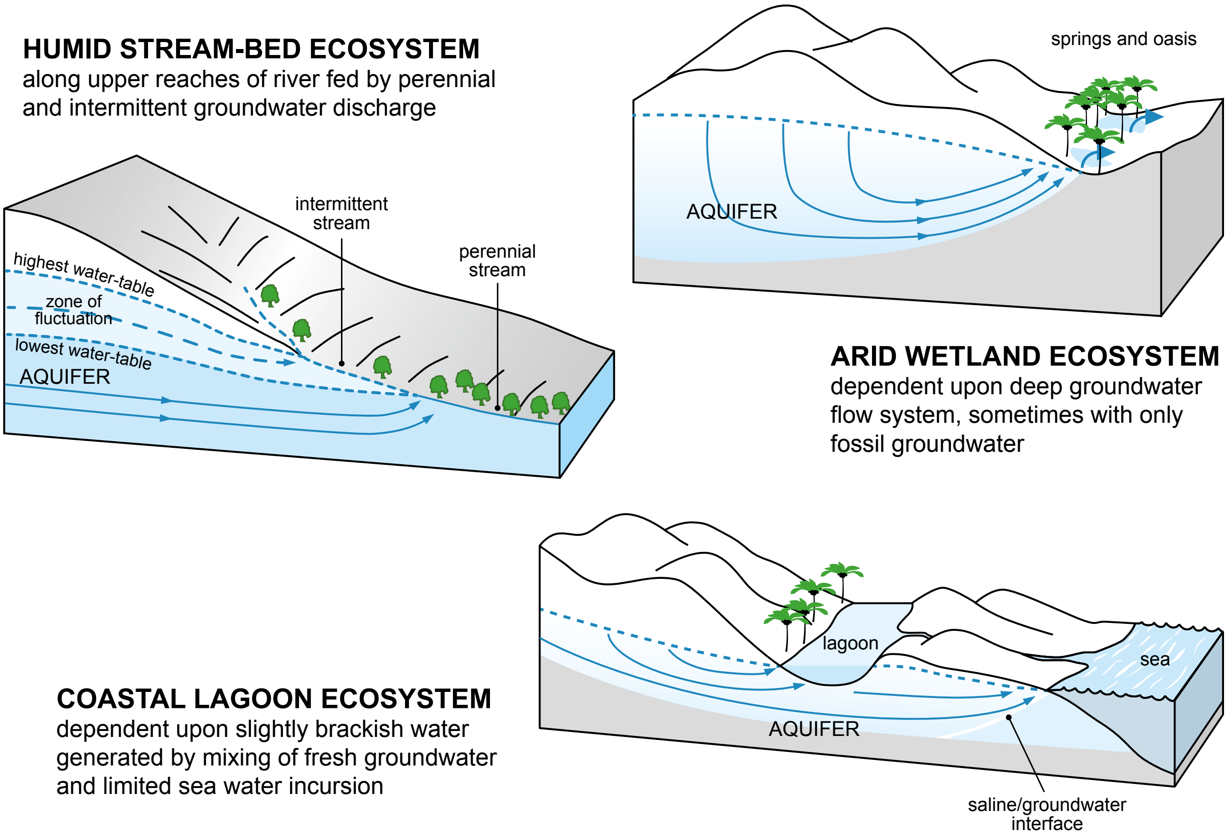


Figure 3.10: Examples of groundwater-related ecosystems and their associated groundwater flow regimes

Groundwater – surface water interactions – anthropogenic impacts. In addition to the naturally occurring interactions discussed above, there are also many groundwater – surface water interactions that are either enhanced or created by a variety of human activities (Figure 3.11).

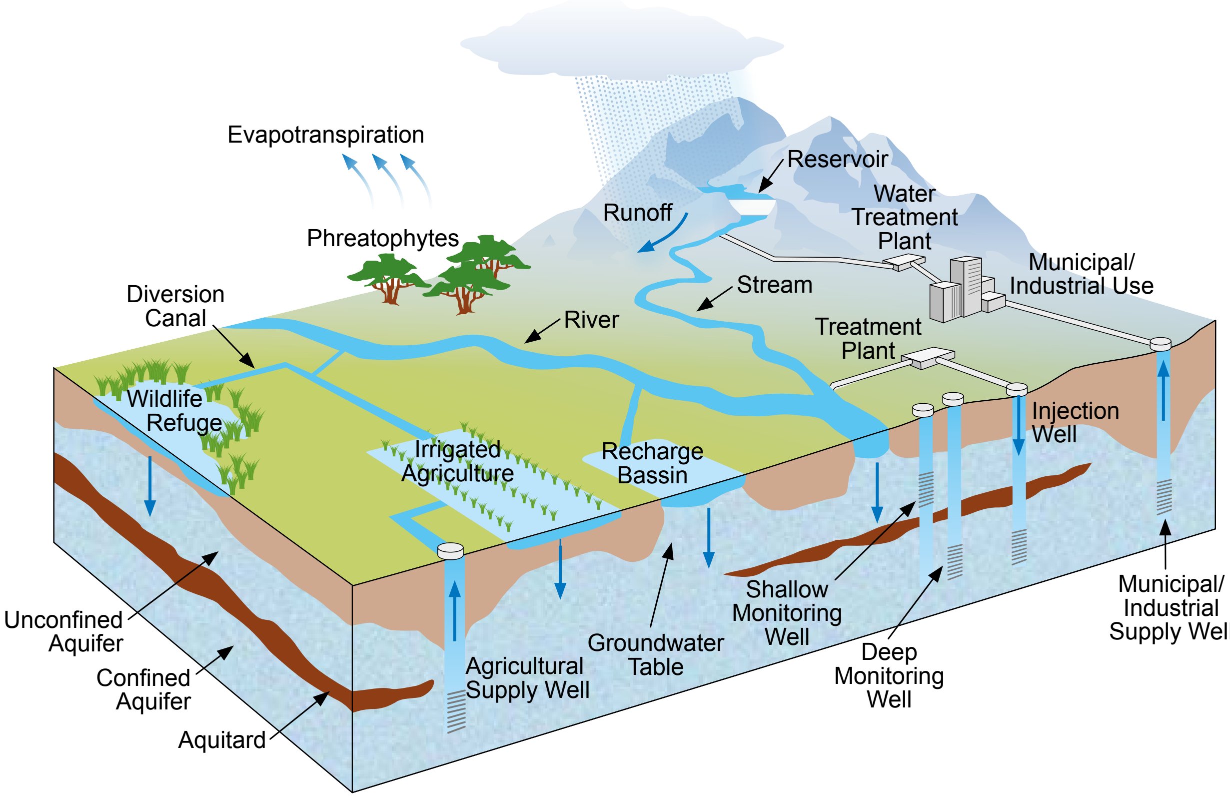


Figure 3.11. Groundwater – surface water interactions.

The block diagram in figure 3.11 shows some of the many fluxes between the groundwater system and surface water. The uneven groundwater surface shown is strongly linked to the direction of these fluxes. In this diagram, which might be considered to represent a semi-arid climate, the natural fluxes are from surface water to the groundwater, while the fluxes from groundwater to the surface are by pumping. In a humid environment, the reverse would likely hold and there would be many natural fluxes from groundwater to surface water by, for example, baseflow, spring discharge or seepage zones.

RBO managers need to be aware of these fluxes and their impacts. Such flows not only transfer water between the ground and surface water systems, but also impact on water quality by transferring dissolved chemicals and pollutants. In urban and industrial environments the flux of polluted water between groundwater and surface water is often a critical management problem that needs to be resolved by improved waste management practices and control and monitoring of agro-industrial practices and processes.

3.6 Summary: Critical issues in groundwater characterization

Groundwater management in river or lake basins should be based on a good understanding of the characteristics of the groundwater system, including its interaction with surface water bodies (rivers, lakes and wetlands). Groundwater characterization involves a number of issues namely:

- Quantification of the rate of groundwater recharge.
- Identification of main areas of groundwater recharge, in context of land use and pollution load sites.
- Understanding the nature and mechanisms of interactions between groundwater and surface water, and
- Assessment of impacts of groundwater pumping on the groundwater system.

The characterization of the groundwater system may be verified by undertaking aquifer system water balances to check our understanding of the inflows and outflows and groundwater modelling in order to predict the impacts of interactions between groundwater and surface water and groundwater development.

There is however a need for a mechanism to provide suitable groundwater resources information for sustainable groundwater development and protection at policy level. This will involve establishing appropriate policies, strategies and regulatory frameworks, and will require an adequate understanding the groundwater system by acquiring information on the distribution of aquifer units and knowledge of the aquifer properties (Box 3.3). Management of aquifers also requires creating mechanisms for involvement of key stakeholders in water demand and water allocation management.

BOX 3.3: SOURCES OF INFORMATION FOR GROUNDWATER SYSTEM CHARACTERISATION

The basic data requirements are as follows:

- hydrogeological maps for 3D aquifer distribution and aquifer boundaries
- hydrogeological surveys for sources/zones of aquifer recharge and natural discharge
- land-use data for recharge zones
- borehole pumping tests for aquifer properties
- borehole abstraction, use and quality data
- meteorological data (rainfall, evaporation, etc)
- groundwater level monitoring.

Although groundwater management, in river or lake basin, needs to be based on a good understanding of the characteristics of the groundwater system, including its interaction with surface water bodies (rivers, lakes and wetlands), there are a number of difficulties and uncertainties that need to be borne in mind. These include among others the fact that groundwater is a hidden resource and cannot be readily observed, that groundwater may occur in large and complex aquifer systems that are difficult to characterize and that aquifers have high spatial variability in their characteristics.

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3.8 Exercise

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 in your catchment:

- Do you have knowledge on how it affects the river, lake or wetlands in your basin?
- Which natural processes or human activities affect these interactions?
- What steps is your L/RBO taking (or should take) to assess or to improve the characterisation of groundwater and surface water relationship?
- Make recommendations on how groundwater and surface water should be managed together within your L/RB.

Report Back:

Each group presents their recommendations followed by a general discussion.

MODULE

MANAGEMENT OF TRANSBOUNDARY AQUIFERS

CONTENT

MODULE 4

Management of Transboundary Aquifers

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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MANAGEMENT OF TRANSBOUNDARY AQUIFERS

LEARNING OBJECTIVES

- To understand the concept of transboundary groundwater and its management issues
- To become familiar with the location and extent of transboundary aquifers in Africa
- To become familiar with the legal frameworks for the management of transboundary aquifers
- To understand some of the current management issues and approaches applied to transboundary aquifers in Africa

4.1 Introduction

Water management is typically perceived and practically carried out within hydrological basins (river basins, lake basins). When such basins transcend national borders, the issues at hand become a matter of international concern. This is because the actions and perturbations to the water resources in one country potentially affect the other countries sharing that transboundary resource. International water cooperation is rising to become a very important topic in water resources management, as water resources become increasingly stressed from various factors such as climate change and human development. Most of the major and many of the smaller river basins in the world are shared between two or more countries and in total 263 river basins are transboundary. Tools for co-management, international law, and general theory of the best options for transboundary water management (TWM) are being steadily developed, and experience across the globe is increasing (INBO and GWP, 2012).

4.2 What is a transboundary aquifer (TBA)?

Groundwater, as well as surface water, inevitably flows across international borders. However the attention to this and possible implications and approaches for TWM related to groundwater have only recently been developed. Focus has hitherto been on surface water, for obvious reasons of visibility of the resource. However since surface water and groundwater are usually linked hydrologically, the groundwater component cannot be ignored if proper accounting for transboundary water interactions is to be achieved and possible associated conflicts are to be avoided.

Transboundary aquifers (TBAs) are those major groundwater systems that span across more than one country. The definition of a TBA is: ‘an aquifer or aquifer system, parts of which are situated in different States’ (Article 2c, Stephan 2009) (Fig. 4.1). Since groundwater is more or less ubiquitous, most borders will be underlain with shared groundwater. However the term TBA seems to be reserved for those larger contiguous and productive aquifers or aquifer systems that merit joint management due to their potential or current importance for water supply or other reasons, e.g. for important connected ecosystems. Currently more than 450 TBAs have been identified globally (IGRAC, 2012). As illustrated in Figure 4.1, transboundary groundwater systems may not have obvious upstream-downstream relations, as opposed to rivers, and they may even change flow direction as a result of changing abstraction patterns.

Even within the same overall system, heterogeneity in properties and layering can give rise to opposing flow between local shallow aquifers and deeper, regional aquifers. Such complexities specific to groundwater make the characterisation and co-management of TBAs more complex.

TBAs need to be characterized in terms of extent (horizontal and vertical), recharge (areas, mechanisms, rates), storage capacity, as well as flow patterns, relationship with surface water systems, vulnerability, current exploitation levels, potential for further development, and existing threats.

Historically such assessments would terminate at the border of each country, but for TWM these assessments need to be done jointly, in a harmonised way, and with balanced focus on all the shared parts of the aquifer systems. An important distinction is between renewable vs. non-renewable aquifers, i.e. aquifers that receive insignificant recharge during present climate and land use, as these will basically not be naturally replenished if exploited.

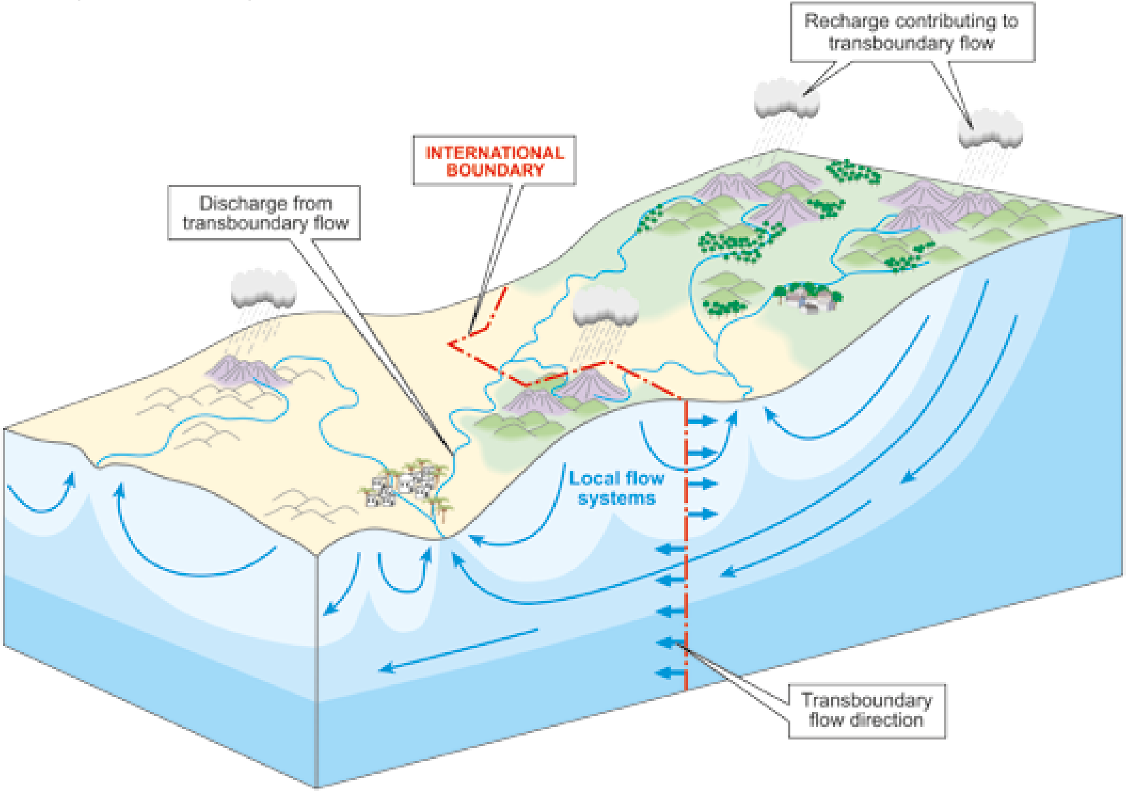


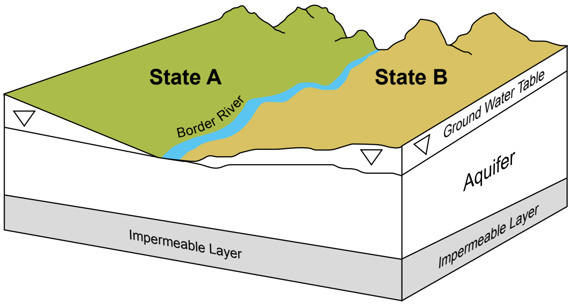
Figure 4.1 Transboundary groundwater

Different classification methods for TBAs have been developed in an attempt to systematically group the TBAs and as a tool to provide coherent management according to different characteristics of the TBAs. One such example is given in Figure 4.2. UNESCO's Internationally Shared Aquifer Resources Management (ISARM) initiative, the Worldwide Hydrogeological Mapping and Assessment Programme (WHYMAP), the International Groundwater Resources Assessment Centre (IGRAC), the UN World Water Assessment Programme (WWAP), the Food and Agriculture Organisation of the United Nations (FAO) and many other partner organizations over the last decade, and the recent TWAP Assessment of Transboundary Aquifers have been compiling and complementing the available information at the global scale related to TBAs.

4.3 Transboundary aquifers in Africa

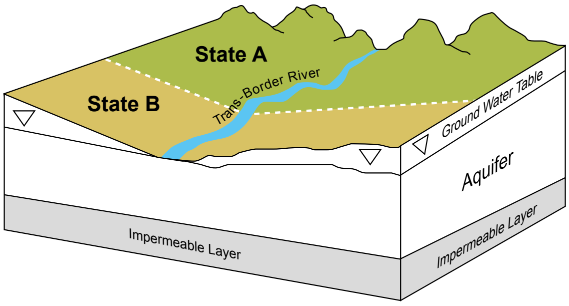
Africa is known for its large proportion of water systems that are shared between nations. Approximately 64 % of the continent's landmass occurs in transboundary international river basins. River basins such as the Nile, Congo, Niger, Volta, Orange-Senqu, and Zambezi are the major ones. A large number of TBAs have also been identified for Africa, presently about 80, but more and smaller ones are likely to be added as more information and knowledge becomes available. Figure 4.3 shows a map of the presently identified TBAs in Africa overlain on the international river basins, and Table 4.1 gives key data for the TBAs. It is clear from this that groundwater and surface water resources do not necessary coincide geographically.

The TBAs encompass a wide variety of characteristics, in size as well as geological setting, recharge and population density. Presently identified TBAs represent approximately 42% of continental land area and 30% of the population. There is a huge difference between the aquifers in terms of population living within individual TBAs, reaching approximately 63 million in the case of the Nubian Sandstone Aquifer System (AFNE12) to less than hundred inhabitants (Medium Zambezi Aquifer, AFS17; and L'Air Cristalline Aquifer, AFWC21) (Altchenko and Villholth, 2013). The same heterogeneity exists in terms of areal extent, ranging from smaller than 1500 km2 (Jbel El Hamra Aquifer, AFNE22 and Figuig Aquifer, AFNE18) to larger than 2.6 mill. km2 (Nubian Sandstone Aquifer System, AFNE12). The latter is comparable to the size of the Lake Chad River Basin (2.4 mill. km2). TBAs are shared between two and up to eight states, the latter being the case for the Lake Chad Aquifer Basin (AFWC14).



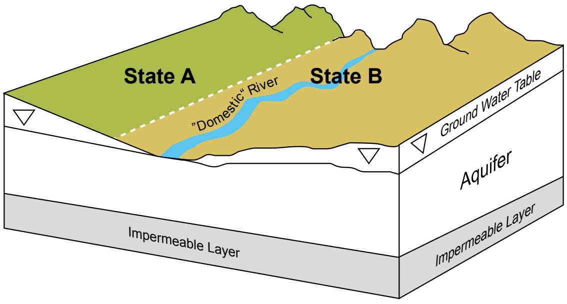
Type A:

An unconfined aquifer that is linked hydraulically with a river, both of which flow along an international border (i.e., the river forms the border between two states)



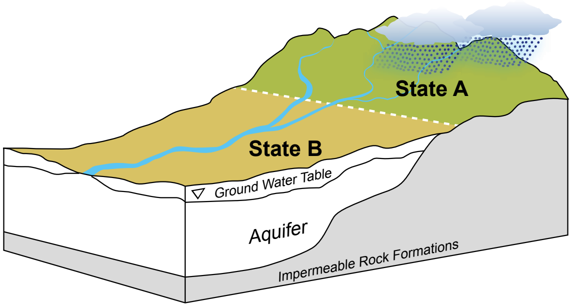
Type B:

An unconfined aquifer intersected by an international border and linked hydraulically with a river that is also intersected by the same international border



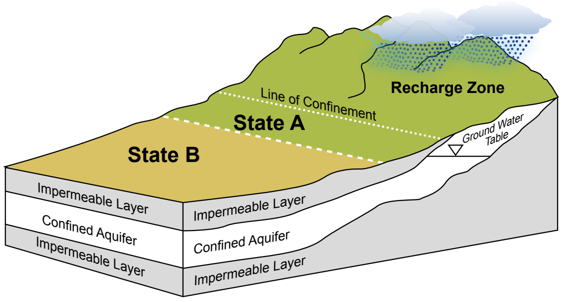
Type C:

An unconfined aquifer that flows across an international border and that is hydraulically linked to a river that flows completely within the territory of one state



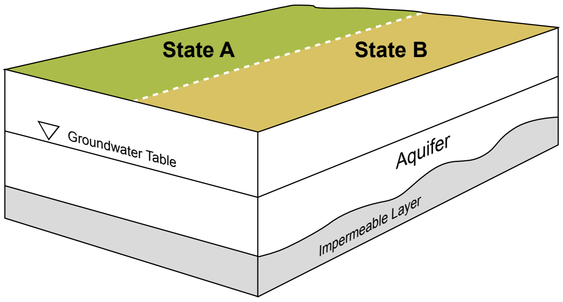
Type D:

An unconfined aquifer that is completely within the territory of one state but that is linked hydraulically to a river flowing across an international border (in such cases, the aquifer is always located in the "downstream" state)



Type E:

A confined aquifer, unconnected hydraulically with any surface body of water, with a zone of recharge (possibly in an unconfined portion of the aquifer) that traverses an international boundary or that is located completely in another state



Type F:

A transboundary aquifer unrelated to any surface body of water and devoid of any recharge

Figure 4.2. Different types of TBA systems, based on flow characteristics and interactions with surface water. Source: Eckstein and Eckstein (2003)

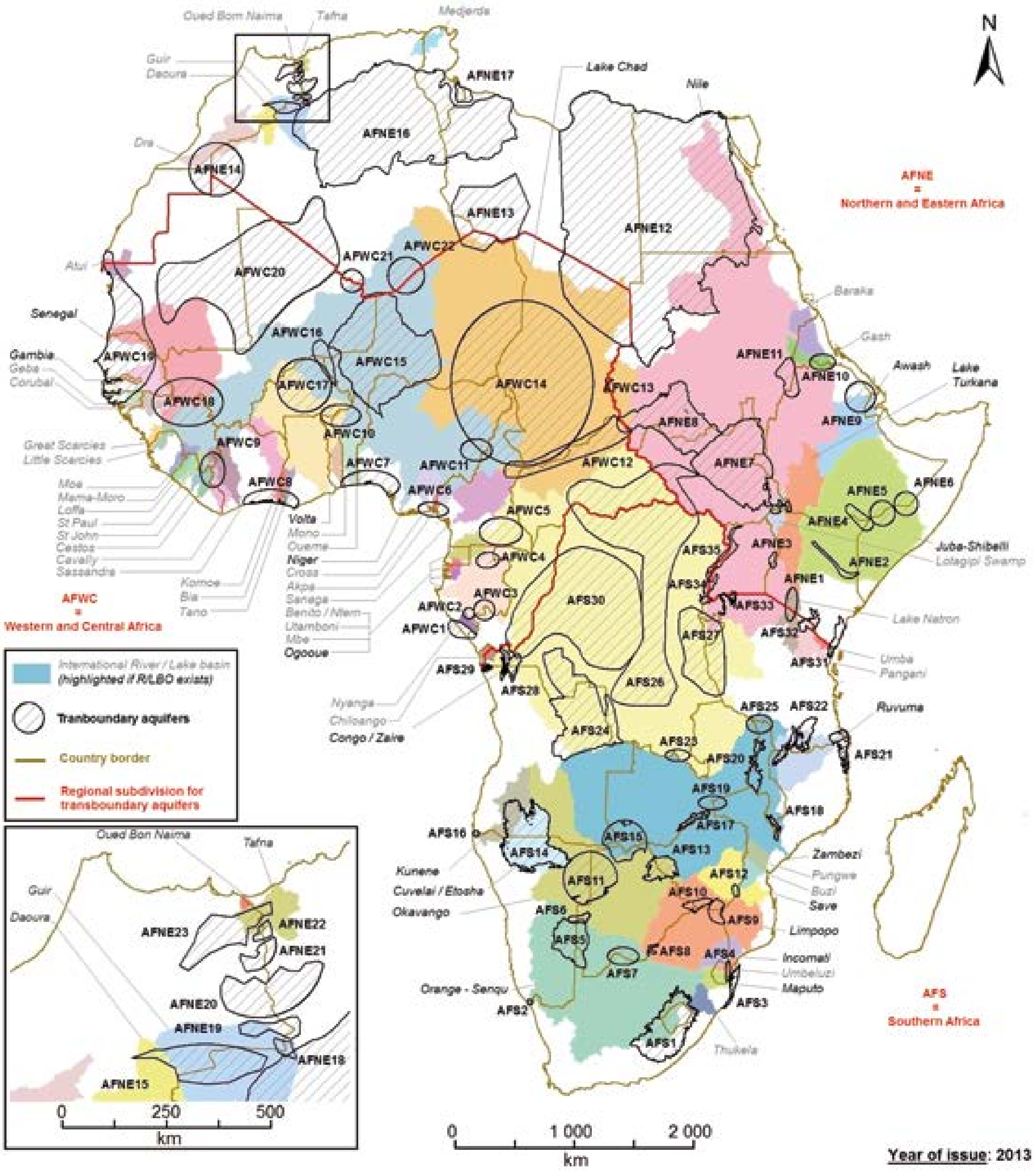


Figure 4.3. Map of transboundary aquifers in Africa. Source: Altchenko and Villholth (2013)

Table 4.1. Key data for transboundary aquifers in Africa (refer to Fig 4.3 for location of TBAs)

Inventory of transboundary aquifers in Africa

ID	Name	Countries sharing the aquifer	Population (inhabitants)	Area (km^2)	Aquifer type	Rainfall (mm/year)	Annual recharge (WHYMAP)
AFS1	Karoo sedimentary aquifer	Lesotho/South Africa	5,568,000	166,000	Consolidated sedimentary rocks	350 – 1,200	VL to M
AFS2	Coastal sedimentary basin 5	Namibia/South Africa	7,900	1,700	Quaternary and consolidated sedimentary rocks	45 – 55	VL to M
AFS3	Coastal sedimentary basin 6	Mozambique/South Africa	548,000	11,700	Quaternary and consolidated sedimentary rocks	700 – 1,200	M to H
AFS4	Rhyolite-Breccia aquifer	Mozambique/South Africa/Swaziland	206,000	5,500	Volcanic/Quaternary	600 – 850	VL to M
AFS5	Southwest Kalahari/Karoo basin	Botswana/Namibia/South Africa	15,500	85,000	Kalahari groups aquifer and Karoo supergroup aquifers	200 – 350	VL to M
AFS6	Ncojane aquifer	Botswana/Namibia	2,300	10,300	Consolidated sedimentary rocks	300 – 350	VL to M
AFS7	Khakhea/Bray dolomite	South Africa/Botswana	57,000	30,000	Dolomite	300 – 450	VL to M
AFS8	Ramotswa dolomite basin	Botswana/South Africa	135,500	3,200	Malmani subgroup of the Transvaal supergroup	500 – 550	VL to M
AFS9	Limpopo basin	Mozambique/South Africa/Zimbabwe	313,800	20,000	Volcanic and basement rocks	400 – 700	VL to L
AFS10	Tuli Karoo sub-basin	Botswana/South Africa/Zimbabwe	70,600	14,330	Volcanic and basement rocks	300 – 450	VL to L
AFS11	Northern Kalahari/Karoo basin	Angola/Botswana/Namibia/Zambia	35,900	144,400	Consolidated sedimentary rocks	380 – 550	VL to H
AFS12	Save alluvial aquifer	Mozambique/Zimbabwe	32,600	4,500	Alluvial	400 – 600	VL to M
AFS13	Eastern Kalahari/Karoo basin	Botswana/Zimbabwe	54,300	39,600	Upper Karoo Sandstone	400 – 600	VL to M
AFS14	Cuvelai and Etosha basin	Angola/Namibia	1,032,400	202,000	Consolidated sedimentary rocks	300 – 900	L to M
AFS15	Nata Karoo sub-basin	Botswana/Namibia/Zimbabwe	195,000	91,000	Ecca sequence	500 – 750	VL to M
AFS16	Coastal sedimentary basin 4	Angola/Namibia	20	2,200	Quaternary and consolidated sedimentary rocks	100 – 150	VL to M
AFS17	Medium Zambezi aquifer	Mozambique/Zambia/Zimbabwe	50,800	10,700	Quaternary and consolidated sedimentary rocks	720 – 780	VL to M
AFS18	Shire Valley aquifer	Malawi/Mozambique	527,000	6,200	Tertiary/Quaternary	780 – 900	M to VH
AFS19	Arangua Alluvial	Mozambique/Zambia	12,500	21,200	Alluvial	700 – 1,100	VL to M
AFS20	Sand and gravel aquifer	Malawi/Zambia	2 233,000	25,300	Unconsolidated intergranular aquifer and weathered basement complex	800 – 1,200	VL to VH
AFS21	Coastal sedimentary basin 3	Mozambique/Tanzania	794,000	23,000	Quaternary and consolidated sedimentary rocks	930 – 1,200	H
AFS22	Karoo-Sandstone aquifer	Mozambique/Tanzania	214,500	40,000	Consolidated sedimentary rocks	900 – 1,700	M to VH
AFS23	Kalahari/Katangian basin	DRC/Zambia	1,006,000	15,600	Katangian and Kalahari sequence	1,200 – 1,300	H to VH
AFS24	Congo Intra-cratonic	Angola/DRC	1,920,000	317,200	Consolidated sedimentary rocks	1,200 – 1,650	H
AFS25	Weathered basement	Malawi/Tanzania/Zambia	852,000	25,842	NI	900 – 2,000	M to VH
AFS26	Karoo Carbonate	CAR/Congo/South Sudan	9,400,000	941,100	Limestone/Sandstone	1,000 – 1,800	H to VH
AFS27	Tanganyika aquifer	Burundi/DRC/Tanzania/Rwanda	11,940,000	222,300	Fractured basalt and granite	800 – 1,800	VL to VH
AFS28	Dolomitic aquifer	Angola/DRC	750,600	21,300	Karst weathered dolomite	1,100 – 1,450	H to VH
AFS29	Coastal sedimentary basin 2	Angola/DRC	34,000	2,250	Quaternary and consolidated sedimentary rocks	800 – 1,000	VL to H
AFS30	Cuvette Centale	Congo/DRC	14,000,000	814,800	Alluvial Sandstones	1,400 – 2,100	H to VH
AFS31	Coastal sedimentary basin 1	Kenya/Tanzania	2,150,000	16,800	Quaternary and consolidated sedimentary rocks	850 – 1,250	M to H
AFS32	Kilimanjero aquifer	Kenya/Tanzania	1,396,000	14,600	Volcanic alluvium	600 – 1,600	VL to M
AFS33	Kagera aquifer	Rwanda/Tanzania/Uganda	493,500	5,800	Alluvial unconsolidated sand and gravels	930 – 1,800	VL to M
AFS34	Mgahinga	DRC/Rwanda/Uganda	1,451,000	4,400	Volcanic	1,250 – 1,650	VL to M
AFS35	Western Rift valley sediment	DRC/Uganda	1,151,000	29,500	Volcanic	800 – 1,250	VL to H
AFWC1	NN	Congo/Gabon	13,300	23,000	NI	1,400 – 1,750	M to VH
AFWC2	NN	Congo/Gabon	48,500	7,100	NI	1,650 – 1,950	H to VH
AFWC3	NN	Congo/Gabon	41,000	23,500	NI	1,750 – 1,950	H to VH
AFWC4	NN	Congo/Gabon	1,700	19,600	NI	1,600 – 1,750	H to VH
AFWC5	NN	Cameroon/CAR/Gabon	178,000	66,400	NI	1,550 – 1,650	H to VH
AFWC6	Rio Delrey	Cameroon/Nigeria	3,300,000	24,000	Upper Miocene to Quaternary	2,500 – 3,130	VH
AFWC7	Keta basin	Benin/Nigeria/Togo	16,896,000	55,400	Quaternary (sand, silt, clay)	950 – 2,450	H to VH
AFWC8	Tano basin	Côte d'Ivoire/Ghana	4,740,000	43,000	Quaternary Terminal Continental and Maestrichtien Aquifer	1,300 – 1,930	H to VH
AFWC9	NN	Côte d'Ivoire/Guinea/Liberia	2,370,000	47,300	NI	1,400 – 2,050	H to VH
AFWC10	Kandi sedimentary basin	Benin/Burkina Faso/Ghana/Togo	1,143,000	47,800	Cambro-Ordovicien and alluvial	850 – 1,100	VL to VH
AFWC11	Garoua - Chari	Cameroon/Nigeria	1,870,000	38,400	Sandstone - Clay	950 – 1,400	H to VH
AFWC12	NN	Cameroon/CAR/Chad/Sudan	716,000	155,400	Sedimentary	700 – 1,600	H to VH
AFWC13	Disa	Chad/Sudan	74,300	1,500	Sandstone	500 – 550	VL to M
AFWC14	Lake Chad	CAR/Cameroon/Chad/Niger/Nigeria	22,419,100	1,300,500	Sedimentary: the Upper Quaternary, the Lower Pliocene and the TC	40 – 1,400	VL to H
AFWC15	Irhazer-Iullemeden	Algeria/Mali/Niger/Nigeria	12,888,600	545,400	Sedimentary deposit including IC and TC	80 – 900	VL to VH
AFWC16	NN	Burkina Faso/Mali/Niger	333,000	3,500	NI	250 – 600	VL to M
AFWC17	Liptako-Gourma aquifer	Burkina Faso/Niger	7,758,300	159,500	Fractured metamorphic	400 – 900	VL to H
AFWC18	NN	Guinea/Mali/Senegal	4,250,000	185,500	Birrimien	850 – 1,650	VL to VH
AFWC19	Senegalo-Mauritanian basin	Gambia/Guinea-Bissau Mauritania/Senegal	11,930,000	331,450	Maestrichtien	20 – 1,850	VL to VH
AFWC20	Taoudeeni basin	Algeria/Mali/Mauritania	82,400	936,000	Multilayers	10 – 350	VL to L
AFWC21	L'air Cristalline aquifer	Algeria/Mali	84	28,400	NI	60 – 100	VL to M
AFWC22	Tin Seririne	Algeria/Nigeria	520	73,700	NI	20 – 50	VL to L
AFNE1	Rift aquifer	Kenya/Tanzania/Uganda	279,000	21,150	Volcanic	450 – 1,100	VL to M
AFNE2	Merti aquifer	Kenya/Somalia	129,000	13,500	Semi-consolidated sedimentary	350 – 750	L to M
AFNE3	Mount Elgon	Kenya/Uganda	806,550	5,400	Volcanic	1,000 – 1,300	VL to M
AFNE4	Dawa	Ethiopia/Kenya/Somalia	223,150	24,000	Volcanic rocks, alluvials and Precambrian basement	300 – 650	VL to L
AFNE5	Juba aquifer	Ethiopia/Kenya/Somalia	197,600	34,600	Aquifers in Precambrian and intrusive rocks	270 – 450	VL to L
AFNE6	Shabelle aquifer	Ethiopia/Somalia	334,000	31,000	Sedimentary and minor volcanic aquifers	280 – 400	VL to L
AFNE7	Sudd basin	Ethiopia/Kenya South Sudan/Sudan	2,926,500	331,600	Precambrian and volcanic rocks with patches of alluvials/ sedimentary	450 – 1,100	M
AFNE8	Baggara basin	CAR/South Sudan/Sudan	2,433,500	239,300	Umm Ruwaba (overlain the Nubian Formation)	300 – 900	L to M
AFNE9	Awash Valley aquifer	Djibouti/Eritrea/Ethiopia	627,400	50,700	Volcanic	110 – 350	VL to L
AFNE10	Mareb aquifer	Eritrea/Ethiopia	1,827,900	22,800	Precambrian and intrusive rocks	450 – 550	VL to M
AFNE11	Gedaref	Eritrea/Ethiopia Sudan	732,000	38,700	Precambrian and volcanic rocks with patches of alluvials/sedimentary	400 – 950	VL to M
AFNE12	Nubian Sandstone aquifer system	Chad/Egypt/Libya/Sudan	67,320,000	2,608,000	Nubian and Post-Nubian	1 – 550 (mainly < 30)	Mainly VL (VL to VH)
AFNE13	Mourzouk-Djado basin	Algeria/Libya/Nigeria	108,000	286,200	Sedimentary	< 20	Mainly VL (VL to M)
AFNE14	Tindouf aquifer	Algeria/Mauritania/Morocco	107,000	160,000	Alternating series of calcareous rocks and sand	30 – 200	VL to M
AFNE15	Errachidia basin	Algeria/Morocco	156,300	18,500	Sandstone, calcareous, dolomite	80 – 200	VL to L
AFNE16	North Western Sahara Aquifer system	Algeria/Libya/Tunisia	4,000,000	1,190,000	Sand, Sandstone, sandy clay, calcareous, dolomite	10 – 300 (mainly < 50)	VL to L
AFNE17	Djaffar Djeffara	Libya/Tunisia	262,400	15,800	NI	130 – 250	L
AFNE18	Figuig	Algeria/Morocco	32,300	1,500	Phreatic Aquifer, Porous	100 – 170	VL to L
AFNE19	Chott Tigri-Lahouita	Algeria/Morocco	26,800	4,700	Porous, Karst, Dolomite Limestone and Sandstone	180 – 250	VL to L
AFNE20	Ain Beni mathar	Algeria/Morocco	23,100	20,000	Karstic, Dolomite Limestone and Dolomite	260 – 350	VL to M
AFNE21	Angad	Algeria/Morocco	25,600	3,500	Porous, Plio-Quaternary	350 – 450	VL to M
AFNE22	Jbel El Hamra	Algeria/Morocco	40,100	1,250	Karstic	440 – 500	VL to L
AFNE23	Triffa	Algeria/Morocco	920,000	13,100	PorousVillafranchian and Quaternary	370 – 450	M

Notes: NN = No name referenced; NI = No information; TC = Terminal Continental; IC = Intercalary Continental;
VL = Very low (0 - 2 mm/year); L = Low (2 - 20 mm/year); M = Medium (20 - 100 mm/year); H = High (100 - 300 mm/year); VH = Very high (> 300 mm/year)

4.4 Approach and mechanisms for TBA management

Groundwater management is a complex endeavour as it requires coordination across many sectors and users (e.g. water supply, agriculture, energy, industry, and environment) and it needs to integrate with surface water management. Trying to do this at the international level poses another dimension of challenges in terms of coordination and integration. Groundwater traditionally has been considered a national matter, but the need for international cooperation on groundwater is increasingly recognised. This is particularly the case where:

- Groundwater resources evidently flow across borders, as in the case where groundwater is primarily recharged in one country but discharges in another (like Type E in Figure 4.2)
- Groundwater development in one country has (or could have) significant implications and adverse impact in the other country
- Significant ecosystems in one country depend on groundwater influx from another country
- Significant groundwater development or land-use changes with implications for groundwater resources (quantity or quality) in neighbouring countries is planned in one country
- Groundwater is a significant resource in drought management and generally for human development for one or more of the sharing countries

The principles of international law for cooperation on transboundary aquifers build on the general principles of cooperation on surface water. Some of these principles relate to:

- Cooperation on the basis of sovereign equality, territorial integrity, mutual benefit and good faith
- The concept of ‘equitable and reasonable use’
- The concept of ‘no-harm’, i.e. that all resource development and management is done with no prior intention of harming the other part
- Prior notification, i.e. that states have an obligation to inform each other before implementing major investments and interventions that may affect the resource in a transboundary sense. Notification also refers to immediately informing other states of emergency conditions related to the watercourse that may affect them, such as flooding

Table 4.2 Particular characteristics of aquifers and implications for management of TBAs

	Special considerations/provisions needed in TBA management								
Groundwater distinct characteristic	Joint user/use registration, regulation, monitoring and enforcement	Prior notification of development plans to other party	Precautionary principle	Conflict resolution	Stakeholder engagement	Long-term monitoring of resource	Flexibility in conceptual model and clear data- sharing arrangements	Land use and waste regulations	Prioritized protection
Open source	xx				xx				
Invisible and heterogeneous		x	x	x	x	x	x		
Vulnerable to land use impacts					x			xx	x
Slow reacting/delay in response/slowly renewable		x	xx	x		xx			
Recharge/discharge is distributed and uneven								x	xx
Boundaries uncertain				x		x	xx		
Climate change impacts uncertain						xx	xx		
Blurred up and downstream relations			x	x	x	x	xx		

- Sharing of data, i.e. institutionalised mechanisms for regular sharing of new data and knowledge related to the TBAs
- The precautionary principle, i.e. that development is not done if insufficient knowledge exists to show that environmental and socio-economic impacts will be low. These protections can be relaxed only if further scientific findings emerge that provide sound evidence that no significant harm will result
- Stakeholder involvement, i.e. that stakeholders are involved and have a say in decisions related to the development of the resource
- Dispute settlement

However, it is important to bear in mind that groundwater has some particular inherent characteristics that necessitate strong emphasis on certain of these principles, i.e. the precautionary principle, long-term monitoring of the resource, joint monitoring/registration of users, prior notification, and prioritized protection (Table 4.2). Because groundwater generally moves very slowly, the precautionary principle, the long-term monitoring and the prioritized protection, e.g. of significant recharge zones, are critical. For the prior notification, development may relate to significant land use change plans or widespread development of the groundwater resource, rather than large infrastructure dams that typically affect surface water sharing. Prior notification could also relate to the spill of chemicals or detection of groundwater contamination in the border region. In order to achieve full and efficient cooperation on TBAs, states need to formulate joint (or separate but coordinated) plans and programmes for groundwater development, use and protection, to implement common/harmonised groundwater management policies, the joint training of technical personnel and the joint undertaking of environmental studies.

In principle, groundwater as part of the unified hydrological system falls under the provisions of international water law[1]. However, the mechanisms for managing international waters traditionally have focused on surface water, and groundwater was either ignored or simply assumed to be covered. Due to recognition of the importance of groundwater as well as its inherent characteristics, there has been an increase in work dedicated to developing separate and integrated frameworks for international law on groundwater.

Four most important pieces of international water legislation, with each their strong and weak aspects, are included in Table 4.3. These conventions are meant as guidelines and encourage states to draft specific binding agreements (treaties) between nations related to their specific shared (ground)water resources and establish permanent transboundary organizational setups for their management.

Since aquifers and river/lake basins seldom coincide (Fig 4.3), the most appropriate body to oversee management of TBAs may not necessarily be the basin organisation specific to the river/lake (if existent). Cooperation among several basin organisations may be necessary. Similarly, separate aquifer basin organisations may be a relevant solution where there is no effective surface water-based transboundary basin organization.

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[1] International water law is a system of norms and rules governing relations between and among sovereign States and plays an important role in the peaceful management of transboundary water resources.

Table 4.3. Four most important pieces of international water legislation for groundwater

	Focusing on groundwater or surface water?	Regional scope	In force	Reference
UN Convention on the Law of the Non-Navigational Uses of International Watercourses	Surface water, and groundwater hydraulically connected to surface water	Global	No[a]	United Nations (1997)
Convention on the Protection and Use of Transboundary Watercourses and International Lakes	Both	Europe[b]	Yes (1996)	UNECE (1992)
SADC Revised Protocol on Shared Watercourse	Surface water, and groundwater hydraulically connected to surface water	SADC region	Yes (2003)	SADC (2000)
UN Draft Articles on Transboundary Aquifers	Groundwater	Global	No	Stephan (2009)

[a] Only one more country needs to ratify it for it to enter into force, as of 27 Feb. 2014.

[b] Enters into force if all 33 states originally parties to the convention approve. So far 23 have approved.

4.5 Specific challenges and cases of TBA management in Africa

The need for transboundary groundwater management in Africa is at present most acute in semi-arid and arid regions where the surface water resources may be limited or seasonally or inter-annually very variable or located far away from significant populations. These are typically also the regions where significant transboundary groundwater reserves are non- or less renewable, increasing the challenges of sustainable TWM.

One of the most important decisions that joint management committees have to make in such conditions is the maximum allowed annual drawdown of the aquifer. This is the case in much of northern Africa and in southern Africa. Transboundary management could also be of concern in areas where surface waters are declining or affected by contamination, e.g. the Lake Chad Basin in western Africa.

Significant conflicts over shared aquifers are not apparent or are still not fully documented in terms of extent and underlying causes. The ‘needs assessment’ (BGR / IWMI 2013) identified alluvial groundwater abstraction for irrigation alongside international water courses (Fig 4.2 Type A and Type B) in some of the surveyed TBOs (LIMCOM, OMVS) as the activity with the most immediate “suspected” transboundary impact. These TBOs expressed concern at the impacts of alluvial groundwater abstraction on transboundary surface water flows, but indicated that no conflicts have yet been experienced.

Reflecting these needs, greater efforts have been pursued in the arid regions in terms of managing the shared groundwater resources. At present, formal agreements exist between countries sharing the Nubian Sandstone Aquifer System (NSAS, AFNE12), the Northwestern Sahara Aquifer System (AFNE16), while significant work is ongoing in the Lake Chad aquifer (AFWC14) and the Iullemeden/Taudeni Aquifer Systems (AFWC20+15). Such efforts are typically supported by international organizations (eg. UNESCO, FAO) and technical institutions with expertise in groundwater characterization (eg. IAEA, IGRAC, BGR, and BRGM).

The agreements relate mostly to the setting up of consultative mechanisms to coordinate, promote and facilitate the rational management of the aquifers and the collection, sharing and interpretation of data as part of so-called transboundary diagnostic analyses. The TBA in Africa that counts on the most advanced level of joint management is the Nubian Sandstone Aquifer System (NSAS, AFNE12), which constituted a Joint Authority in 1989 for the study and development of the aquifer and with quite broad responsibilities. The aquifer-sharing states (Egypt, Libya, Sudan, and Chad) and the Joint Authority also agreed on a strategic action plan in 2013 for the shared vision and future cooperative management of the NSAS.

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4.7 Exercise

This exercise provides an example guideline of the manner in which TBOs may approach the management of TBAs in the first instance.

Step 1.

For your country, list the transboundary aquifers or groundwater resources with potential or apparent transboundary issues in terms of development, use, and management.

Step 2.

Categorize and rank the resources in terms of problems or possible solutions to human and environmental needs.

Step 3.

Compare your list with the lists for your neighboring countries and identify the areas of joint priority for transboundary and cooperative management.

Step 4.

Identify technical and management interventions that could be best dealt with jointly to address the issues identified in Step 1-3.

Step 5.

Assess the interventions in terms of the benefits and trade-offs for the countries, in terms of addressing equity, sustainability and efficiency.

Step 6.

Indicate where the institutional responsibility lies to carry out the proposed management interventions. Highlight in particular the role / interventions that can be best carried out by the TBO.

MODULE

GROUNDWATER MONITORING AND INFORMATION MANAGEMENT

CONTENT

MODULE 5

Groundwater Monitoring and Information Management

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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Picture: *IWMI*

GROUNDWATER MONITORING AND INFORMATION MANAGEMENT

LEARNING OBJECTIVES

- Why and how to monitor groundwater levels, abstraction and quality
- Understanding the different objectives of monitoring
- How to design and operate a cost effective and target oriented monitoring system
- How to store and manage data and information
- How to use monitoring data and information for management

List of abbreviations

CBA	Cost Benefit Analysis
QA	Quality Analysis
QC	Quality Control
BO	Basin Organization
IWRM	Integrated Water Resources Management

5.1 Introduction

Monitoring groundwater: the entry point to management

Groundwater monitoring and groundwater data acquisition are pre-requisites for any effective management of groundwater resources, in terms of both the groundwater quality and the availability of the groundwater resource itself. Because of the complexities of groundwater systems, the design and operation of an effective groundwater monitoring is far from simple. Yet well-designed monitoring systems are capable of providing vital aquifer information at a reasonable cost.

This module discusses the different purposes and objectives of monitoring for management based on which a monitoring system can be designed and operated in an effective way.

The underlying principle is that groundwater monitoring should always be target oriented. This means that the management question should be defined first and monitoring should be designed accordingly. In this way, the purpose of monitoring and its results are also better acknowledged by the water managers and water users who in the end will pay for the cost of monitoring. Monitoring should never become a purpose in itself.

Transboundary groundwater monitoring

Transboundary groundwater monitoring has a number of significant differences from internal monitoring systems and strategies. These differences are due to the nature of the groundwater resource itself, and the legal mandate and the institutional capacity of transboundary organizations (TBOs).

Anthropogenic impacts on groundwater resources do not generally have an extended upstream / downstream reach, but tend to be rather localized. This is relevant when dealing with transboundary groundwater monitoring, which often focuses on the monitoring of a heavily utilized or threatened groundwater resource either side of an international border. There are exceptions; for example, heavy exploitation of alluvial aquifers along transboundary rivers tends to have significant impacts on river flow, thus reducing flow to downstream riparian states.

The legal mandate of TBOs does not usually extend to the act of monitoring itself, or even storing the data, but may be restricted to viewing, collating and assessing the monitoring data and determining the transboundary impacts. TBOs may not have the institutional capacity to carry out the analyses of the monitoring data. In these areas, the TBO will generally have to rely on information provided by the national water management institutions that share the common groundwater resource.

The role of the TBO may be more focussed on bringing together monitoring data for transboundary aquifers from the affected states and providing a forum and set of guidelines for integrating the monitoring systems and negotiating the outcomes.

The groundwater monitoring cycle

The purpose oriented approach to groundwater monitoring is also reflected in the monitoring cycle which comprises the complete process of problem definition, management objectives, information needs, data acquisition, data storage, interpretation and dissemination, giving rise to relevant accurate information for aquifer understanding and for consequent management actions (Figure 5.1)

The essence of monitoring includes the design of the monitoring system, and the collection, processing and interpretation of data in order to respond to a suite of well-defined information needs for management purposes. All the steps in the monitoring process should be carefully defined and designed for the specific purpose of the monitoring. Groundwater specialists may tend to put the emphasis on the collection of the data and its interpretation and may give less attention to the dissemination of the results to other stakeholders. Yet the monitoring cycle is only complete if it has provided the required information for managers or water users to take action.

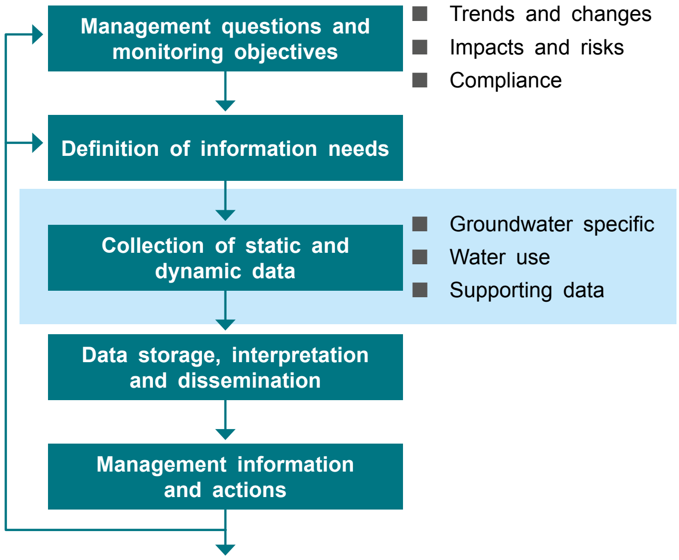


Figure 5.1: Monitoring cycle: information > data > information.

Monitoring objectives: response to information needs

There are four basic objectives for establishing a monitoring system

Resource monitoring to increase the understanding of the groundwater system in a basin (recharge, discharge, interaction with surface water, changes in quality and quantity over time)

Compliance monitoring to get information on the effectiveness of management measures. This has two main dimensions

- Measuring groundwater use and aquifer response: to collect the necessary information for management measure related to quantity (such a restrictions to number of wells, well yields and well spacing or regulation to prevent groundwater levels of wells and well fields to drop below a certain level)
- Measuring groundwater quality parameters of abstracted groundwater to check compliance with prescribed maximum levels.

Protection monitoring for potential impacts on specific groundwater infrastructure or groundwater bodies: typical examples are the protection of:-

- Well fields or springs for public water supply against depletion and quality hazards
- Urban infrastructure against land subsidence
- Archaeological sites against rising water tables
- Strategic water reserves against depletion or quality hazards
- Groundwater dependent ecosystems against undesirable changes in water quantity and/or quality

Pollution containment monitoring to provide early warning information on impacts of potential pollution hazards from

- Intensive agricultural land use
- Industrial sites of specific industries
- Solid waste land fills
- Land reclamation areas
- Quarries and mines

A sharp and clear formulation of the monitoring objectives is the important first step as it helps to (i) define the stakeholders that are involved (both upstream and downstream) and (ii) interact with them on the required information needs that should be provided by the monitoring system
The set of requirements for the design of the monitoring system may combine more than one of the above objectives. An example is shown in Figure 5.2 where the comparison between time series of rainfall and groundwater levels demonstrates the rainfall-recharge relationship (resource monitoring) and also the impact of a nearby deep production well on the shallow groundwater at observation well 6:11.

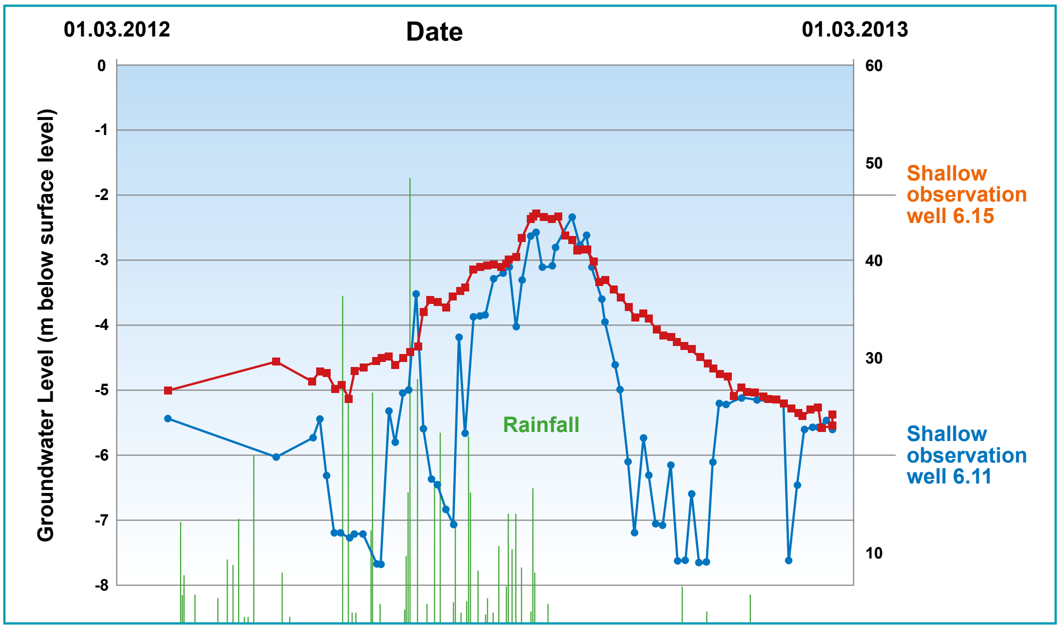


Figure 5.2: Groundwater level (blue and red) and rainfall (light green) time series. Both observation wells show an impact of the rain event within one day. Sudden variations in water levels at observation well 6.11 indicate that it is affected by a nearby production well whereas the observation well 6.15 does not reveal any influence.

5.2. Monitoring practice

Collection of static and dynamic data

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. This determines the type of data that have to be collected and the location and distribution of the monitoring network boreholes. Table 5.1 below summarizes the type of data that may be needed and distinguishes between static and dynamic data.

Table 5.1 Types of data required for groundwater management

TYPE OF DATA	STATIC DATA No significant variation with time (from archives)	DYNAMIC DATA Variation with time (from field stations)
Groundwater occurrence and aquifer properties	■ Water well records (hydrogeological logs, initial 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) ■ Groundwater level variations at well
Supporting information	■ Climatic data ■ Land use inventories ■ Geological maps/ sections	■ River flow gauging ■ Meteorological observations ■ Satellite land use surveys

The first step is to collect and review available (static) data in archives and reports in order to establish the reference situation. Based on that, a network of observation points has to be setup to collect dynamic data if possible from dedicated observation or monitoring wells (figure 5.3).

For groundwater monitoring, data such as the groundwater level, piezometric pressure and water quality have to be collected 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

The use of abandoned wells or existing abstraction wells for monitoring is a cost effective addition to piezometers, but in the case of using active abstraction wells care should be taken that:

- The water level measured is the static water level
- The water sample taken is representative and reliable

Other dynamic data that may be needed are water use, rainfall, river flow, population change and changes in land use.

Figure 5.3 Example of a dedicated monitoring well: a 1" or 2" screen pipe with 3 or 4" upper casing that prevent the wells from flooding and allows for a proper screwed cap for protection. 1" observation wells are for water level recordings only (with a water dipper or a diver). 2" observation wells also allow for water sampling with a bailer

How to measure aquifer response to groundwater abstraction?

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. This information is normally based on results of long-term pumping tests and/or numerical modelling that simulates different abstraction scenarios. Well-field construction and abstraction licenses are then issued on the basis of such predictions.

The groundwater flow direction and rate are 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:

- 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 (see Figure 5.2)
- 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.

BOX 5.1: EXAMPLE SEE FIGURE 5.2

The situation in Figure 5.2 corresponds to following practical example

- 3 production wells were drilled in recent years and the pumping tests on the new wells provided information on the aquifer characteristics (transmissivity, permeability) and on the performance of the wells (specific yield).
- The specific yield is monitored annually by a short duration pumping test. A change in the specific yield over the years means that (i) the well performance decreases eg. due to clogging or (ii) that the aquifer conditions are changed e.g. due to over-pumping
- Groundwater levels in the monitoring wells in combination with rainfall data show that (i) the annual recharge is far higher than the combined abstraction from the production wells and the shallow wells and (ii) that the production wells affect the shallow groundwater only in radius of 200-250 meter around the wells.

This information was used to inform the users of the shallow wells and agree with them on a joint management plan for the groundwater abstraction from the aquifer

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

Groundwater monitoring networks must be designed by specialists on the basis of management requirements, and with a special focus on monitoring in the recharge and 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. Discharge areas tend to be more localized and are often marked by wetlands, seepage zones, baseflow or springs.

Groundwater level measurements can be made manually or automatically either in observation or abstraction wells, 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 action required.

How to monitor groundwater use?

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

Indirect monitoring of groundwater abstraction is always less accurate, but at least an estimation is obtained. Indirect monitoring 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. Information on the areal extent of irrigated land, or the daily and cumulative actual evaporation can be assessed. These techniques are expanding rapidly with different sensors and approaches all the time.
- Estimates of change in regional groundwater abstraction for domestic supply can also be obtained through information on demographic changes and random checks on per ***capita water*** use.

The above approaches refer mainly to groundwater abstraction in rural areas, where the use for irrigation is the largest consumer. Intensive groundwater use for domestic water supply is also encountered in fast growing cities, where the water service provision is inadequate. This is the case in many African cities and has led to massive private groundwater abstraction. Monitoring this water use can be done by using demographic data in combination with satellite images showing the urban expansion and estimating the water use per household through samples (e.g. random surveys).

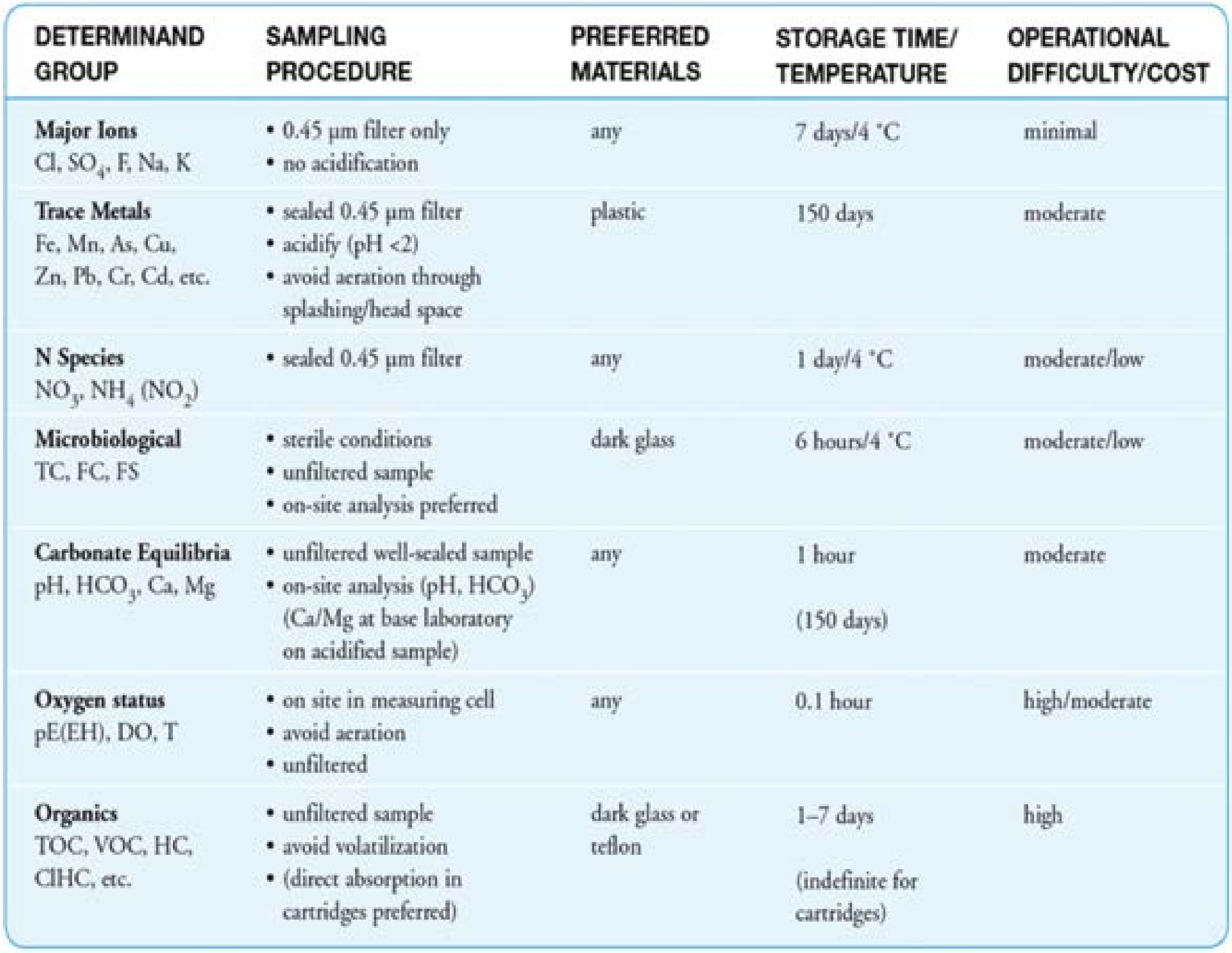
How to monitor for groundwater quality?

A primary focus of groundwater quality monitoring is usually the public water supply from water wells and springs via piped distribution systems. Two key components are the sampling of the water and chemical analysis in the laboratory. Sampling of the water from wells is critical as it may cause major ***sample modification*** such as air entry, degassing and volatile losses, which need appropriate sampling procedures (Table 5.2). In situ measurement of the EC, pH and temperature are needed to validate the condition of the sample during the analysis in the laboratory

A “full” water quality analysis is initially required (ideally), followed by more limited analysis of carefully selected 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 that 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 provide 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.

Table 5.2 Summary of sampling procedures and precautions for specific groups of quality parameters.



DETERMINAND GROUP	SAMPLING PROCEDURE	PREFERRED MATERIALS	STORAGE TIME/ TEMPERATURE	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 cartridges preferred)	dark glass or teflon	1–7 days (indefinite for cartridges)	high

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. In Africa most groundwater quality concerns are related to:

- declining urban groundwater quality because of inadequately built pit latrines / septic tanks and uncontrolled effluent discharge from industry
- salinisation of groundwater caused by inappropriate irrigation methods
- seawater intrusion, due to lowering of water table by water supply wells near / along the coast.

To achieve timely information, a basic understanding of the nature of the problem and a conceptual model of the pollution flow-path is needed. Monitoring wells should than be designed and placed to get timely information on changes in water quality and provide enough time to take mitigation measures. Figure 5.4 shows a typical example of defensive water quality monitoring, based on a prior knowledge of the groundwater flow path and the origin of the water quality threat

Which are typical cases in your basin where dedicated GW quality monitoring is needed

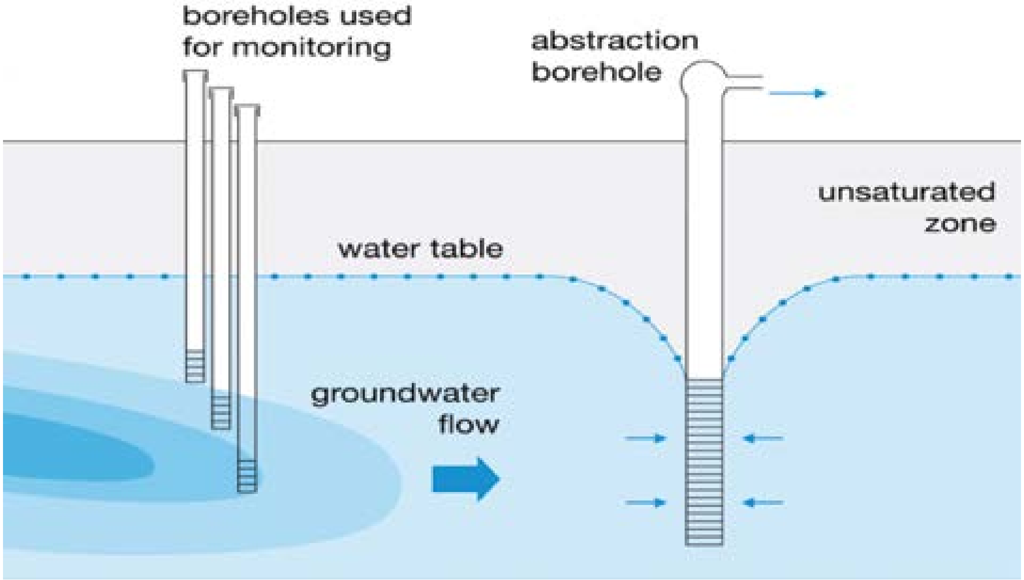


Figure 5.4: Schematic representation of groundwater quality monitoring for specific management objectives

5.3 Data storage and information management

Information Storage and Processing

The monitoring data are stored in a database and processed to provide desired 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. A detailed discussion on the type of processing and processing methods for the different purposes goes beyond the scope of this course. For further reading reference is made to the Guideline on Groundwater Monitoring for General Reference Purposes (IGRAC) and the Groundwater Monitoring Guidance Manual (Commonwealth of Pennsylvania, Department of Environmental Protection, 2001)

An important element of a monitoring database is the quality control of the data. Once wrong data are entered in the system, it will be difficult to correct it at a later stage and may result in wrong or misleading information. The slogan is here that prevention is better than cure. Some key guidelines for a quality control (QC) and quality assurance (QA) system are:

- Train the observer: cross checks in the field, keep eyes open
- Guidelines: follow procedures (e.g. for sampling)
- Keep copy of field readings
- QA on chemical analysis
- QC procedures for data entry in the data base
- QC control in data processing

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 to keep stakeholders informed. The choice of methods will depend on the resources available and the target audience. The TBO will need to decide the methods of transmitting such information to the users and the managers according to the set objectives and also how to respond to queries on the published information. Table 5.3 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.

It must be noted that for TBO, the stakeholders tend to be the national water authorities of the riparian states and multi-state organisations such as SADC in southern Africa. There is seldom situation where TBOs are legally responsible to end water users for water quality or water level declines. Nevertheless TBOs can play an important role in disseminating information to the general public and in advocating for appropriate water management strategies in cases where monitoring reveals significant trans-boundary impacts.

Table 5.3: Examples of information products for different stakeholders

Target Audience	**Information outputs required**	**Dissemination methods/channels**
Water Managers	■ Quantity and quality of groundwater available for allocation; ■ List of groundwater users and permit holders ■ List of non-compliance by water permit users and actions taken ■ List of complaints by groundwater users/ actions taken ■ Location and yield of well fields/ boreholes	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 discharge wastes into the water	■ Water allocation decisions ■ Consumption patterns by all the users ■ Revenue raised from permits and how it is used	Regular status reports such as a leaflet/ newsletter
Political stakeholders such as government officials	■ Summarised information on the status of the groundwater water management and allocation	Half-yearly or annual report

Information Types and Characteristics.

There is a wide range of information types that can be selected and used for different purposes. (see Table 5.4 below).

Table 5.4: Information types and their characteristics

Information Type	Characteristics
1. Static information	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 information	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 information	Processed information is information that meets a defined need and is processed from raw data.
5. Report-type information	Report-type information is a combination of text, figures and tables, organised within a set of narrative text.
6. Spatial-type information	Spatial-type information is information stored in the form of maps and is geo-referenced to a map.

Examples of Some Information Management Tools

Rapid advances in information and communication technology have enabled a number of new information management tools to be developed and thus assist (T)BOs in their 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, infrastructure, borehole sites, pollution hotspots etcetera.
- ***"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.
- ***Content Management Systems (CMS)*** use the Internet standard of presenting linked web-pages 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 (T)BO 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.

Information Management Plan

The reality of human resources and financial constraints will limit a BO's ability to collect, analyse, interpret, use and share information. Thus the BO 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 information, 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 BO. The above systematic exercise may also help BOs define the information management capacity development needs and also the possible areas where investments in technical improvements and systems can be made.

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 organization 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 Information Management Unit (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.

5.4 Benefits and cost effectiveness of monitoring

Benefits of monitoring

Monitoring is considered expensive because the return on investment is generally not visible in the short run. Yet monitoring provides important information for a sustainable management that prevents irreversible damages and associated costs (see module 8 Groundwater Hazards)

- Monitoring secures the effectiveness of management measures and as such avoids mitigation costs. An example is the impact of excessive groundwater abstraction from deep wells for irrigation on the water level of shallower wells that are usually owned by small farmers and who may then be faced with the need to drill new, deeper wells
- Monitoring provides income to the regulator as it provides the evidence for charges and penalties that are included in the regulations such as progressive rates for groundwater abstraction and penalties under the polluter-pays principle

Quantifying these impacts in monetary terms provides the opportunity to do a cost benefit analysis (CBA) for the establishment of a monitoring system and for showing that the investment of today will provide significant returns in the medium and long term.

Effectiveness

The cost-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 significantly. Monitoring accuracy for both 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.

Cost effectiveness measures may include:

- Monitoring by objectives and defining clear information needs
- Include cost-benefit analysis in the project design
- Use of data already collected in other programs
- Use of existing wells (abstraction wells and abandoned wells) as monitoring wells
- Use of indicators: water level/temperature /Electric Conductivity (EC)
- Promoting self-monitoring and self-regulation by the water users
- Effective QC and QA system with a focus on prevention

5.5 Access and exchange of national data to the TBO.

According to the “Guide of good practice – Optimization of monitoring”1, most of the data and information on transboundary aquifers are produced under national and local management policies and practices. The main challenge for the international transboundary basin organisation is that the basic data is often “dispersed, heterogeneous, incomplete and rarely comparable or adapted to the needs”. In addition, national authorities may also be reluctant to provide information, considered to be strategic, to neighbouring countries. The transboundary basin organization provides the proper framework for basin-related data management, which is often one of the pillars of its mandate.

Water resources management in transboundary basins requires organizing data production and information sharing for the various planning, monitoring, assessment, and early warning activities. In many cases, the production of the data required for resource management is insufficient. Furthermore, the sharing of data and information related to a transboundary basin is often difficult for relational, structural and technical reasons. Transboundary basin organizations are faced with two major challenges:

1. Initiate sustainable capacity development for member countries to produce the data required for water resources management, taking into account the production costs that can be high;
2. Developing procedures, tools and methods to enhance the value of the existing data to meet the information expectations of the public and decision-makers.

Therefore to fulfil the task of a basin-wide data management, the TBO has to meet proper legislative and institutional conditions. A first step is always to assess existing data sources, on-going projects and stakeholders in data production and monitoring. Afterwards the TBO has to develop common rules on data sharing.

Any sharing of data and information is only useful if the data are comparable and homogeneous. It is therefore required to check the comparability of data and possibly clarify the concepts, definitions, coding systems, units and common calculation methods to be used when exchanging information. Finally, a capacity development programme is required to qualify the human resources in operating a basin information system.

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[1] **IOH (2012):** Guide of good practices - Optimization of monitoring, Coordination of the activities of basin organizations

5.6 Global data

Global data might provide valuable information for water resources management. In 1999 the World Meteorological Organization (WMO) adopted a resolution for exchange of hydrological data and products to broaden and enhance, whenever possible, the free and unrestricted international exchange of data, in consonance with the needs of the global hydrological community and the requirements for WMO's scientific and technical programmes. Exchange of data at the regional level is being enhanced through the WHYCOS programme and at the global level WMO has established a series of data centres:

- The Global Runoff Data Centre (GRDC) established in 1988 is supported by, and located in, the Federal Institute of Hydrology in Koblenz, Germany.
- The Global Precipitation Climatology Centre (GPCC) located at the German Meteorological Service in Offenbach.
- The International Groundwater Resources Assessment Centre (IGRAC), established jointly with UNESCO in 2003, is the UNESCO Groundwater Centre, in Delft, The Netherlands.
- The International Data Centre on Hydrology of Lakes and Reservoirs established in 2007 and hosted by the State Hydrological Institute under Roshydromet in St Petersburg, Russian Federation.
- The Global Terrestrial Network - Hydrology (GTN-H) was established in 2001 as a „network of networks" to support a range of climate and water resource objectives, building on existing networks and data centres, and producing value-added products through enhanced communications and shared development. Its objective is to make available data from existing global hydrological observation networks and to enhance their value through integration.

Global Groundwater Monitoring Network

The Global Groundwater Monitoring Network, coordinated by IGRAC, facilitates **periodic assessments of changes in groundwater quantity and quality** by aggregating data and information from existing groundwater monitoring networks and regional hydrogeological knowledge. The GGMN is a participatory process that relies upon contributions of networks of groundwater experts. **The web-based GGMN** application enables users to periodically produce online maps showing groundwater change in time on a regional scale. Simplicity of the application and clear information ownership (data remains with the supplier) are guaranteed to ensure the essential support and commitment of the global groundwater community for the GGMN programme.

5.7 Reference

IOH (2012):
Guide of good practices - Optimization of monitoring, Coordination of the activities of basin organizations

5.8 Exercise

Time allocation: 2 hours.

Participants to form 3 groups.

Each group to work with one of the topics below:

1. Monitoring a dune infiltration system to protect a drinking water well field against seawater intrusion
2. Monitoring plan for an industrial site to prevent spreading of possible contaminants through the groundwater
3. Monitoring system for trend monitoring in a sedimentary shallow aquifer in river basin

Activities:

- Define the monitoring objectives and basic design parameters.
- What are the main benefits and who are the main beneficiaries of the monitoring?
- Suggestions to make the monitoring plan cost effective.
- How to assure sustainable financing?
- Who will implement the monitoring and how is the monitoring information handled to address the management objectives?

Report back of 15 minutes each group after 45 minutes.

MODULE

GROUNDWATER REGULATION, LICENSING, ALLOCATION AND INSTITUTIONS

CONTENT

MODULE 6

Groundwater regulation, licensing, allocation and institutions

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

Editorial Staff: *Vanessa Vaessen, Ramon Brentführer – BGR*
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Picture: *BGR – Bundesanstalt für Geowissenschaften und Rohstoffe, Philip Schuler*

GROUNDWATER REGULATION, LICENSING, ALLOCATION AND INSTITUTIONS

LEARNING OBJECTIVES

- To appreciate the need for regulation of groundwater within the framework of river basin organizations;
- To create awareness about the benefits of a groundwater licensing and allocation system;
- To understand how groundwater licensing and allocation systems may be implemented and;
- To consider the institutional arrangements for groundwater management.

6.1 Introduction

Groundwater regulation is required in order to control groundwater development and activities that might compromise groundwater availability and quality; to address increasing competition and conflict between groundwater users; and to control the increasing threat of groundwater pollution. Water regulation is an important groundwater management strategy that is implemented through development and implementation of a licensing and water allocation system. Groundwater regulation has provisions for issuance of water rights or water permits with accompanying conditions to any activity that may affect the quantity and quality of groundwater. Anybody granted a right or permit has therefore to ensure that his/her groundwater development or other activities that might compromise groundwater availability conforms to the permit conditions or else he/she is penalized. These standards are set and enforced by the groundwater regulatory agencies.

6.2 Regulation of groundwater within a river basin framework

Overview

It is increasingly recognized that groundwater and surface water impact on each other and that greater integration of their management is essential. However, although groundwater is recognized as being closely linked to surface water, integrated management of groundwater and surface water within the framework of river basin management has not yet been fully realized in Africa. This deficiency can be partially addressed through groundwater regulations that provide mechanisms for 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 groundwater resources, including water abstraction and use rights
- A system of wastewater discharge licenses, helping to protect groundwater against pollution
- Definition of the rights and duties of groundwater users
- Protection of user rights, of the rights of third parties and of the environment
- Requirements for the registration of well drillers based on the qualification and experience of well drillers

- Possible administrative intervention in critical situations (aquifer depletion, drought or pollution)
- Provision for cooperative interaction between groundwater administrators and groundwater users.

Groundwater regulation process

Many countries in Africa now require permits or licenses for abstraction of groundwater, discharge of wastewater and well construction activities. Catchment planning, aquifer resource planning and land surface zoning are then all subject to their meeting the requirements stipulated in those permits for groundwater conservation and protection. Any establishment that is involved in groundwater development and in activities that might compromise groundwater availability and quality has to obtain a permit or license in order not to contravene the law. The permit is issued upon application to the regulatory body that takes into account the conditions of the groundwater system and the intensity and nature of proposed groundwater abstraction or activity.

Modern groundwater regulation tends to be flexible, enabling and enforceable through the following actions:

a) **Regulation of groundwater abstraction and issuance of water use rights or permits**
Regulation of groundwater abstraction through issuance of groundwater abstraction/use permits serves as the basis for charging abstraction fees. In many countries in Africa this is flat rate for any motorized groundwater abstraction while in a few countries it is based on the volume of water abstracted.

b) **Regulation of groundwater pollution and issuance of wastewater discharge permits**
Licensing for the discharge of wastewater into the ground provides for conditions on the mode of discharge and the level of treatment required, and is designed to protect groundwater against pollution. The 'polluter-pays-principle' is normally embodied in the regulatory framework where charges are related to the pollution load discharged to the ground.

c) **Instituting sanctions for non-compliance**
Sanctions in form of penalties are instituted for those who constantly refuse to comply with the provisions of the laws and permit conditions. These penalties may range from fines to imprisonment terms, depending upon the severity of impacts and the persistence of the offence.

d) **Controlling well construction activities**
Control of water well construction activities by drilling contractors is done to ensure high standards of well construction, improved reporting on the hydrogeological conditions encountered, and reduced likelihood of illegal well construction. This is normally done through issuance of drilling permits.

e) **Catchment or aquifer level resource planning**
Provision for water resources planning with reference to surface water basins and/

or aquifer systems is sometimes done based on an inventory of water resources and of existing uses identified either as part of specific water use assessments or as part of environmental impact assessments. Such plans provide an integrated basis for the assessment of individual applications for water rights or permits and may be legally binding. All decisions on applications must be consistent with their provisions.

f) Conjunctive use of groundwater and surface water

Recognizing the role of conjunctive water use, it may be advantageous in some circumstances to have a single permit that covers, for example, both groundwater abstraction and discharge of effluent of an acceptable quality to a surface watercourse; or a single permit for surface water diversion and use coupled with recharge of an effluent of acceptable quality to the ground.

g) 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 water well 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.

h) Facilitating water-user and stakeholder participation

The participation of groundwater users and other stakeholders in groundwater management has become increasingly acknowledged and appreciated due to the realization that legal provisions are more likely to be implemented when stakeholders have a say and are actively involved. 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.

These organizations however need to be given legal status and to be integrated into broader institutional mechanisms for groundwater resource management and protection.

i) Provisions for Groundwater Monitoring

Groundwater regulation normally provides for the monitoring of the status of groundwater in terms of quantity and quality and the use of water by the users themselves, but with regular oversight compliance monitoring by the groundwater regulatory institutions at various levels.

6.3 Groundwater Licensing

Water resources have traditionally been allocated on the basis of social criteria, ensuring that water for human consumption, for sanitation, and for the production of food is given first priority.

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 available. As a consequence there is greater competition between water for drinking, irrigation, industry, environment etc.

Most countries in Africa have their water resources in public ownership, with government having the overall responsibility for resource management. The right or permit 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 regulatory authority. A ‘water right’ or a “water permit” usually constitutes the right to use (but not ownership of) the water itself. Authorizations to abstract and use groundwater are instrumented through permits, licenses, concessions or authorizations, generally called here ‘water rights’ or “water permits”.

Need for a groundwater licensing system

A licensing system for groundwater (through issuance of permits to abstract and to use groundwater) is aimed at regulating interdependencies among water users. It is introduced as a means to:

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

However the development of a comprehensive licensing system has wider benefits, since it provides a sound foundation for the development and protection of water resources and for the conservation of aquatic ecosystems. Certain other steps towards more integrated water resources management can only be effectively tackled when a groundwater licensing system has been effectively established:

- 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.

Although the existence of groundwater licensing systems do not guarantee water supply of a given quantity and quality, they offer water users greater supply security for investment purposes and a valuable asset as bank collateral to obtain development credits.

BOX 6.1 AN EXAMPLE OF A PERMIT (FROM UGANDA)

GROUNDWATER ABSTRACTION PERMIT

(The Water Statute, No. 9 of 1995, and the Water Resources Regulations, 1998)

In exercise of the powers conferred upon the Director by sections 5, 18 and 29 of the Water Statute, 1995; and in accordance with regulation 16 of the Water Resources Regulations, 1998, this is to grant a Groundwater Abstraction Permit

Number:

To :

To abstract water in accordance with the terms and conditions of this permit The permit is granted in the terms and conditions set here in the Annex, which is part of this Permit, and under all other terms and conditions set in the Water Statute, 1995 and the Water Resources Regulations, 1998

This permit is granted for a period not exceeding 5 year(s), which come into force on

Monday, November 21, 2005 until Wednesday, November 24, 2010.

Issuance Date: Monday, November 21, 2005

…………………………………………………………………………

DIRECTOR OF WATER RESOURCES MANAGEMENT

Setting conditions for water permits

All water permits must be issued with conditions. The set conditions fall into two categories namely: standard conditions and special conditions. Standard conditions are derived from the law and apply to all permit holders irrespective of their location and the nature of activity. Special conditions are specific to the applicant and depend on the type of activity to be regulated, the amount of groundwater to be abstracted, the nature and size of the aquifer or area and the special interests to be protected. An example of a Groundwater Abstraction Permit is indicated in Box 6.1 above.

Table 6.1: Terms and conditions usually specified in groundwater abstraction and use permits (modified from GW-Mate Briefing note 5)

TERM OR CONDITION	COMMENTS
duration of right/permit	This requires flexibility but ranges between 1 to 5 years
points of abstraction and use	These need to be specified as they may vary
purpose of use	Important to distinguish consumptive and non-consumptive use
rate of abstraction	This needs to be specified as it is the basis of compliance monitoring and also charging fees
specification of works	Details of depth, diameter, completion, sanitary protection, etc need to be stated.
environmental requirements	These deal with any provisions needed to protect the resource or ensure no adverse environmental impacts are caused by groundwater use under the permit
permit fees	Fee are usually paid for using the water under the permit
record of transactions	Obligation to declare and submit information on groundwater use and any other information collected as part of the permit
loss or reduction of right	Forfeiture without compensation for non-use or non-compliance
suspension or cancellation of right or permit	Indicates the circumstances under which the permit may be suspended or cancelled as a penalty or in emergency without compensation
review of right/permit	States the needed periodic adjustment with compensation according to supply/demand
renewal of right/permit	States requirements and conditions for renewal of the permit

Implications of a groundwater licensing system

Water abstraction and use rights/permit systems 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. 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 6.1 summarizes the main conditions that are usually specified in groundwater abstraction and use rights/permits.

6.4 Groundwater allocation

Main criteria of allocation

Water allocation objectives normally 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:

- Flexibility in the allocation of water, so that the resource can be reallocated from user to user, 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.
- Equality in the allocation process is important. Prospective users should perceive that the allocation process provides equal opportunity gains from utilizing the resource to every potential user.
- Political and public acceptability, so that the allocation serves publicly approved values and objectives, and is therefore accepted by all 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.

Administering a groundwater allocation system

Groundwater allocation should be handled together with surface water allocation under a single water allocation system. Where administration systems are separate for various reasons, attempts should be undertaken to integrate them, or if necessary, to introduce coordinating mechanisms. In this way physical interactions between the two water bodies are taken into account in water allocation.

River basin organizations need to introduce this ‘conjunctive’ practice of allocating water, taking into account both surface and groundwater resources. To be effective, the responsibilities of the RBO require both understanding and management of groundwater and aquifer recharge events and linked actions.

Table 6.2: Special considerations related to groundwater licensing (modified from GW-Mate

CONSIDERATION	COMMENTS
Technical	
■ groundwater quality concerns	Possible effect of new abstraction and impact of wastewater discharge have to be considered
■ level of surface water connection	Connection between groundwater and surface water 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 business	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 when 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

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

- The limits to acceptable use of groundwater are clearly specified, usually by specifying a maximum drawdown level in the aquifer; and
- The order of priority of use by conjunctive users (i.e. of both sources) is determined with regard to other users who have only one source.

The table 6.2 summarizes main points to be considered when administering a licensing and water allocation system. The level of surface water connection should be assessed in terms of effects on third parties (users downstream), and to ensure watercourse baseflow, protection of environmental ecosystems, and sustainability of springs. This therefore requires consideration of both surface water and groundwater during groundwater allocation.

BOX 6.2 CRITICAL CONSIDERATIONS DURING GROUNDWATER ALLOCATION

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 licensing and allocation 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

To ensure better compliance of groundwater users, stakeholder participation should be enhanced in parallel with information management to give transparency to the allocation process. Monitoring of water use and water resources is also critical for 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, assessing and monitoring of applications;
- **Information System:** based on adequate software to manage applications, permit issuance, 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 6.2) include the complexity of the implementation process, and the enabling environment that may facilitate user compliance.

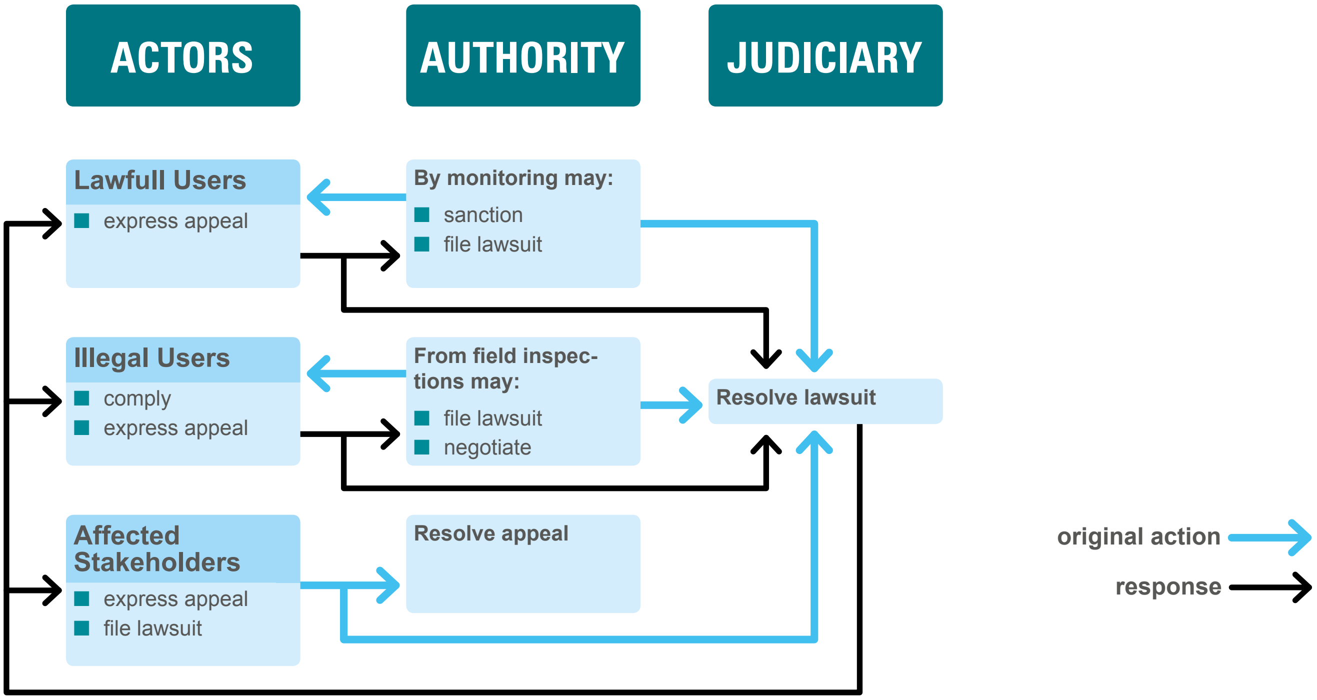

Figure 6.1: Main interactions on the introduction or consolidation of a groundwater rights system (adopted from GW Mate Briefing note 5)

In order to ensure that there is an effective groundwater licensing and allocation system, regulatory and enforcement agencies need to pay special attention to key issues as highlighted in Box 6.3 below.

BOX 6.3. KEY PRIORITIES ISSUES FOR REGULATORY AND ENFORCEMENT AGENCIES

- Sufficient staff of adequate capability to enforce regulations and make appropriate assessments;
- Laws which are practical, enforceable and are based on accurate knowledge of resource management and environmental impacts
- Staff who are knowledgeable about good management practices and have appropriate scientific knowledge
- A sense of ownership on the part of stakeholders so that they accept the monitoring, enforcement and regulation procedures; ownership can be built through use of awareness raising techniques and participatory management
- Adequate financial resources to support the staff and operations, and transparency in financial management, to minimize regulatory failure;
- Selecting meaningful indicators for technical, economic and social issues and appropriate benchmarks;
- Designing and implementing a program of legal education and awareness building – for the regulating parties and public at large. This contributes to putting legal instruments into practice and ensuring that the use of regulatory instruments is not limited to specialists.

6.5 Main interactions in groundwater licensing and allocation system

In managing a groundwater licensing and allocation system, the most important actor is the applicant or holder of a water-use permit (Figure 6.1). 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 eventually be needed.

6.6 Allocation of non-renewable groundwater resources

In the case of non-renewable aquifer systems, implementation of a groundwater abstraction rights system is a 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 an initial review and then 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 organizations could take the place of more legally formalized abstraction permits.

Many major aquifers containing large reserves of non-renewable groundwater are transboundary, 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 harmonization of relevant groundwater legislation and regulations, particularly the groundwater rights systems.

The water allocation system should take special consideration 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 are left in the aquifer system;
- The difficulties in estimating the impacts of drawdown on 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.

6.7 Institutional framework for groundwater management

An enabling environment is required for effective management of water resources, including groundwater. The institutional arrangements for management of groundwater resources will bring clarity to the roles and responsibilities of the national and/or provincial institutions responsible for groundwater 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.

Given the problems created by growing water scarcity and pollution, regulatory systems vest all water resources in the state, or recognize the state's superior right to the management of water resources. Thus groundwater has been declared as a 'public good' thereby turning the former owners of groundwater into users, who must apply to the state for a water abstraction and use rights/permits. Since 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. Current legislation tends now to require water resources planning at the level of an entire aquifer or river basin.

An idealized structure and functions for a government agency acting as a groundwater guardian is suggested in figure 6.2. A separate management organization that deviates for the idealized structure may however be established for management of very large aquifers. In most cases groundwater management will be fully integrated into organizations with responsibility for both surface and groundwater. The historical problem that groundwater management receives inadequate attention under this arrangement needs to be addressed.

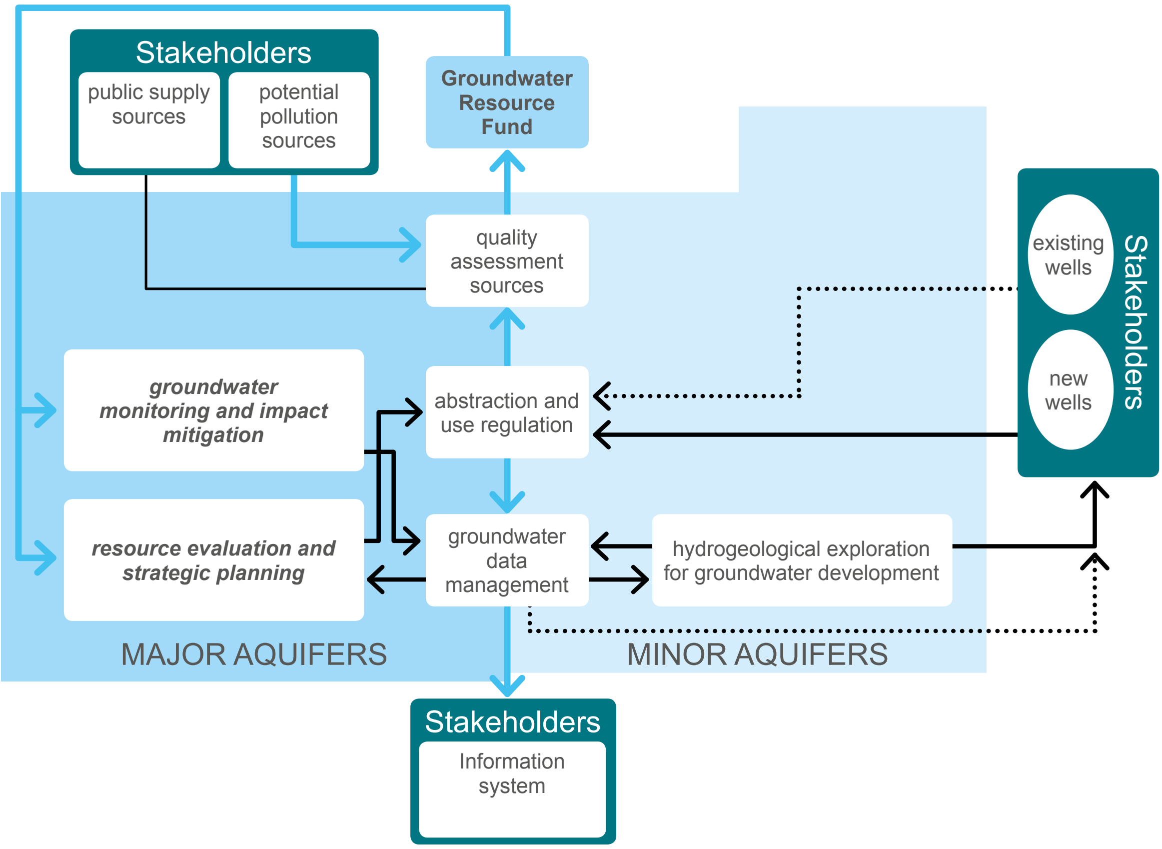

Figure 6.2: Idealised structure and functions for a government agency acting as groundwater guardian. (Foster & Kemper, 2002-06)

6.8 Implementing a groundwater regulatory system

Successful implementation of groundwater regulatory system (table 6.3) depends on a number of factors including:

- The administrative set-up and the level of training of water administrators
- A clear understanding of the institutional roles and functions at all relevant levels
- An adequate level of public awareness and acceptance of legal provisions
- Political willingness to promote and attain sustainable groundwater management.

An administrative set-up suited to national or state conditions should support groundwater regulation:

- 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; ie. the role of the local authorities in water resources management (since they represent local interest); the establishment of intermediate institutions (aquifer management organizations) that have legal power in relation to specified aquifers and with adequate representation of different water-user associations, various water-use sectors and a clear-cut relationship with the local water authority.

Table 6.3: 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.

6.9 References and further reading

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6.10 Exercises

To promote good discussion to consider what elements of the legislation, regulation and allocation could be undertaken at regional TBO level and what at national BO level. Is the regional level useful to agree common policies/ frameworks and the country level BOs where the application will take place?

EXERCISE 1

IMPLEMENTING GROUNDWATER REGULATORY AND ALLOCATION SYSTEMS

Purpose

To share experience in implementation of groundwater regulatory and allocation systems at national and transboundary levels

Activity: break into two groups and discuss:

1. Regulation of groundwater at national and transboundary levels highlighting differences and similarities
2. Key considerations during development and implementation of an allocation system for transboundary groundwater resources

Duration: 45 minutes

EXERCISE 2

ENFORCEMENT OF GROUNDWATER REGULATIONS AND PERMIT CONDITIONS

Purpose

To share experiences in enforcement of groundwater regulations and permit conditions

Activity: break into two groups and discuss:

Enforcement of groundwater regulations and permit conditions at national and transboundary levels highlighting possible enforcement mechanisms to employ, challenges expected at each of the levels and how can they be addressed.

Duration: 45 minutes

MODULE

7

THE ROLE OF STAKEHOLDER PARTICIPATION AND COMMUNICATION IN GROUNDWATER MANAGEMENT

CONTENU

MODULE 7

The role of stakeholder participation and communication in groundwater management

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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THE ROLE OF STAKEHOLDER PARTICIPATION AND COMMUNICATION IN GROUNDWATER MANAGEMENT

LEARNING OBJECTIVES

- To appreciate the essential role of stakeholders for groundwater management.
- To understand ways to categorise stakeholders and to identify different stakeholder interests and responsibilities.
- To receive guidance on maintaining groundwater awareness and stakeholder participation over time.
- To understand the importance of advocacy and proper communication to support groundwater management.

7.1 Why Stakeholder Involvement?

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 stakeholder interest in, and acceptance of, the groundwater management system is a prerequisite for its successful implementation.

The key differences between management of surface water systems and groundwater systems are that in groundwater systems:

- The users are often in control of the “on-off” switch and can pump water from privately owned wells when they want without reference to a controlling authority. Surface water on the other hand is often distributed via a central authority.
- There may be many thousands of private boreholes and users within a groundwater management area, which makes management and control by a central authority impossible.
- For this reason, the task of managing and monitoring the aquifer must involve the users, supported by the catchment / aquifer authority.

Stakeholders typically want to participate because they have an interest in the resources of a particular aquifer that they want to protect or advance. This may be because they use (or want to use) groundwater, or because they practise activities that could cause groundwater pollution, or because they are concerned with groundwater availability and environmental impacts due to their own or other’s activities.

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. Benefits that arise from stakeholder participation are:

- more informed and transparent **decision-making**;
- **conflict prevention** by development of consensus and information sharing;
- **social benefit**s, because it tends to promote equity among users;
- **economic benefits**, because it tends to optimize pumping and reduce energy costs;
- **technical benefits**, because it usually involves stakeholders in maintenance and leads to better estimates of water abstraction;
- **environmental benefits**, because specific local concerns are addressed and incorporated into the management
- **management benefits**, because they trigger local stakeholder initiatives to implement demand and supply measures and reduce the cost of regulation.

What specific benefits from stakeholder participation can you identify in your Basin?

Additionally, and very importantly, participatory management of highly stressed aquifers should **help in the implementation of otherwise unpopular decisions** such as jointly changing groundwater consumption patterns in the long-term communal interest.

Other stakeholder decisions may also relate to land use, waste management, and protected areas. By involving stakeholders, this helps to improve overall governance of the resource by giving credibility and accountability to the management process.

Stakeholder involvement should be seen as an on-going, long-term process that adapts to the contextual conditions and needs, and changes therein. Stakeholders, particularly groundwater users, will tend to have a long-term interest in protecting the aquifer and ensuring that groundwater use is sustainable. Their interest in management is usually deeper than ‘catchment managers’ who may have a job definition that includes managing the aquifer, but whose livelihoods and not dependent on the groundwater that they manage.

It is in this context that the catchment or aquifer ‘authority’ should consider and value the input from and the needs of the stakeholders.

7.2 Who does Stakeholder Participation and how is it done?

The participation of stakeholders can take many forms. At its most successful level it can occur even without formal organization – and there are several examples of groundwater being managed at local level by strong community values and norms without groundwater user associations or the initiative of a water resource regulatory agency. This could be called autonomous stakeholder participation.

However in most cases some sort of external support may be needed to ensure stakeholder mobilisation and participation in decision-making bodies and processes. In the theory, there is a distinction between different levels of participation, from nominal consultation to genuine involvement of the stakeholders (Table 7.1)

Stakeholder mobilisation may take place at any time for a variety reasons, and it is important to be clear on the purpose of stakeholder mobilisation. It may be for information gathering; to assist with compliance and water level monitoring; or to carry out various management functions in their local area. It is important to be honest with oneself as well as the stakeholders as to what the expectations are. Unfortunately, stakeholder participation is often carried out just to comply with donor and other procedural requirements.

Despite the long and difficult process of mobilising and organising the stakeholders, the largest challenge is probably to maintain active 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 may have to take time from their own work activities to participate. In this regard, it is a responsibility of the water management agency to provide and present concrete incentives and benefits of being involved in the water resources management process in the river basin.

Long-term effective participation will require communication of information and accessibility and transparency regarding the groundwater situation and data resulting from monitoring and all other aspects of water management in the area. This will need to be presented in formats suitable for easy interpretation and may embrace a variety of target groups as stakeholders in groundwater management who are not experts. These may include government departments, politicians, local government as well as community representatives.

Table 7.1: Types of stakeholder participation

	Characteristics
Manipulative participation	Participation is simply a pretence
Passive participation	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)

Some mechanisms that build commitment are:

- Make complex groundwater situations understandable through proper communication (see section 6)
- Empower stakeholder organizations through having decision power over their own local water resources and through information
- Ensure all stakeholders are properly represented in higher-level management bodies
- Support the implementation of clear, equitable, and easily enforceable local groundwater management regulations

What experiences have you had in dealing with stakeholders in groundwater management?

Has your catchment authority established any formal stakeholder management groups? What have you learned about stakeholder participation from that exercise?

The key lesson from experiences all over the world is that groundwater management is more about mobilising (enabling and nurturing) users and other stakeholders to manage their interactions among themselves and with "their" aquifer than a top-down resource management.

Another lesson is that the stakeholder engagement strategy is an integral and continuous component of groundwater management and is not a once-off event.

7.3 Identification and Assessment of Key Stakeholders

A key purpose of stakeholder analysis is to ensure that the groundwater managers and the stakeholders adequately understand the stakes of different interest groups, including their expectations and skills. It should be linked to the development of an institutional process of long-term engagement with stakeholders in groundwater management (see section 7.4 for examples).

Step 1: Identification and grouping of key stakeholders in the groundwater management area[1].

- Who are the potential beneficiaries?
- Who are or might be adversely impacted?
- Have vulnerable groups[22] 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?
- Are there important stakeholders outside the area?

A common problem when dealing with stakeholder identification is to define the groundwater system boundaries.

Water affects society in many ways and the socioeconomic development of a major aquifer in a country may affect stakeholders on the national and even international scale. An example is the establishment of a drinking water bottling company in the area. It will have local as well as national and even potentially international stakeholders.

Step 2: Assess stakeholder interests and the potential impact of a project or a development pathway 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 7.2). Questions to answer in order to assess the interests of different stakeholders or stakeholder groups include:

- What are the stakeholder expectations?
- What benefits are likely to result for the stakeholder?
- What resources might the stakeholder be able and willing to mobilize in a process of developing management and adaptive capacity?
- What stakeholder interests conflict with groundwater management and IWRM goals?
- Which stakeholders may have antagonistic interests?

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.

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[1] This could be a (sub) river basin, an aquifer area, or any identified area with particular need for intensified groundwater management.

[2] These may be poor people or people particulary dependent on groundwater or groundwater dependent ecosystems.

Table 7.2. Potential range of interests and activities of groundwater stakeholders. GW-Mate 2010

Sector / Stakeholder	Water-use Classes	Polluting Process	Other Categories of Stakeholders
Rural / Farmers	domestic supply; livestock rearing; subsistence agriculture; commercial irrigation.	household waste disposal, farmyard drainage; intensive cropping (pesticide / herbicide pollution); wastewater irrigation.	drilling contractors; educational establishments; professional associations; journalists/mass media; relevant government entities.
Urban / Municipalities / Householder	water utilities; private supply	urban wastewater; disposal/reuse; municipal landfills.	
Industry & mining	self-supplied companies.	wastewater discharge; solid waste disposal; chemical/oil storage facilities	
Tourism	hotels and campsites.	wastewater discharge; solid waste disposal.	
Environment	river/wetland ecosystems; coastal lagoons.		

Step 3: Assess stakeholder influence and importance. In the third step, the task is to assess the influence and importance of the stakeholders identified in Step 1 and categorise them accordingly (Table 7.3). Influence refers to the power that the stakeholders have, such as formal control over the decision-making process or informal in the sense of hindering or facilitating implementation of groundwater management processes.

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

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

Both the influence and importance of the different stakeholders can be ranked along simple scales and mapped against each other. This exercise is a necessary step in determining the appropriate strategy for the involvement of the different stakeholders.

Some consideration needs to be given to the position of those that do not (yet) use groundwater. It will often not be socially and practically possible to exclude current non-users from using groundwater in the future, and management arrangements that define the rules of access for new users are required.

Could you give examples of each of these categories in your basin area?

Table 7.3. 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 may not be those of groundwater management. They may be a risk to progress, but could also present an opportunity if incentivised.	**D. Low Interest/Importance, Low influence** These stakeholders are of least importance to the project.

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

7.4 Institutional Mechanisms for Stakeholder Participation in Groundwater Management

Stakeholder participation in groundwater management can take place at various territorial levels, ranging from individual water wells to an aquifer system and even to the river basin or national level. Some examples of water management institutions for stakeholder involvement in Africa are given in the following paragraphs.

Water user associations (WUAs) in local communities help in distributing groundwater from wells or springs to their members for domestic uses and irrigation, collecting operational charges and settling water disputes in accordance with customary rules. In principle, the WUAs represent the interests of the users and ensure equitable access, and reliable and cost-efficient water supply. Often the remit of WUAs is limited to operation and maintenance of the water supply and any distribution systems, and only weakly linked with the management and protection of the resource. It is important to broaden their mandate (or to create special organizations) to address groundwater resource management and protection with recognized legal (formal or informal) rights and duties, and to vest them with judicial personality, so as to facilitate their work and enable contractual relations with local water and land regulatory agencies. In some cases, WUAs relate to both surface water and groundwater sources, and here the specific rights and duties of groundwater users must be clearly defined. Also, the WUAs need to have certain autonomy in relation to local groundwater management, while also adhering to policies and regulations of higher-level water management organisations, such as the river basin organisations.

Other forms of local organisations of water users are groundwater user groups (GWUGs) and village water-supply councils (VWSCs). They often play a key role for irrigation water provision and drinking water-supply protection (and in some cases sanitation) in rural areas, and their roles can be extended to manage demand and enhance supply. In the case of small aquifers and/or situations with weak government institutional capacity, non-governmental organizations (NGOs) can be of great help for promoting stakeholder participation and groundwater management, but they need to be supported or overviewed by the local or regional water resources agency.

In the case of larger high-yielding aquifers, which often include more diverse interests, higher-level stakeholder participation through an aquifer management organization (AMOR) is required and should include all local WUAs, GWUGs and VWSCs, and other main categories of stakeholders. AMORs should also include representatives of national and/or local (ground)water resource agencies and of the corresponding local government authority, and in some circumstances can (and should) be formed at the initiative of the national water administration, especially when zones with critical groundwater status are declared.

Identification and delineation of groundwater management areas (GMA)
Regardless of the size of the aquifer, stakeholder participation needs to be defined around coherent groundwater bodies. The delineation of appropriate boundaries for a groundwater body (groundwater management area) for an AMOR, and even for simpler forms of organization in smaller aquifers, is critical. This will not always be straightforward, especially for large aquifer systems with low hydraulic gradients, and sub-division into groundwater bodies will need to be done as logically as possible. When the so-defined groundwater body is part of a larger aquifer system, it is important to establish institutional mechanisms to integrate groundwater management and stakeholder participation at the system level.

Which bodies and (ground)water management units are applicable to your Country / Basin?

Since most shallow aquifer systems are interconnected with surface water systems, AMORs (or equivalent organisations) should be represented in river basin agencies – something that at present hardly ever occurs. Moreover, representatives of the various main categories of groundwater stakeholders should be called upon to comment on high-level policy decisions at national river basin commission level. In Figure 7.1, a schematic of the institutional framework for Zimbabwe, based on river catchments, shows the various levels of representation and degrees of interaction, which can vary somewhat according to the specific case. Representation of stakeholders at higher level is governed by official procedures in the WUAs and the Catchment Councils.

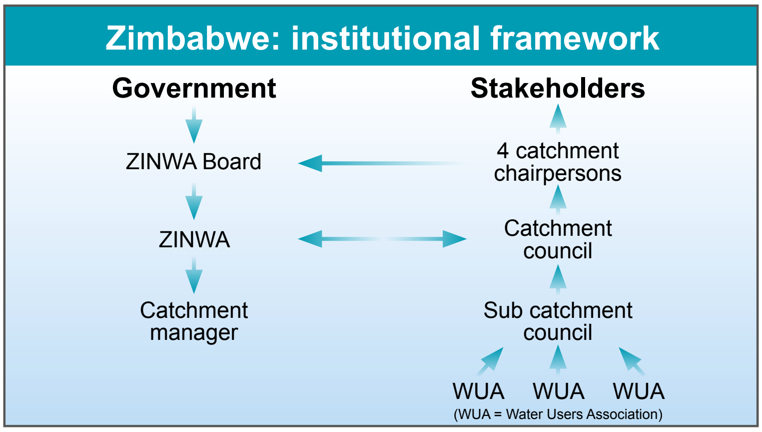

Figure 7.1: An example of institutional framework for stakeholder participation

7.5 Stakeholder functions in Groundwater Management

There are many ways in which stakeholders may participate in the management of groundwater resources and aquifer systems (Table 7.4). Some measures are relatively easy to implement and enforce locally (maintaining distance between water wells or bans on certain types of crops). Other measures require more coordination (like monitoring, setting targets) and will be easier to implement if AMORs, GWUGs, WUAs (and local NGOs acting on their behalf) are recognized and supported by the local (ground) water resource agency and by the user communities.

Table 7.4: Functions commonly performed or supported by stakeholders in participatory schemes of groundwater administration and management

Stakeholder functions in Groundwater Management	**Level at which function performed**		
	Water User Association	Water Mgmt Agency	National Authority
Maintain GW supply / distribution	☺		
Collect water use charges	☺		
Groundwater monitoring	☺	☺	
Make rules on water use	☺	☺	
Policing of groundwater use	☺	☺	
Implement GW protection		☺	
Participate in setting targets		☺	
Settle groundwater disputes		☺	☺

7.6 Who are Groundwater Stakeholders for Transboundary Basin Organizations?

The key stakeholders for groundwater management in transboundary basin organizations are usually very different from the key stakeholders in an internal or national catchment authority. Internal catchment authorities will normally interact with various groups of groundwater users and these then are the communities that will become involved in the various stakeholder participatory management organizations, at various different levels and scales.

For TBOs, there is almost never any direct link or interaction with actual groundwater users. The stakeholders in transboundary groundwater management will almost always be the national water authorities in the riparian states and there will most likely be direct interaction with such authorities on transboundary groundwater management issues. Even at catchment council and sub-catchment council level, there will probably be very little or no direct interaction with the TBO.

Nevertheless TBOs have a vital role in transboundary groundwater management since they can in the first instance serve as a formal conduit for reporting any transboundary impacts of groundwater abstraction or groundwater pollution in riparian states. The

TBO can provide an official legally constituted forum where national groundwater authorities can bring such issues, and where the resolution of such issues can be aired.

The TBO provides an appropriate institutional edifice where transboundary groundwater management can take place through such instruments as:

- maintenance of a transboundary database for the affected aquifers,
- planning instruments and guidelines on monitoring abstraction, water levels and water quality,
- transboundary interactive groundwater models for the affected aquifers
- setting abstraction allocations and effluent discharge limits and
- providing a forum for resolving disputes.

7.7 What is Communication and why is it important in Groundwater Management?

Are groundwater communication materials produced in your basin clear enough for policy makers, decision makers and other stakeholders?

Communication goes beyond information management and deals with all the necessary interactions between the stakeholders in groundwater resources management.

Here we are dealing mostly with the issue of communicating and consulting on groundwater with stakeholders in order to support their participation in local and broader management of the resource.

There are two key types to communication for stakeholder participation in groundwater management:

- The first relates to generating a clear understanding of the groundwater resource, how it exists, how it gets recharged, how it responds to abstraction, how it responds to pollution etc. This type of communication is mostly educative so that stakeholder better understand the resource that may well underpin their livelihoods.
- The second is focused on informing the stakeholder who are participating in groundwater management (especially those using the resource), on the results of their monitoring of water levels, their compliance with abstraction allocations, the quality of their groundwater resource, the recharge. This ensures their continued interest in helping to manage the resource because they can see the effects of their participation in management and in enforcement.

A fundamental challenge is to convey and discuss 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 "the groundwater resource is infinite compared to its abstraction" and "the pumping of groundwater has no downstream effect". The groundwater professionals have to communicate an invisible resource to the local user and the policy level stakeholders ("out of public sight, out of political mind").

The key concepts in groundwater communication are:

- The stakeholders are not groundwater experts and have different backgrounds and interests. In communicating the groundwater message, it should be realized that there are different perceptions, different interests and views among the stakeholders and this should be kept in mind when designing a communication strategy and material (figure 7.2).
- The image of groundwater changes. 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 are not introduced effectively (or only partially) the stress on the resource remains. Since the resource is invisible and the physical processes not well understood, the water managers and users may develop negative perceptions in which groundwater is linked to problems and constraints. Groundwater experts are usually called in to evaluate the resource when problems arise and active management becomes essential to assess the technical and hydrological feasibility of management options. This can be addressed through early and participatory communication and dialogue with stakeholders by understanding specific issues and presenting targeted information on groundwater recharge, flow and discharge for the area in question in a simple way using graphics and/or model simulations, which can be understood by non-groundwater professionals.

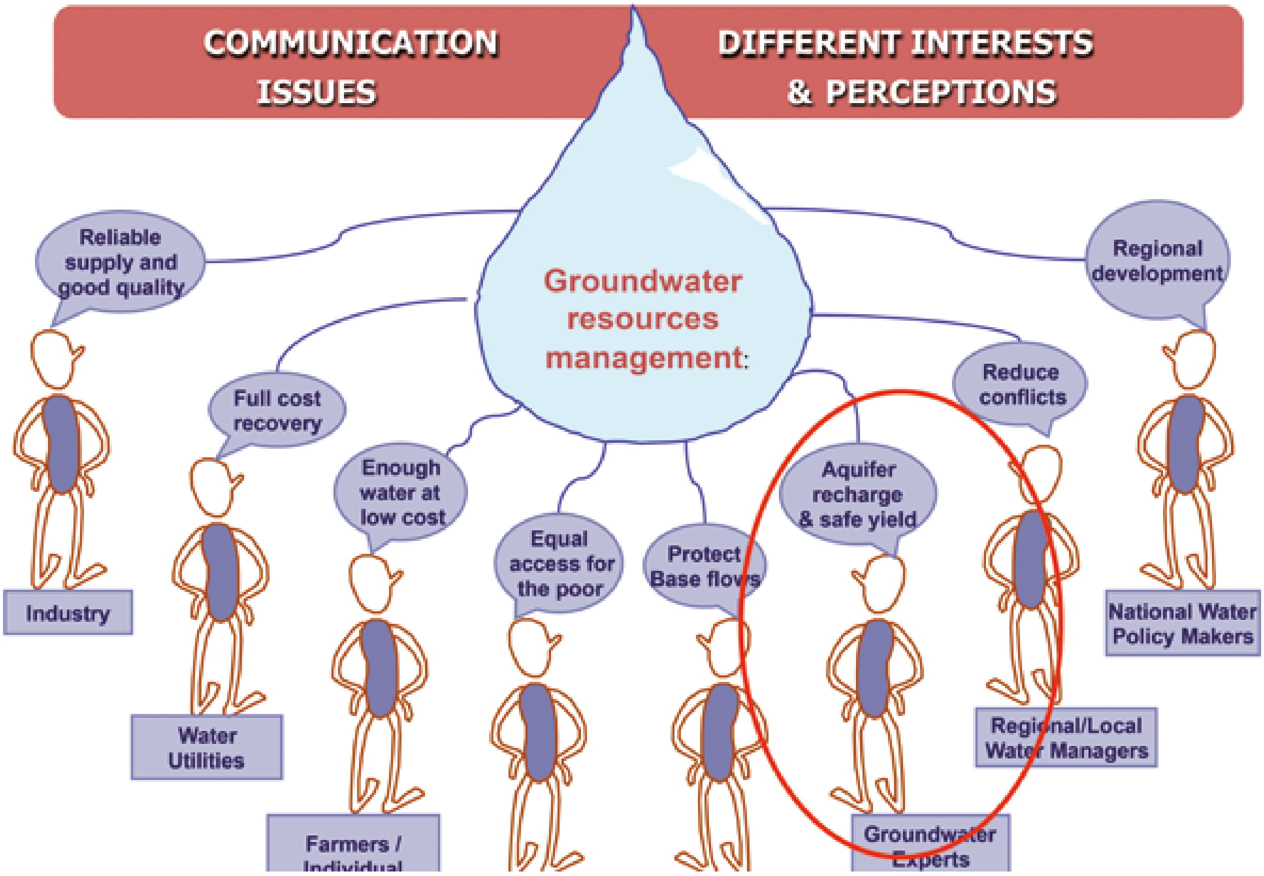

Figure 7.2 Communication with stakeholders: Different interests and different perceptions

The different communication methods reflect these conditions:

- 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
- internet communication
- exhibitions
- others - training, teaching, entertaining

There is wide range of materials available for the different methods of communication ranging from books, papers, reports to flyers, brochures, notice boards, films or animations and other audio-visual material. 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 methods and materials, 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 (Figure 7. 3)
- Animations and videos: such as The Water Channel, which contains a large number of videos on water management, including over 20 on groundwater[3]

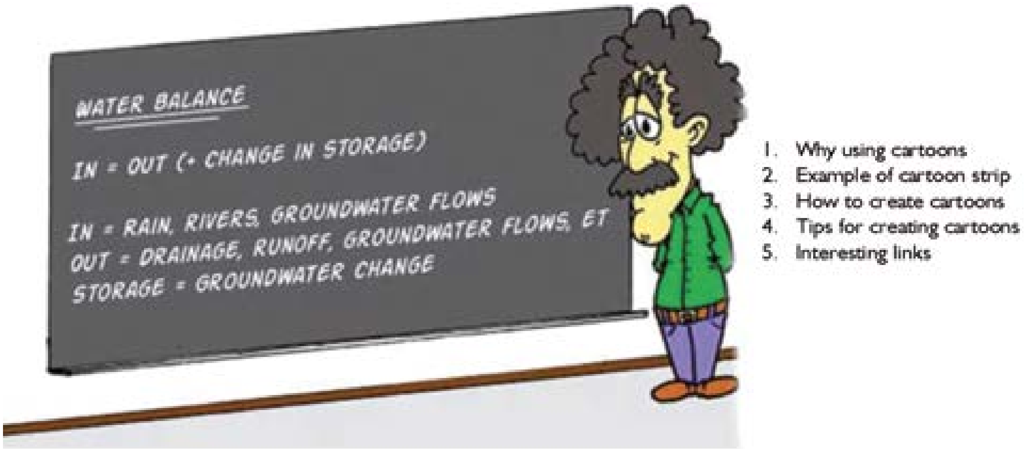

Figure 7.3 : Cartoon from website Know With the Flow: ***http://www.knowwiththeflow.org/***

Communication skills are essential in the process and are concerned with how we act and behave in our communication. They include oral presentation, written presentation and non-verbal communication.

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[3] http://www.thewaterchannel.tv/

The material in a presentation should be concise, to the point and tell an interesting and relevant story to the stakeholders. 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 - your body movements express what your attitudes and thoughts 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 and interaction you are involved in

7.8 Further reading

Cap-Net, 2008,
Integrated Water Resources Management for River Basin Organisations
http://www.cap-net.org/node/1494

GW•MATE, 2010,
Briefing Note 2, 6 and Briefing Note 7
http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTWAT/0,,contentMDK:21760540~menuPK:4965491~pagePK:148956~piPK:216618~theSitePK:4602123,00.html

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

7.9 EXERCISE

Stakeholder Participation in Groundwater Management.

- The City of H has not been able to supply municipal water to a low-density suburb for 10 years due to degradation of the distribution network.
- Most (75%) residents have resorted drilling boreholes for domestic water supply and other uses, sometimes without permits. There are no controls on abstraction and the total abstraction is not known.
- In this area, there is commercial groundwater use for 1) a landscape nursery / lawn seller, 2) a brick factory and a sand / gravel washing plant and 3) two bulk water sellers, who sell groundwater to local residents and beyond for $10 per m3 delivered.
- In addition, an unlined municipal landfill receiving unsorted waste located on the edge of the area is potentially polluting the groundwater.
- Water levels have declined such that most shallow (<30m deep) boreholes have dried up. Well yields and water quality have declined in most areas.
- Many residents have to buy water from the bulk water sellers.
- The groundwater system is an unconfined fractured aquifer in crystalline rocks, with limited storage and uncertain recharge.
- The scientific community has indicated that groundwater use must be reduced by 50% to achieve a stabilization of aquifer water levels.
- A hydraulically coherent aquifer management area (AMA) has been designated by the catchment council.
- The Stakeholders are *(Course participants are allocated to play the roles of the various stakeholder groups)*
  - The catchment council responsible for all water management in the catchment
  - The commercial users of groundwater
  - The water sellers
  - The residents as domestic water users
  - The scientific / technical community
  - The city authorities
- Each stakeholder group must prepare a list of their three (3 only) priority issues and justify these. (5 minutes per stakeholder group; no debate at this time: 30 mins total)
- Each stakeholder group must offer one (1 only) preferred solution to each of their key issues and explain how this will help achieve the desired goals of both water supply and aquifer protection. Issues of monitoring and compliance must be addressed in the solutions offered. (5 minutes per stakeholder group; no debate at this time: 30 mins total)
- General Discussion Debate of the problem, issues raised, solutions offered etc. (30 minutes to 1 hour – depending on facilitator.)
- After the general discussion, each stakeholder group to prepare a short document on the particular roles of that stakeholder group in future management of the groundwater resource: determining allocation; prioritizing use types; supporting management costs; monitoring (abstraction compliance and water levels); planning management and development; communication and information dissemination. (1 to 3 pages) – to be done in the evening and feedback the next day: 5 minutes per stakeholder group.

MODULE

8

GROUNDWATER HAZARDS

CONTENT

MODULE 8

Groundwater Hazards

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

Editorial Staff: *Vanessa Vaessen, Ramon Brentführer – BGR*

Layout: *ff.mediengestaltung GmbH, Hannover, Germany*

Picture : *BGR – Bundesanstalt für Geowissenschaften und Rohstoffe*

GROUNDWATER HAZARDS

LEARNING OBJECTIVES

The objectives of this module are to:

- Assess the risk of groundwater pollution and quantity impairment
- Protect groundwater from pollution and over-exploitation

8.1 Introduction

Under natural conditions, groundwater is usually potable and needs almost no treatment before distribution and use. The good water quality is a result of the protection of the soil and rocks in the unsaturated zone above the water table. They filter out bacteria and protect groundwater from contaminants on the surface. But the massive input of pollutants generated by modern agriculture, industry and lack of sanitation facilities can overburden the ability of the unsaturated zone to filter out contaminants and protect groundwater. Once a groundwater aquifer is polluted, rehabilitation is a very expensive and long-lasting task. Because of the very long time lags that might take place before a pollution impact on the resource is noticeable, good management of the aquifers, including pollution prevention activities, are of great importance.

In the case of transboundary aquifers, the sustainable use of groundwater is often hindered by the lack of legal and institutional mechanisms, hence a lack of common management of these aquifers. To enable cooperation between neighboring countries, necessary legal and institutional mechanisms as well as capacities at national level have to be put in place first. The development and implementation of appropriate legal instruments and management tools for catchment-based resource protection still constitute some of the challenging aspects regarding transboundary aquifer management. First steps to follow are the identification of these aquifers and formulation of appropriate instruments to enhance cooperation for sustainable and integrated management and use of these resources for socio-economic benefits.

This module examines groundwater quantity and quality aspects and identifies water management options to preserve and protect groundwater resources.

8.2 Groundwater Quantity: Over-exploitation

High population growth results in an increased need for water for agricultural production and industrial development, which in terms leads to more groundwater pumping globally (UNEP, 2003; FAO, 2003; Burke and Moench, 2000). Increased pumping can leads to extreme lowering of water tables. The impacts of groundwater over-exploitation are numerous and often irreversible (Figure 8.1). Direct impacts are:

1. Lowering of groundwater levels/pressures;
2. Reduction of groundwater discharge to springs, stream base flow and aquatic ecosystems;
3. Deterioration of groundwater quality (salinization) as a result of sea water intrusion in coastal aquifers and up-coning of deep saline water;
4. Land-surface subsidence;

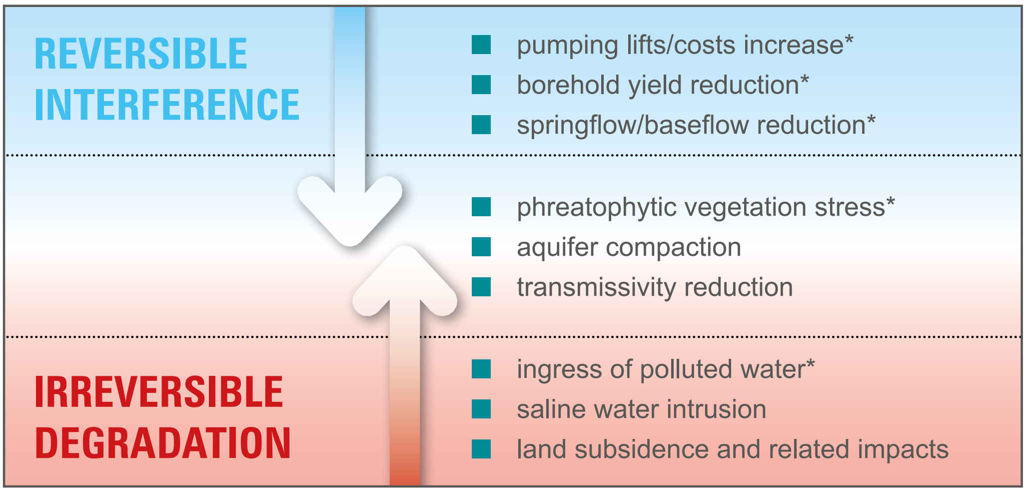


Figure 8.1: Consequences of excessive groundwater abstraction. Source: GW-Mate

* consequences vary widely in impact depending on aquifer susceptibility to change under intensive pumping – and some impacts commence well before the level at which total groundwater abstraction rate exceeds long-term average aquifer replenishment rate

Impacts of groundwater over-exploitation

Physically, aquifer overexploitation is reached whenever abstraction rates overcome the long-term recharge rate. In practice however, over-exploitation is invariably much more concerned with the consequences of intensive groundwater abstraction (Figure 8.1) than about its absolute level. Thus the most appropriate definition for over-exploitation is probably that it is reached when the overall costs of the negative impacts of groundwater exploitation exceed the net benefits of groundwater use, although these impacts are not always easy to predict and/or to quantify in monetary terms. It is also important to stress that some of these negative impacts can arise well before the groundwater abstraction rate exceeds long-term average recharge. Therefore the way in which over-exploitation is interpreted varies with the type of aquifer system involved, the key issues being the volume of exploitable storage and aquifer susceptibility to irreversible side-effects during short-term overdraft.

Lowering of groundwater levels/pressures

Lowering of the water table is a relatively slow process. In contrast to a surface water body, the water table is not lowered simultaneously within the whole aquifer but in the immediate surroundings of the well. Groundwater travel time is much slower than in surface water because of its movement through pores and fissures. When wells pump water from these aquifers, the water table near the wells is lowered in the form of a cone of depression. Within this cone of depression, the groundwater flows towards the well. If two cones of depression overlap, there is interference between the wells and the volume of water available to each well reduces. Well interference can be a problem when many wells are competing for the water from the same aquifer, particularly at the same depth.

Long-lasting pumping at high rates might cause irreversible lowering of water tables reducing the aquifer discharge to surface water bodies (Figure 8.2).

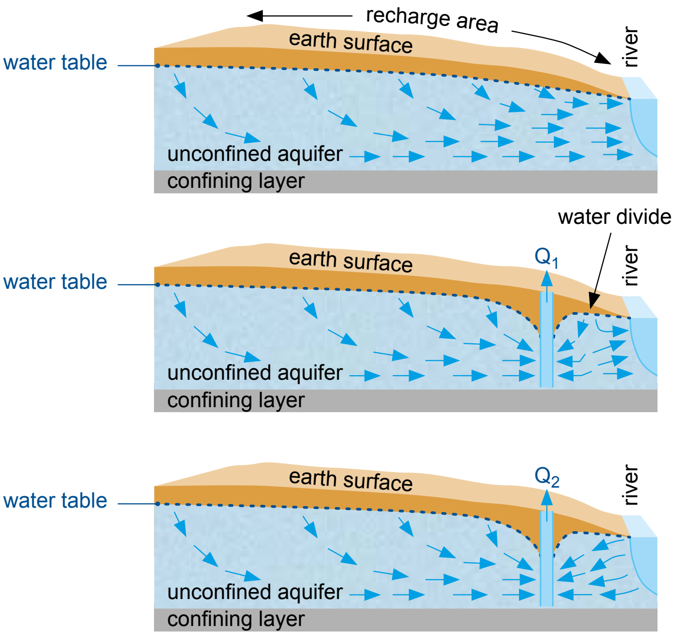
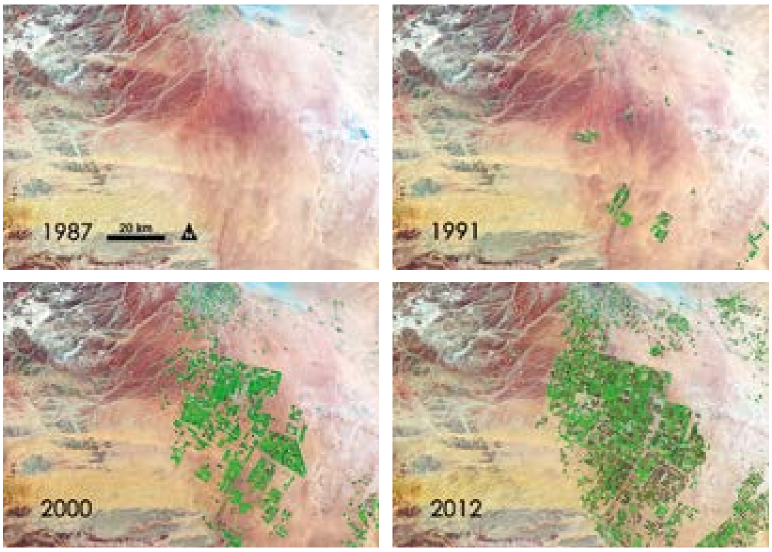


Figure 8.2 : Continuous pumping at high rates lowers the water table reducing the aquifer discharge into the river (middle). It can also lead to a change of the flow situation in which the river water reaches the well.
Source: modified from US Geological Survey

Cones of depression only appear in unconfined aquifers, which are aquifers that have direct hydraulic connection to the atmosphere. In the case of confined aquifers, it is the pressure in the aquifer that reduces in the surounding of the pumped well.

In the case of transboundary aquifers, the problem of groundwater depletion applies predominantly to deep aquifer systems, which are mostly confined. This is a major problem because generally these aquifers receive little or no recharge, e.g. in North Africa and the Middle East. Large abstraction, as is necessary for irrigation, over long periods of time leads to ever decreasing groundwater levels. This problem can be observed quite impressively in the desert of Saudi Arabia. Landsat satellite images reveal an increase of the agricultural area from 1987 to 2012 (Figure 8.3). Due to the lack of recharge, the increased irrigation has caused dropping groundwater tables (FAO, 2009). On the long term, this will also affect the groundwater resources in the neighbour countries, like Jordan. Recently Jordan also started pumping from the same aquifer to provide water for the city of Amman, and this is exacerbating the situation.

Figure 8.3: Extent of agricultural area in the desert of Saudi Arabia at the border to Jordan from 1987 to 2012. The green dots are irrigated areas using groundwater.
Source: USGS



Reduction of groundwater discharge to springs, stream base flow and aquatic ecosystems

Ground- and surface water systems often interact closely (see module 3 “Aquifer characterisation”). Groundwater provides river base flow even in dry periods and supplies freshwater ecosystems (module 3). When groundwater is pumped excessively, surface discharges as springs, base flows and seepages tend to dry out, sometimes permanently, damaging groundwater dependent ecosystems and reducing groundwater to user communities.

Subsidence

Subsidence is yet another particularly widespread impact of excessive over-pumping, with some notable examples in a number of major cities in China, Japan, Mexico and the US (Figure 8.4). Land subsidence occurs when excessive amounts of groundwater have been withdrawn from a porous aquifer. As a result, the porous aquifer materials compact and settle, resulting in a lowering of the ground surface in the area (www.sjra.net). Land subsidence can lead to many problems such as: changes in land surface elevation; damage to structures such as storm drains, sanitary sewers, roads, railroads, canals, levees and bridges; structural damage to public and private buildings; and damage to wells. Most commonly, though, subsidence is known for causing the potential for flooding.

Figure 8.4: Land Subsidence in the San Joaquin Valley, California, USA Source: www.sjra.net

Salinisation

Over-pumping fresh water aquifers in coastal areas may cause saline waters to intrude into the freshwater zones of aquifers. This occurs by up-coning of saline water and mixing with fresh water, giving rise to an irreversible aquifer salinization (see section 8.3 and Fig 8.7). It is a major problem for a great number of coastal cities around the world.

8.3 Groundwater Quality: Pollution

When considering groundwater quality and deterioration, one has to distinguish between natural and anthropogenic contamination. Under most natural conditions groundwater is potable without any treatment. There are some exceptions worldwide, where the natural groundwater has concentrations of various soluble materials at levels that are harmful to health, human, animal or plant. A very well known case is the high arsenic concentration of the porous aquifer in Bangladesh. Salinization is also an example of natural contamination, but is very often intensified by human activities. It seems that in the African context, most groundwater quality concerns are related to:

- Declining urban groundwater quality due to a combination of leaking pit latrines / septic tanks and uncontrolled effluent discharge from industry and municipal wastewater and landfill facilities.
- Salinization of groundwater due to over abstraction for irrigation leading to declining groundwater quality
- Saline water intrusion due to lowering of water table by water supply wells near / along coastal areas.

Naturally-occurring groundwater quality hazards

Groundwater becomes mineralized to varying degrees due to soil/rock-water interactions, which result in the dissolution of certain minerals and chemical elements. Nine major chemical constituents (Na, Ca, Mg, K, HCO3, Cl, SO4, NO3, Si) make up 99% of the solute content of natural groundwater.

The degree of dissolution depends on the length along flow path, the travel time, the solubility of soil/rock minerals and the amount of dilution by fresh recharge water. Reactions of rainwater in the soil/rock profile during infiltration provide groundwater with its essential mineral composition. Groundwater in the recharge areas of humid regions is likely to be low in overall mineralization, compared to arid or semi-arid regions where the combination of evaporative concentration and slower groundwater movement can produce much higher concentrations.

Under certain conditions and in some geo-environments, naturally occurring but hazardous elements are taken into solution at excessive concentrations:

- Arsenic (As) is the trace element currently giving greatest concern in groundwater, being both toxic and carcinogenic at low concentrations
- Fluoride (F) is an element that is sometimes deficient, but in excessive concentrations it can be a problem, especially in arid climates and in volcanic and granitic rocks
- Manganese (Mn) and iron (Fe) in soluble form occur widely where anaerobic groundwater conditions arise. When water is extracted, manganese and iron oxidize, giving rise to unacceptable groundwater taste and/or color. While Fe is not a health hazard, consumption of water with high manganese concentrations might have neurological effects on humans. The WHO has set the upper limit for Mn concentration in groundwater at 0.4 mg/l

Various other trace elements (including notably Ni, U and Al) can occur under natural conditions in groundwater and are listed by World Health Organization (WHO) as potentially hazardous in drinking water.

If excessive toxic trace elements are present in a potential groundwater supply, then an emergency plan should be implemented and a longer-term strategy identified. The emergency plan is likely to comprise the following:

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

Anthropogenic Pollution

Worldwide, aquifers are experiencing an increasing threat of pollution from urbanization, industrial development, agricultural activities and mining enterprises (Figure 8.5). In some cases, it may take many years before the impact of pollution by a persistent contaminant becomes fully apparent. Groundwater from deep wells, or from springs or groundwater dependent ecosystems often has a long flow path and may take decades or longer to move from recharge to discharge area. This can lead to complacency over the pollution threat. The unfortunate implication is that once people become aware that a groundwater source has become polluted, large volumes of the aquifer are usually already contaminated. Mitigation measures then tend to be very costly and remediation is technically problematic and time consuming. Such contaminated aquifers may be unsuitable for use for decades or centuries. This is why prevention measures such as groundwater protection have to be integrated into land-use planning activities.

Groundwater pollution occurs if the subsurface contaminant load generated by man-made emissions (waste dumping, discharges and leakages) is inadequately controlled, and exceeds the natural attenuation capacity of underlying soils and strata. Natural subsoil profiles actively attenuate many water pollutants and have long been considered potentially effective for the safe disposal of human excreta and domestic wastewater. The auto-elimination of contaminants during subsurface transport within the rock/soil is the result of biochemical degradation and chemical reaction, but contaminant retardation (due to sorption on clay minerals and/or organic matter) is also important, since it greatly increases the time available for processes resulting in contaminant elimination. However, not all subsoil profiles and underlying strata are equally effective in contaminant attenuation, and this leads to the hazard of contaminating unconfined (phreatic) shallow aquifers.

Threats of groundwater pollution arise from a variety of different point and non-point contaminant sources (Figure 8.5 and Table 8.1) originating from industrial, agricultural, domestic (inadequate sanitation), fuel storage, medical and other common sources.

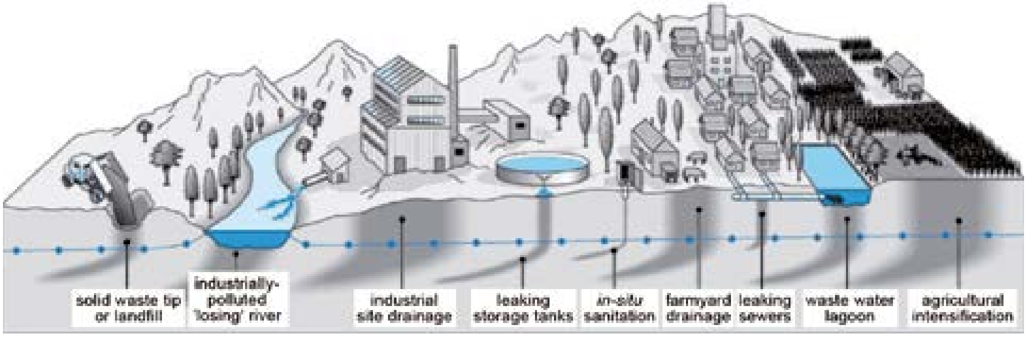


Figure 8.5: Different land-use activities that commonly generate groundwater pollution threats. Source: GW-MATE Briefing Note Series, Note 8, 2002-2006

Table 8.1: Some common groundwater contaminants and associated pollution sources.

Pollution Source	Type of contaminant
Agricultural Activity	nitrates, ammonium, pesticides, faecal organisms
On-site Sanitation	nitrates, faecal organisms, trace synthetic hydrocarbons
Gasoline Filling Stations & Garages	benzene, other aromatic hydrocarbons, phenols, some halogenated hydrocarbons
Solid Waste Disposal	ammonium, salinity, some halogenated hydrocarbons, heavy metals
Metal Industries	trichloroethylene, tetrachloroethylene, other halogenated hydrocarbons, heavy metals, phenols, cyanide
Painting and Enamel Works	alkylbenzene, tetrachloroethylene, other halogenated hydrocarbons, metals, some aromatic hydrocarbons
Timber Industry	pentachlorophenol, some aromatic hydrocarbons
Dry Cleaning	trichloroethylene, tetrachloroethylene,
Pesticide Manufacture	various halogenated hydrocarbons, phenols, arsenic
Sewage Sludge Disposal	nitrates, various halogenated hydrocarbons, lead, zinc
Leather Tanneries	chromium, various halogenated hydrocarbons, phenols
Oil and Gas Exploration/Extraction	salinity (sodium chloride), aromatic hydrocarbons
Metalliferous and Coal Mining	acidity, various heavy metals, iron, sulphates

Source: GW-MATE Briefing Note Series, Note 8, 2002-2006

Groundwater salinisation

The existence of saline groundwater and the process of groundwater salinisation can come about by a number of distinctive mechanisms, only some of which are pumping-related and/or associated with the seawater intrusion.

The main mechanisms of groundwater salinization are indicated schematically in Figure 8.6, and range from the mobilisation of paleo-saline or connate waters[1] at depth to essentially surface processes related to soil water-logging due to rising water-tables. In-depth investigations are required to diagnose existing occurrences of saline groundwater, and to assess the potential that such processes might occur during a major or progressive change of groundwater abstraction. The importance of this cannot be over-stressed since once a major rise in salinity or intrusion of saline water has occurred, it may take a very long-time (decades or even millenia) and considerable cost to remediate — and will destroy the groundwater resources for both potable water-supply and many agricultural irrigation uses.

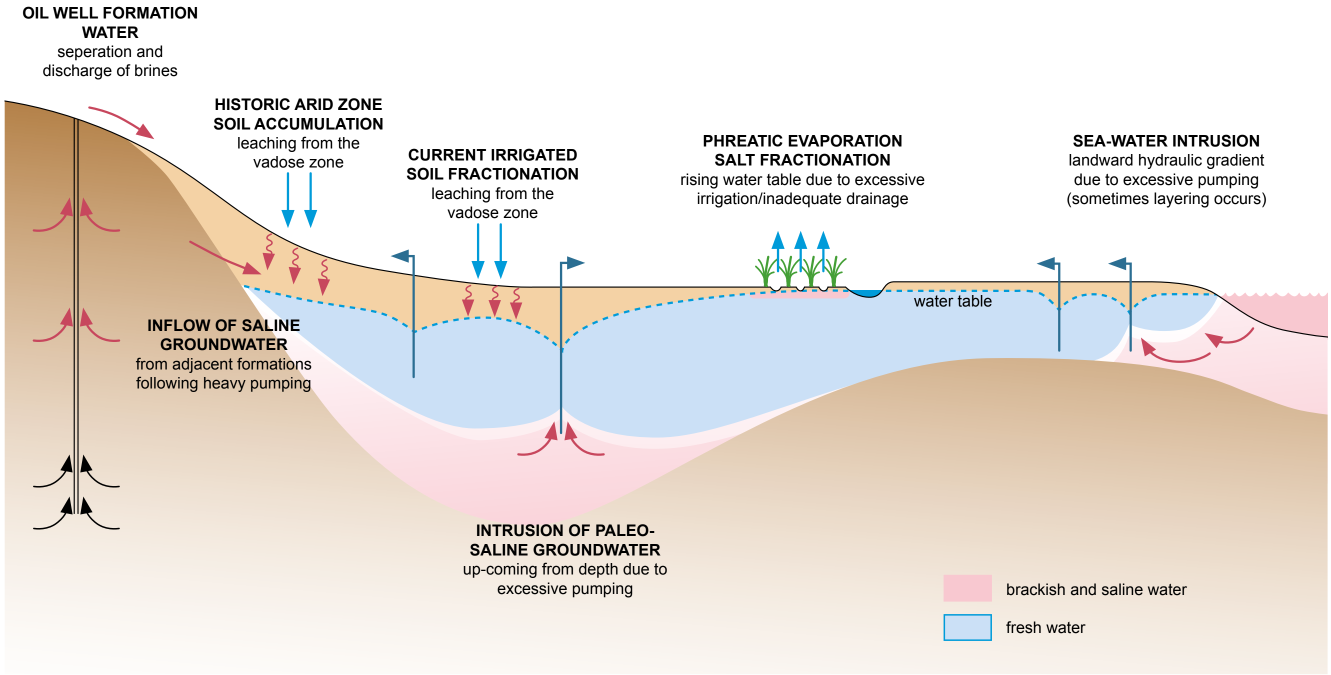


Figure 8.6: Salinisation as possible effect of groundwater over-abstraction. Source: GW-MATE

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[1] Groundwater recharged in the past, thousands of years ago, that stagnates in channels or depressions and has thus time to interact with the surrounding rocks. It is generally high saline and as such cannot be used for water supply without treatment

8.3 Assessment of groundwater pollution, aquifer vulnerability and over-exploitation

To protect groundwater from pollution and overexploitation, it is essential to assess the hydrogeological setting and the anthropogenic impact.

Groundwater extraction and recharge rates

In the light of all the above considerations, it will be evident that water resource managers need to have an estimate of the acceptable abstraction[2] from a groundwater system. Although in reality such estimates can also be misleading because to make them it is necessary to have value judgements about what is 'acceptable'. In this case ecosystems also have to be considered as stakeholders that are aquifer dependent.

To assess a safe yield, the quantities of input (recharge) and output (discharge) to the groundwater system have to be estimated. An important component of the output, abstraction by pumping, varies according to human demand. However there is often substantial scientific uncertainty of the quantification of individual recharge and discharge components due to the inherent complexity of natural geo-systems and wide spatial and temporal variability of rainfall and runoff events (including climatic cycles) as well as of groundwater abstraction. Therefore groundwater balance calculations in many regions always should be treated with caution. Nevertheless, for most practical purposes, it is sufficient to make approximate estimates, and refine these subsequently through groundwater level monitoring and analysis of aquifer response to abstraction over the medium-term.

It is always essential when attempting to evaluate contemporary groundwater recharge rates to appreciate the significance of the intimate linkages between land-use and groundwater recharge, which is an essential input for integrated water resources management. The common paradigm of 'constant average rates of present-day aquifer recharge' is false. In reality the contemporary rate of aquifer recharge varies considerably with:

- Changes in land-use and vegetation cover, notably the introduction of irrigated agriculture, but also vegetation clearance and soil compaction
- Urbanisation processes, and in particular the level of water-mains leakage and the degree of land-surface impermeabilisation;
- Widespread water-table lowering by groundwater abstraction and/or land drainage, which leads to increased areas and/or rates of infiltration in some aquifer systems;
- Changes in surface water regime, especially the diversion of riverflow.

Moreover groundwater abstraction data is almost unavailable, since direct monitoring of groundwater abstraction is costly because meters have to be fitted to all pump outlets, and this requires the full cooperation of water users, which is not always easy to achieve. Intensive groundwater use for domestic water supply is also encountered in fast growing cities where the water service provision is inadequate. This is the case

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[2] Acceptable extraction or safe yield is the rate at which a well can be pumped in a long-term without causing harm either to the well construction (water level falls below the screen) or to the aquifer (irreversible lowering of the water table)

in many African cities and has led to massive and indiscriminate private groundwater development. Indirect monitoring of groundwater use can be done using demographic data in combination with satellite images and urban planning maps that show the urban expansion and estimating water use per household.

Pollution sources and vulnerability

Groundwater is vulnerable to many different sources of pollution. The location, nature and amount of pollution sources have to be known to assess the pollution load to land surface and hence potentially to the groundwater. The pollution loads are relatively easy to identify, especially point source pollution, but it is the vulnerability of the aquifer system in combination with the pollution load that translates the into groundwater hazard.

Hydrogeological data such the thickness and hydraulic properties, such as permeability, of the unsaturated zone are necessary to assess the vulnerability of aquifers to pollution loads. The groundwater hazard can be determined by overlaying pollution load maps onto aquifer vulnerability maps.

There are a number of aquifer vulnerability assessment methods that consider a variety of factors that contribute to an aquifer’s vulnerability. Two of the better known assessment schemes are known by their acronyms: DRASTIC and GOD. To provide a general insight into aquifer vulnerability characterization it is useful to consider the elements considered in the eg. Drastic method. Each element in the vulnerability assessment is allocated a relative score, and the final score is rannked against a ranking chart which may characterize the aquifer from: very high vulnerability to very low vulnerability.

- D = depth to the groundwater (the deeper, the less vulnerable)
- R = net recharge (the greater the recharge rate, the more vulnerable)
- A = aquifer medium (low permeability aquifers are less vulnerable)
- S = soil medium (permeability, adsorbtion capacity)
- I = impact of the vadose zone (combination of S and D)
- C = hydraulic conductivity (similar to A)

Due to the repetition of some of the parameters, hydrogeologists have tended to modify Drastic and come up with more stream-lined vulnerabilty assessment methods.

Once the aquifer vulnerability has been assessed, then the risk to the groundwater can also be assessed. The definition of groundwater pollution hazard is the interaction between aquifer pollution vulnerability and the contaminant load applied on the subsurface environment as a result of human activity at the land-surface. Contaminant load can be controlled, but aquifer vulnerability is fixed by the natural hydrogeological setting.

Systematic groundwater pollution hazard assessments should be integrated into groundwater quality protection measures and should become an essential component of environmental best practice.

Management of groundwater pollution.

As expressed earlier, prevention of pollution is far preferable to trying to cure it. The key management options for preventing groundwater pollution are:

- Seperation: keep waste materials and productive aquifers far apart. This usually takes place during the planning phase of any development, especially where there is a high level of waste generated. Environmental impact assessments are designed specifically to ensure that such separation occurs in a timely manner.
- Containment: Where waste is generated in proximity of groundwater or surface water supplies, then containment of the waste in impermeable ponds is a management option. Solid waste landfills should be designed such that there is an impermeable base, which may be some form of high density polyethelyne liner or a compacted clay base.
- Waste management: the sorting of waste into different components is highly successful and allows the reuse / recycling of some wastes (plastic, metal, glass, paper and cardboard) and composting of organic waste. This reduces the overall waste load and allow the seperation of toxic waste which can be treated or contained in high level waste facilities. Waste sorting and seperation is often commercially viable.
- Remediation: finally there is remediation of polluted aquifers. As expressed earlier, this is technically complex, long duration and expensive. Methods such as pump, treat and reinject treated water; aquifer flushing with fresh water etc. have been used with limited success. Insoluble pollutants, the so-called LNAPL and DNAPL (Light and dense non-aqueous phase liquids) are particularly difficult to treat.

8.5 Groundwater protection

Whether a given pollution hazard will result in a threat to a groundwater supply-source depends primarily on its location with respect to the source water-capture area and secondarily on the mobility of the contaminant(s) concerned. A number of groundwater protection zones should normally be defined (Figure 8.7) based on hydrogeological data about the local groundwater flow regime. Various analytical and numerical models are available for this purpose. The scale and intensity at which the survey, mapping and analyses of various components needed to assess groundwater pollution hazard are undertaken, will vary with the importance and sensitivity of the groundwater resource: water-supply protection or aquifer resource conservation.

A primary focus of groundwater quality monitoring is usually public water supply networks from water wells and springs via piped distribution systems. Two key components involve (i) regular sampling of the water, and (ii) chemical analysis in the laboratory.

Groundwater pollution hazard assessments should prompt municipal authorities or environmental regulators to take both preventive actions (to avoid future pollution) and corrective measures (to control the existing threats). To protect aquifers against pollution it is essential to constrain land-use, effluent discharge and waste disposal practices.

Simple and robust zones need to be established, based on aquifer pollution vulnerability and source protection perimeters. For each zone certain activities have to be defined that give an acceptable risk to groundwater. Groundwater protection zoning also has a key role in setting priorities for groundwater quality monitoring, environmental audit of industrial premises, and pollution control within the agricultural advisory system.

A sensible balance needs to be struck between the protection of groundwater resources (aquifers as a whole) and specific sources (boreholes, wells and springs). While both approaches to groundwater pollution control are complementary, the emphasis placed on one or other (in a given area) will depend on the resource development situation and on the prevailing hydrogeological conditions.

In dealing with threats to groundwater, communities and stakeholders need information about the resource. Groundwater protection can best be accomplished by controlling potential contaminant sources and by managing landuse in prime recharge areas. Using knowledge of local geology and groundwater flow directions, estimates can be made of land areas that contribute to recharge a particular aquifer. Controls can then be established to ensure appropriate land uses and chemical practices within the recharge areas. In many instances, recharge areas cannot be set-aside in their natural states.

Within certain basins, domestic, industrial, agricultural and commercial operations discharge different forms of potential contaminants, which can contaminate groundwater with bacterial matter, pesticides, chemical spills, toxic wastes, etc. In this regard, groundwater protection efforts must focus instead on management of the diverse potential contaminant sources. Some possible management techniques include public education, inventory and monitoring of potential contaminant sources, and zoning of local land use activities (Figure 8.7) in order to protect community groundwater supplies.

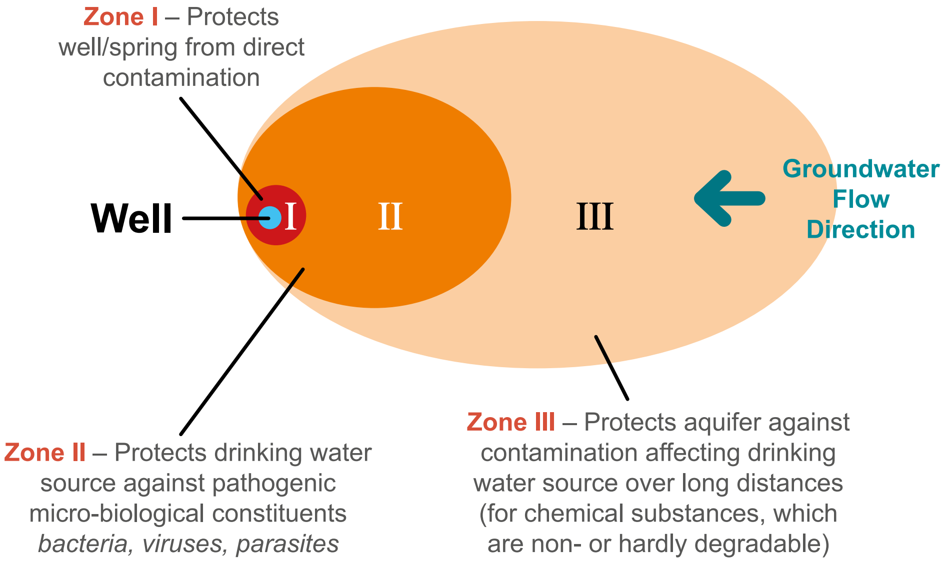

Figure 8.7: Idealized schematic zones for protection of a well in an unconfined aquifer. Source: Modified after GW-Mate, 2006

For groundwater protection zones to be effective, they need:

- To be embedded in the regulatory framework and enforced
- Stakeholders to be aware about them and adhere to them
- To be regularly monitored
- Land-use restrictions to balance competing user-interests.

8.6 Summary

In discussing groundwater hazards, it can be helpful to consider them in the context of generic hazard management. Since we are concerned with the management of groundwater hazards, the question to ask is: “How does a catchment manager protect the groundwater resources and the aquifers in his catchment against hazards?”

The measurement of groundwater recharge, groundwater flows and even mapping of the aquifers and abstraction potential are expensive and complex. Faced with such a large information lack, how does the manager start to make decisions? Box 8.1 presents terms that are used in disaster studies and their interactions. Such a framework can be helpful for a catchment manager tasked with protecting groundwater resources.

The manager first has to identify the important groundwater sources being used in their catchment / basin, then assess the hazards for each, look at the vulnerability to each hazard to determine the risk. The hazards (pollution hot spots) are relatively easy to identify but it is the aquifer vulnerability that translates the hazard into risk.

Once the catchment managers have an assessment of risk, they then have a basis for action (mitigation) that may include control of specific polluting agents or practices, adjusting abstraction or other interventions. If managers use a structured approach on disaster management (Box 8.1), this can provide a framework for identifying risk and thereby targeting effective response / remediation. Managers, despite the complexity and unknowns in groundwater, still have a framework for management steps that they can take to protect the groundwater resource from pollution.

BOX 8.1: SOME TERMINOLOGIES USED IN DISASTER STUDIES

i) Hazard - A potentially damaging physical event, human activity or phenomenon that has potential to cause loss of life or injury, property damage, socio-economic disruption of life and environmental degradation, among others.

ii) Vulnerability - A set of conditions resulting from physical, social, economic and environmental factors that increase the susceptibility of a community to the impact of disasters or the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard.

Disaster = Hazard + Vulnerability

iii) Risk - The probability of harmful consequences or loss resulting from the interaction between natural hazards and vulnerable conditions of people and property.

Risk = (Hazard X Vulnerability)/Capacity

iv) Mitigation - Short and long term actions, programmes or policies in advance of a natural hazard or in its early stages, to reduce the degree of risk to people, property and productive capacity.

v) Impacts - Specific effects, consequences or outcomes of hazards or disasters.

vi) Preparedness - Pre-disaster activities designed to increase the level of readiness or improve operational capabilities for responding to an emergency.

vii) Response - Actions taken immediately before, during or directly after a disaster to reduce the impacts and improve recovery.

viii) Resilience/Capacity – The capability of the community to cope with disasters.

Source: Report on the Status of Disaster Risk Reduction in Sub-Saharan Africa Region, 2008.

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8.8 Exercise

Exercise 1

Title: Water Quality Management

Issue:

Mining impact on water quality in the West Rand: Calculation and interpretation

The West Rand area of Johannesburg is one of the largest gold producing regions in South Africa. The area is underlain by quartzites and dolomites. Some of the mines were closed in 1980’s and since 2002 acidic mine water is decanting into the environment. Local farmers depend on the dolomitic aquifer for water supply. The discharge of toxic-rich effluent from gold mines and the proximity of slimes dams, tailings and rock dumps can also cause chemical and biological damage to aquatic ecosystems through flooding, clogging, altering streams and wetlands and deposition of radioactive and toxic metals within the drainage of the karst system. The run-off from slimes dams enters the drainage network that feeds into the surface water, karst system and groundwater.

During the mining process, rocks which are situated far below the surface are brought to the surface, where they are crushed and processed. Gold is extracted through chemical processing and the barren material is stored in slimes dams. The crushing and chemical processing expose and mobilize pyrite (FeS_2), a natural sulphur-rich component of the rock that is then exposed to the atmosphere and water. The oxidized sulphates in combination with water and bacterial breakdown produce sulphuric acid that in turn reacts with the rocks and soils to release and mobilize the metals. The acids and metals which are released are found in the rivers and groundwater that is contaminated by the runoff from slimes dams, tailings, rock dumps and mine effluent. This is known as Acid Mine Drainage (AMD).

Question:

Acid mine decant flows downstream into dolomitic terrain in the West Rand. Discharge measurement was undertaken at six stations in two different months (February and August). February is a rainy month, while August is dry. Station P1 exclusively contains acid mine decant and the measured values change downstream. Calculate the seepage rate/amount of acid mine water into dolomitic aquifer. Give possible reasons for the loss, the impact and increase at some stations. Recommend mitigation measures.

Acid mine decent in the West Rand, Johannesburg							
Discharge		**February**	**August**		**Seepage in Feb**	**Seepage in Aug**	
Q (m^3/s)	P1	2.214	1.075				
Q (m^3/s)	P2	1.2177	0.7				
Q (m^3/s)	P3	1.014	0.588				
Q (m^3/s)	P4	0.3	0.28				
Q (m^3/s)	P5	0.9	0.3				
Q (m^3/s)	P6	0.45	0.207				
				Total			m^3/s
				Total			m^3/year

Exercise 2

Purpose: To share experience of groundwater quantity problems.

Activity: Break into groups of 4 or 5.

Each group to (in 1 hour):

a) Identify a common groundwater quantity problem in your country.
b) Discuss the nature and scale of the problem – is it anthropogenic or natural?
c) How is the problem being managed, and who is responsible for the management?
d) What have been the aims of the management and how successful has it been?
e) What would you change to improve management of the problem?

MODULE

9

GROUNDWATER FOR FOOD SECURITY

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DIESEL WATER PUMP

CONTENT

MODULE 9

Groundwater for Food Security

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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Layout: *ff.mediengestaltung GmbH, Hannover, Germany*

Picture: *IWMI*

GROUNDWATER FOR FOOD SECURITY

LEARNING OBJECTIVES

- To comprehend the scale and significance of groundwater in agriculture globally
- To know the regions with over- and under-utilisation of groundwater for irrigation
- To appreciate the economic and livelihoods implications of groundwater irrigation
- To understand the context and role of groundwater irrigation in Sub-Saharan Africa
- To understand the risks involved with groundwater irrigation
- To understand strategies to optimize and manage groundwater irrigation around the world
- To understand the nexus between water-, food-, and energy security.

9.1 Introduction and background

Groundwater is widely used in agriculture around the world. About 70 % of all groundwater used goes to agriculture, mostly irrigation (Fig. 9.1). At a global scale, between 20 and 40 % of irrigation water needs are satisfied by groundwater (Fig. 9.2 and Foster and Shah, 2012). Agriculture is the largest consumer of water compared to all other uses, such as domestic and industrial. Most water in irrigation is consumptively used by evaporation or transpiration as compared to non-consumptive use, such as domestic and industrial use that is returned as wastewater and can be reused.

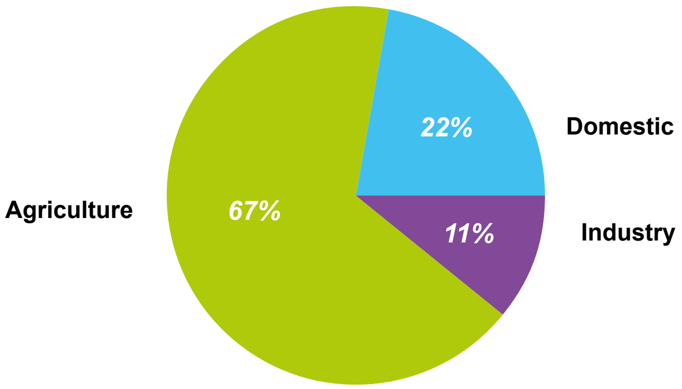

Figure 9.1. Global share of groundwater use for the three major sectors (van der Gun, 2012)

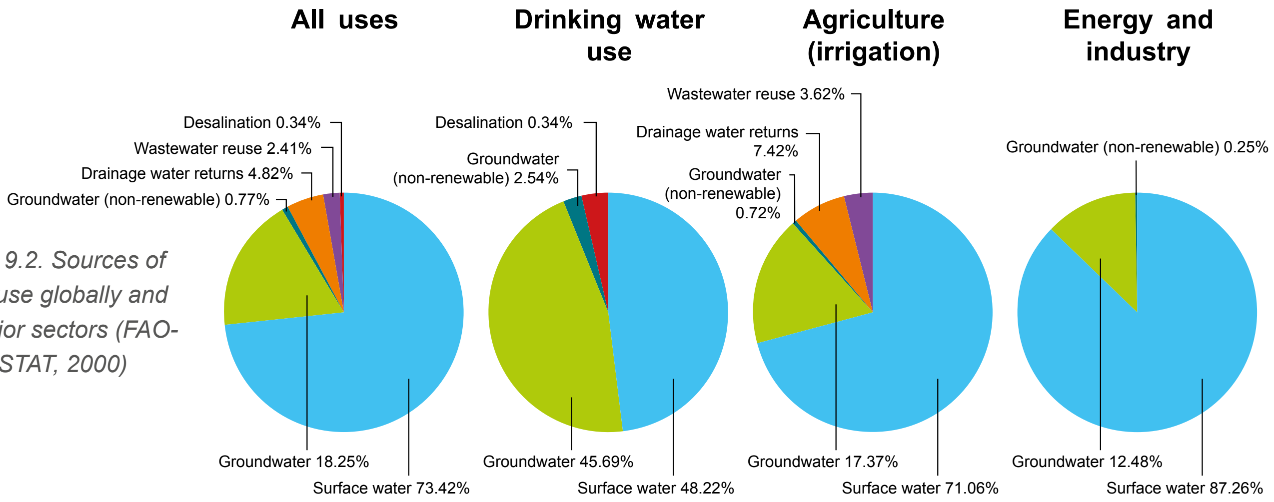

Figure 9.2. Sources of water use globally and for major sectors (FAO-AQUASTAT, 2000)

That groundwater use is significant in agriculture can be seen from Figs. 9.3 and 9.4 where the global distribution of groundwater use and groundwater-irrigated areas, respectively, are shown. There is a good correspondence between those areas with intensive irrigation and those with high groundwater use.

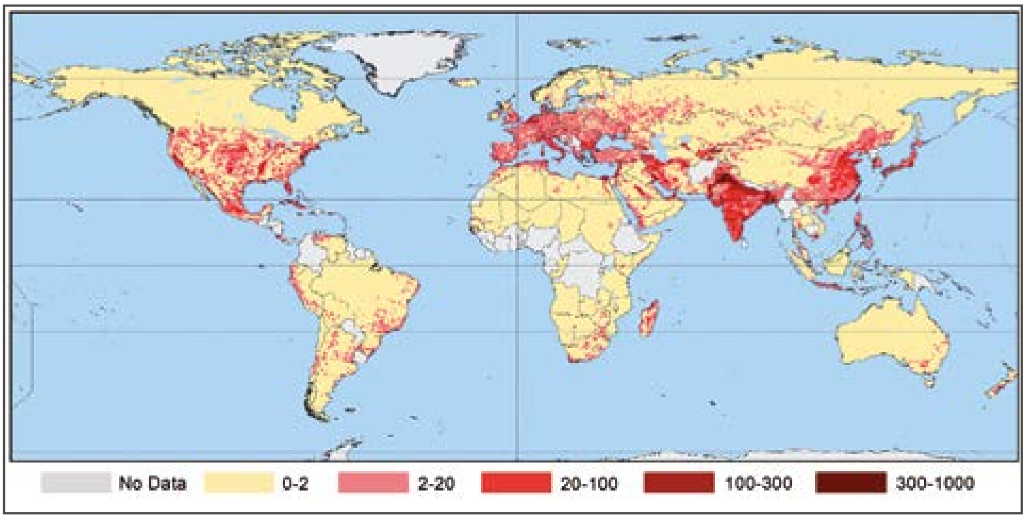

Figure 9.3. Global map of groundwater use
(Wada et al., 2010. Units in mm/yr in 0.5° 0.5° grid cells)*

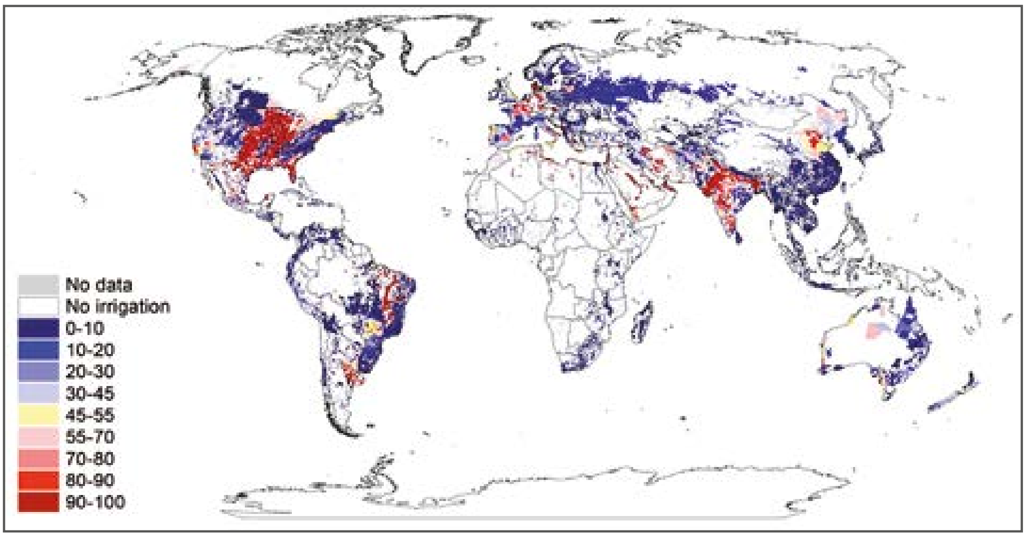

Figure 9.4. Global map of groundwater-irrigated areas
(Siebert et al. 2010. Percentage of irrigated area supplied by groundwater)

Most of this irrigation occurs in arid and semi-arid areas where the replenishment of groundwater is low (Fig. 9.5). This can easily be explained by the larger requirement to supplement crops with irrigation water in these areas. However, it also implies that there is a greater risk of over-exploiting the groundwater resources in these areas, because they are not replenished very rapidly or regularly.

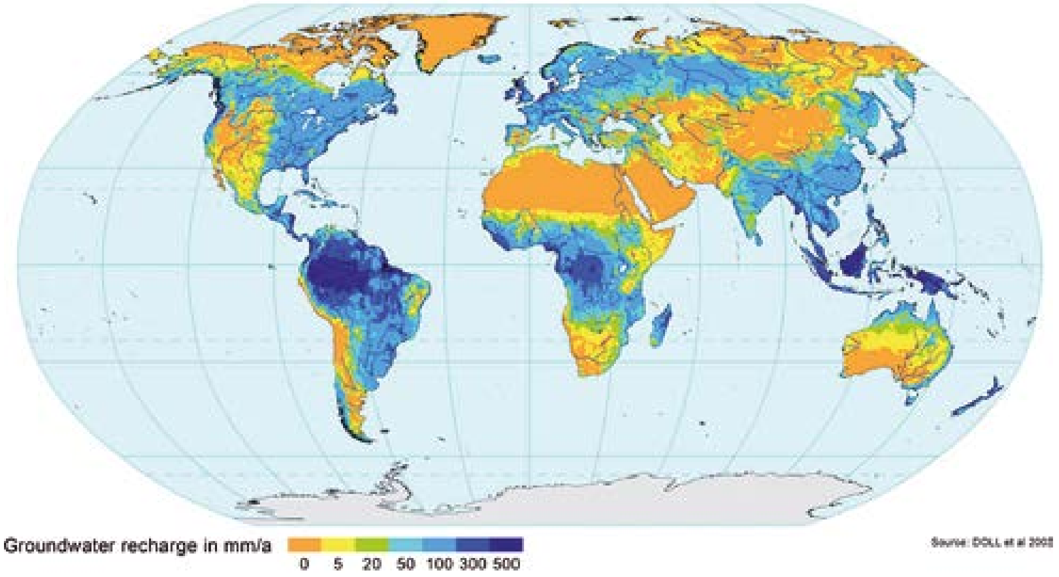

Figure 9.5. Average annual groundwater recharge, 1961 - 1990 (Döll and Fiedler, 2008)

Groundwater use within agriculture was initiated in Asia with the advent of the Green Revolution in the 1960s. Many countries, but particularly India, Pakistan, and China, supported more effective and productive agriculture through groundwater irrigation and use has significantly increased since then (Figure 9.6).

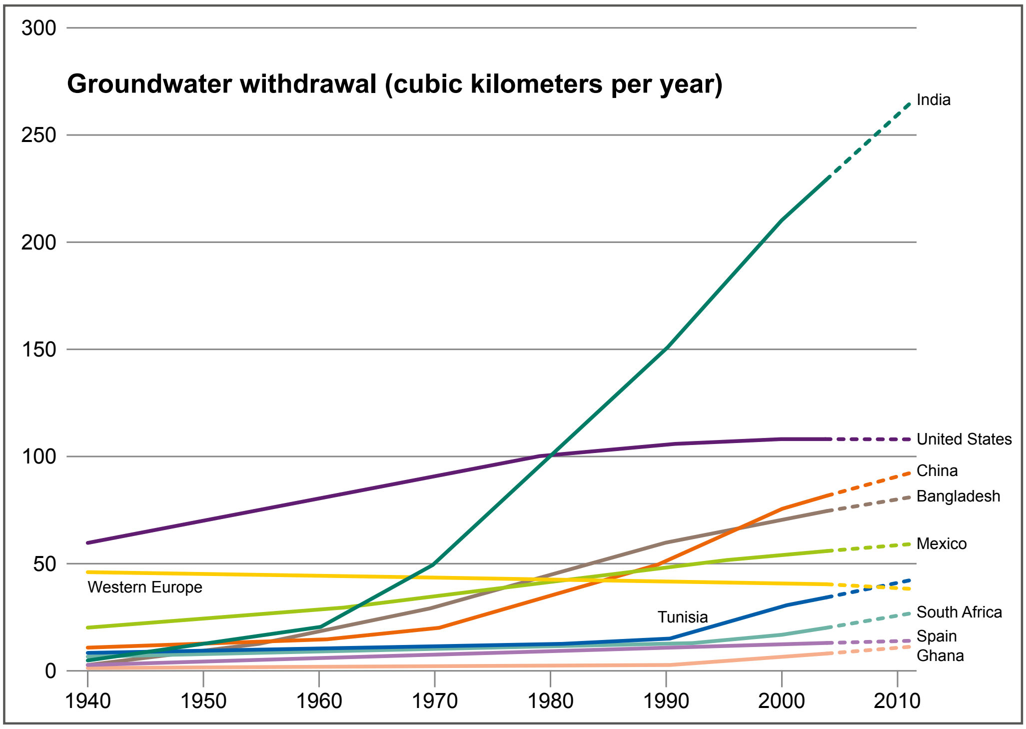

Figure 9.6. Groundwater withdrawal for selected countries (Shah, Burke, and Villholth, 2007)

This growth has been unprecedented in the human history and has implications for the available water resources and the environment in those areas where groundwater exploitation is particularly intense, as we shall see later.

9.2 Why is groundwater use in irrigation so popular?

Some of the inherent properties of groundwater are particularly favourable for irrigation (Box 9.1). These relate primarily to its ubiquitous and perennial presence compared to e.g. rivers. Such factors partly explain the preference of farmers to use groundwater rather than other water sources, most notably surface water.

In addition to these ‘built-in’ factors favouring groundwater, there have been a number of external factors that have helped promote groundwater use for irrigation. These include the development of drilling and pumping technologies needed to access and abstract the water. In early phases of development and in poor communities, groundwater use from shallow aquifers tends to dominate, but as the resource is exploited, the need to drill deeper arises with concurrent need for mechanical pumping, rather than human-powered lifting.

BOX 9.1. FAVOURABLE PROPERTIES OF GROUNDWATER FOR IRRIGATION

- ***Ubiquity:*** Groundwater is available almost everywhere and thus allows for decentralized and incremental development and management where needed
- ***Drought resistance:*** Groundwater is typically less vulnerable to drought than surface water sources since groundwater has a lagged response to changes in rainfall and faces fewer losses of water to evaporation. Hence, crop cultivation is also possible during dry spells and in drought periods, to a certain extent
- ***Reliability:*** Groundwater provides on-demand irrigation, which provides farmers freedom to apply water when their crops need it most. Improved reliability furthermore encourages farmers to invest in intensification through use of improved seeds, fertilizers, cultivation practices like water saving irrigation, and crop diversification. All these factors lead to increased land and water productivity
- ***Immediacy:*** Groundwater irrigation can be developed quickly by individual farmers or small groups, unlike large surface irrigation structures, which might require government participation or a large cooperative effort
- Low-cost: Capital costs of groundwater structures are much lower per area of irrigation than those of surface structures since reservoir construction is not required and water sources can usually be developed close to the demand. However operating costs tend to be higher for groundwater irrigation schemes
- ***Versatility:*** Groundwater may be strategically developed for multiple uses in rural remote areas, ensuring water for domestic as well as productive uses and hence addressing several development goals
- ***Flexibility:*** Groundwater may be developed in conjunction with other sources of irrigation to optimize overall water use and storage options

Cost-effective pumps are increasingly available, with makes from Asia being supplied and traded in many countries today. Drilling technologies, adapted to the various settings, are also generally available in most countries, though cost and efficiency varies quite a bit. Sales and services for these technologies are generally much better in Asia than in Africa, reflecting the longer history of groundwater development in that region.

Another external factor that has facilitated groundwater development for irrigation is the expansion of rural electrification. This is exemplified in India, where groundwater irrigation proliferated in certain regions due to subsidized electricity supply to farmers. Electricity seems to be the favoured source of power due to lower prices and its ‘cleanliness’ compared to e.g. petrol or diesel. However, rural electrification still lags behind in parts of the world, like Sub-Saharan Africa (SSA), effectively hampering groundwater irrigation development.

Furthermore the increase in food demands (due to growing populations and affluence in lifestyles) has spurred the farmers to intensify their agriculture through irrigation and to cultivate higher-value crops. It has been found that due to the reliability of the resource and farmers’ ability to control the application of groundwater, the yields and productivity of groundwater is higher than surface water (Deb Roy and Shah, 2003). With lower risk of crop failure when using groundwater, farmers also tend to invest more in other crop inputs, like fertilizers and pesticides, generally further increasing their productivity.

Food production with groundwater tends to increase production of vegetables and other higher-value crops relative to that of staple crops, especially in SSA. Hence, diets of poor farmers could improve in nutritional value when their food is sourced from groundwater, though no documented results for this are available. In Asia, groundwater is used also for staple crops like wheat, maize and rice.

Finally, increased knowledge of the groundwater systems by farmers, as well as their experience of positive outcomes, has further encouraged accelerated growth of groundwater fed irrigation observed in many parts of the world.

9.3 Livelihood impacts

For the reasons mentioned above, irrigation, and in particular groundwater irrigation, has been associated with poverty alleviation. A broad-scale positive correlation is found between groundwater irrigation development and reduced incidence of poverty in India (Fig. 9.7). This supports smaller-scale findings that farmers adopting groundwater irrigation are better-off than counterparts, who do not take up groundwater irrigation or take up other forms of irrigation (e.g. Shah et al., 2013). In Southeast Asia alone, it is estimated that more than 1 billion people are relying directly on groundwater for irrigation (Villholth and Sharma, 2006). However groundwater irrigation must prove profitable for the farmers investing in it, and in some cases (as in SSA) costs are often too high and hence prohibitive for the poorer farmers to invest. This implies that the benefits tend to accrue to less deprived farmers and development is slower (Villholth, 2013). Whether this aggravates disparity is not clear.

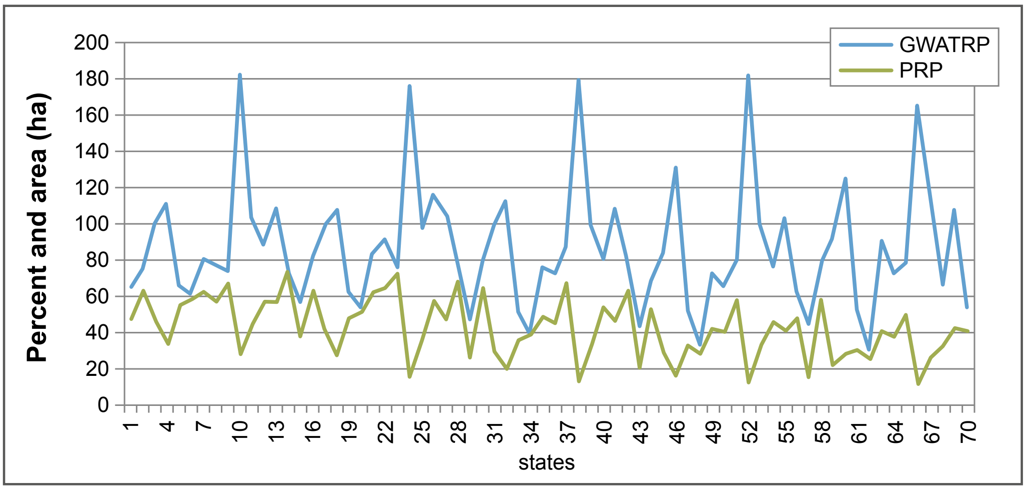

Figure 9.7. Relationship between groundwater irrigated area per thousand rural population (GWATRP) and percentage of rural poverty in Indian states (PRP) (Narayanamoorthy, 2007)

The case of Sub-Saharan Africa

Groundwater use in irrigation in SSA varies from small-scale smallholder schemes of less than one hectare to large-scale mechanized schemes larger than 100 hectares. A simple typology that encompasses the most prominent forms of groundwater irrigation in SSA is suggested in Table 9.1, which distinguishes between the depth of the groundwater utilized and the funding source.

Table 9.1. Typology of groundwater irrigation systems in SSA, including examples

		Depth of wells		
		Deep		Shallow
Funding source	Private	1. Commercial, larger-scale, mechanized, export-oriented		2. Informal, small-scale, farmer-driven
		Examples:	*Flower farms in Ethiopia, Center-pivot grain farms in Zambia*	*Vegetable growing schemes in Northeast Ghana*
	Public	3. Deep systems, subsidized		4. Shallow systems, subsidized
		Examples:	*Public schemes in Raya-Kobo in Ethiopia*	*Fadama systems in Nigeria*

Which category does most of the groundwater irrigation in your country fit into?

The distinction of depth is important, because investment costs to start groundwater irrigation increase significantly with depth. Deeper systems (Type 1 and 3) also tend to be more resilient against droughts as compared to shallow well systems. The distinction between funding source is also important as the control and management of the various systems differ widely. While the shallow informal smallholder systems (Type 2) are mostly unrecognised and unregulated by the public sector, the deeper systems (Type 3), due to significant public investments, are formally recognised by the public sector, typically requiring delegation of management to users' organisations. Finally, Type 4, exemplified by the fadama systems in Nigeria, encompasses shallow systems, but supported through public funds. As in Asia, groundwater irrigation has proven instrumental in poverty alleviation in SSA, when the poorest population groups simultaneously get access to groundwater through cheap wells and pumps as well as the necessary enabling factors associated with farming, e.g. access to energy, credit, agricultural inputs, and training (Villholth, 2013). Data from particular cases are given in Table 9.2.

Pictures illustrating the various systems are shown in Fig. 9.8.

Figure 9.8. Illustrations of the various groundwater irrigation types

The hydrogeology, in combination with the socio-economic and political factors, governs which types of groundwater irrigation are developed. Since the potential for groundwater irrigation development in SSA in general is large, various methods have been proposed to estimate the potential in terms of size of area and distributed locations. It is estimated that another 26 million households could benefit and about 13 million hectares of farmland could be sustainably irrigated with groundwater in thirteen selected countries of SSA (Pavelic et al., 2013). A simple compilation and analysis of groundwater irrigation-related indicators revealed a certain ranking in potential of fourteen different SSA countries (Box 9.2).

BOX 9.2. GROUP RANKING OF SELECTED COUNTRIES IN SSA WITH RESPECT

1. Low or localised potential:
   Kenya, Mali, Niger, South Africa, Tanzania
2. Still appreciable potential:
   Burkina Faso, Ethiopia, Ghana, Malawi, Mozambique, Nigeria, and Zambia
3. Great potential, but demand for irrigation limited at present:
   Rwanda, Uganda

If not on the list, which group do you think your country falls into?

Table 9.2. Data from irrigation cases, including groundwater irrigation, in SSA, with focus on smallholder systems

Country, region	Irrigation started	Plot size per HH[a] (ha)	GW depth, well type	Combined w. rainfed?	Lifting device, irrigation device	Crops, GWI season	GWI practitioners	Land tenure	GWI type (cf. Table 3)	GWI dev. stage[b]	Farming w. highest productivity[c]	External financial support	Reference
Ethiopia Raya-Kobo Valley	>1995	~ 0.25	Deep, wells (60-170 m)	Yes	Elec. pumps, furrow/ buckets/ sprinkler	Onion/ tomato/ pepper Dry season	Smallholder farmers	Lease/ share cropping/ own	3	2	Motor pump irrigation from GW	Partly gov't/ NGOs	Gebregziabher et al. (2013); Ayenew et al. (2013); Abate (2006)
Ghana Upper East Region	1890's	0.01-0.21	Shallow, dugouts/ HDWs[d]	Yes	Rope and buckets	Tomato/ onion/ pepper Dry season	Mostly women and youth	Lease	2	1	Bucket irrigators from GW	Limited	Obuobie et al. (2013); Namara et al. (2013); Dittoh et al. (2013)
Niger Niamay Capital District	>1990	0.13	Deep + shallow, various	Yes	Hand/foot pumps, buckets	Onion/ tomato/ cabbage Dry season	2/3 women	Individual/ collective	2	1	GW irrigation	Partly gov't/ NGOs	Torou et al., 2013
Nigeria Northern Nigeria	>1993	0.5 - 1.0	Shallow, boreholes	Yes	Motor pumps, flooding	Onion, cabbage, pepper, tomatoes All year	Smallholder farmers	Individual/ lease	4	2-3	GW irrigation	World Bank/ Gov't	Abric et al. (2011); Nkonya et al. (2010); Dabi (no year)

[a] HH: Household; [b] GWI development stage acc. to Deb Roy and Shah (2003). 1 signifies early stages of groundwater development while 4 indicates mature and over-development of groundwater; [c] Gross revenue per ha; [d] HDW: Hand-dug well

9.4 Too much and too little groundwater development for irrigation is a concern

Regions like SSA and Southeast Asia differ widely in the scale and significance of their groundwater irrigation (Fig. 9.4 and 9.6). In India, as an example, groundwater contributes to more than 60 % of the irrigated areas, whereas the same figure for SSA is between 10 and 20 % (Villholth, 2013). While irrigation in general is much lower in SSA than in Asia, demonstrating some overall impediments, these data show the quite different contexts and trajectories of groundwater development across the globe. It is generally surmised that Southeast Asia presents a case of overdevelopment of groundwater, while SSA is one of under-exploitation. In the first case, while groundwater has proven instrumental in alleviating poverty on a large scale in India, the conditions in some parts of the country are presently considered unsustainable, contributing to environmental degradation, diminishing profits from irrigation, and increasing conflicts between water users, etc. In SSA, it is considered that groundwater holds a large potential for further supporting small- and large-scale irrigation development, food production and poverty alleviation. In Table 9.3, the countries in the world with over-exploitation of groundwater are listed according to their depletion rates. It is seen that both developed as well as developing countries are struggling with depletion of groundwater resources.

Some of the reasons for the disparity in groundwater development between Asia and SSA are:

- Larger population density in Southeast Asia, necessitating intensified agriculture
- Cheaper and easier access to pumps and drilling technologies in Southeast Asia
- More profound embedding of the Green Revolution in Asia
- Lack of community tradition in irrigated cultivation, compared to rain-fed arable cropping and extensive livestock rearing in SSA
- Poor rural infrastructure, roads, storage facilities etc.
- Limited commercial ventures in SSA.
- Very low levels of rural electrification in SSA, coupled with the elevated cost and distribution difficulty associated with use of diesel fuel for pumping
- Inadequate access to financial credit for irrigation hardware acquisition and purchasing essential production inputs in SSA (such as quality seeds and agrochemicals)
- Better and more productive aquifers in Asia

Which of these reasons do you think are most critical?

Table 9.3. Reported groundwater abstraction rate (A) and model-estimated groundwater depletion rate (D) for selected countries in subhumid to arid regions, with ranges of uncertainty given in parenthesis, for the year 2000. Depletion is the rate of abstraction exceeding long term average recharge (Wada et al., 2012)

Country	Abstraction (A) (km^3 / yr^{-1}	Depletion (D) (km^3 / yr^{-1}	D/A (%)
India	190 (±37)	71 (±21)	37 (±19)
United States	115 (±14)	32 (±7)	28 (±9)
China	97 (±14)	22 (±5)	22 (±9)
Pakistan	55 (±17)	37 (±12)	69 (±48)
Iran	53 (±10)	27 (±8)	52 (±24)
Mexico	38 (±4)	11 (±3)	30 (±11)
Saudi Arabia	21 (±3)	15 (±4)	72 (±30)
Russia	12 (±2)	1.5 (±0.5)	14 (±7)
Italy	11 (±3)	2.3 (±0.6)	21 (±13)
Turkey	8 (±2)	2.4 (±0.8)	31 (±18)
Uzbekistan	6.5 (±1.8)	4.0 (±1.4)	63 (±43)
Egypt	5 (1.3)	3.0 (±1.2)	61 (±43)
Bulgaria	4.8 (±1.4)	2.0 (±0.8)	42 (±32)
Spain	4.6 (±1.1)	1.7 (±0.6)	37 (±23)
Argentina	4.5 (±0.9)	0.9 (±0.3)	20 (±11)
Libya	4.4 (±1.2)	3.1 (±0.9)	70 (±43)
Ukraine	4.2 (±0.9)	0.3 (±0.08)	7 (±3.5)
Romania	3.5 (±1)	1.3 (±0.6)	38 (±30)
Kazakhstan	3.4 (±1)	2.0 (±0.5)	59 (±35)
South Africa	3.0 (±0.7)	1.5 (±0.5)	50 (±30)
Algeria	2.5 (±0.7)	1.7 (±0.6)	69 (±48)
Greece	2.4 (±0.6)	0.34 (±0.1)	14 (±8)
Morocco	2.4 (±0.4)	1.6 (±0.5)	67 (±34)
Australia	2.1 (±0.4)	1.0 (±0.3)	48 (±24)
Tajikistan	1.9 (±0.5)	1.2 (±0.4)	61 (±40)
Yemen	1.9 (±0.5)	0.9 (±0.3)	49 (±31)
Turkmenistan	1.85 (±0.5)	1.25 (±0.5)	70 (±50)
Syria	1.59 (0.4)	1.23 (±0.3)	78 (±41)
UAE	1.55 (0.3)	1.18 (±0.4)	76 (±42)
Tunisia	1.55 (±0.5)	0.65 (±0.2)	42 (±30)
Peru	1.23 (±0.4)	0.32 (±0.08)	26 (±17)
Bolivia	0.68 (±0.2)	0.25 (±0.08)	37 (±25)
Israel	0.61 (±0.2)	0.38 (±0.1)	62 (±41)
Kyrgyzstan	0.61 (±0.2)	0.31 (±0.1)	51 (±37)
Jordan	0.52 (±0.2)	0.22 (±0.08)	42 (±38)
Mauritania	0.51 (±0.1)	0.36 (±0.1)	71 (±35)
Oman	0.50 (±0.2)	0.2 (±0.06)	39 (±33)
Kuwait	0.29 (±0.1)	0.25 (±0.09)	87 (±70)
Qatar	0.18 (±0.05)	0.15 (±0.06)	83 (±60)
Globe	**734 (±82)**	**256 (±0.38)**	**34 (±9)**

9.5 Solutions to under- and over-use of groundwater for irrigation

Modifying current approaches to use and management of groundwater for irrigation may not be straightforward, neither in the over- nor the under-exploitation cases. However, optimising use in both cases is imperative for long-term sustainable environmental and socio-economic outcomes. For SSA, the situation is more a case of under use of the groundwater resource for irrigation. The role of groundwater managers will then be more aligned to finding ways to stimulate development of this sector.

Some questions that may arise for water managers are:

- How do RBOs in Africa manage the development of groundwater fed irrigation in SSA?
- How can RBOs avoid the overexploitation of groundwater that has been witnessed in south-east Asia?
- What role can RBOs play in stimulating groundwater use for irrigation?
- What may be effective management systems for groundwater irrigation at different scales of development and use?
- What can be the role of TBOs in management of groundwater irrigation?
- Why should RBOs in Africa invest in groundwater management for irrigation when groundwater use is so limited and conflicts hardly exist and are very localized?

In Table 9.4, some overall options for improving use and management for groundwater irrigation are provided.

Table 9.4. Approaches to enhance sustainable use of groundwater for irrigation in Southeast Asia and Sub-Saharan Africa

Which of these approaches are top-down or bottom-up? How to facilitate each?

Sub-Saharan Africa	South-East Asia
Develop national and regional policy for groundwater irrigation development	Diversify livelihoods away from groundwater irrigation
Develop maps and knowledge of the aquifers at various scales	Encourage groundwater development in less developed regions
Promote and support aquifer development by appropriate gw irrigation systems (table 9.1)	Ration electricity supply to irrigation while making it reliable
Expand reliable rural electrification	Increase irrigation efficiency
Improve rural roads	Encourage rainfed and drought-resistant crops
Provide incentive subsidies for eg. pumps, electricity, drilling etc.	Encourage local management of groundwater among the farmers
Improve market chains for equipment & crops	Encourage artificial groundwater recharge
Promote user based gw allocation and management systems.	Conjunctive use of groundwater and surface water
Improve land tenure security	
Incentivize rural food processing industries	
Expand curriculum of extension workers to include groundwater irrigation aspects	
Develop micro-credits targeted to smallholders to access groundwater irrigation	
Empower farmers to organise themselves to request policy changes	

Such social changes tend to take time to gain a strong foot-hold but where real economic and financial gains are to be made, communities around the world have shown rapid adaptability to take advantage of favorable conditions. RBOs can be the catalysts for such positive changes in SSA.

9.6 The new approach: The nexus between water-, energy-, and food security

As there is limited access to water, sanitation, food and energy (often due to poor management and governance structures), a rapidly growing population will put even more stress on the availability and the sustainability of the planet's resources. The systems that help produce and bring fresh food and energy as well as clean, abundant water to all of us, are intertwined. It takes water to create food and energy, it takes energy to move and treat water and to produce food, and sometimes we use food as a source of energy. These systems have become increasingly complex and dependent upon one another as the resources come under increasing pressure. As a result, a disturbance in one system can wreak havoc in the others, so it is important to achieve a sustainable balance between the three. Therefore, it is important to realise the interdependency in these sectors to avoid the growing trade-offs between these development-goals.

When groundwater resources are accessed to provide for irrigation demand, the nexus between water-, energy and food security is evident. There will be an energy demand to lift the water to the surface and to distribute it to the crop. Energy access and price are strong drivers for groundwater abstraction. Several countries around the world have subsidised diesel or electricity for the agricultural sector to secure farmer's incomes and national food sovereignty. Such subsidy incentives tend to lead to an expansion of the area on which water intensive crops are cultivated with water inefficient technologies that finally result in the depletion of groundwater. Especially in many arid countries where groundwater resources are non-renewable this is a particular problem. Such depletion also has vast implications for the energy sector which looses income and becomes bankrupt.

Agricultural output remains fundamental to national well-being and to economic output. However, integrating the interdependencies between energy-, food- and water security in national policies and programmes have the potential to improve the economy, conserve natural resources, and increase food security.

In many places in Africa, electricity is not developed in rural areas and causes a constraint for the development of groundwater, beyond simple manual lifting for small-scale irrigation. Conversely, electricity development often is associated with greater dependence on groundwater for irrigation

No system is perfectly elastic and there will be many complex trade-offs, spatially and materially, in the nexus between water-, food-, and energy security. Export of food is a virtual export of energy and water; and vice versa for food imports. In summary, when advocating for the development of groundwater-based irrigation, basin organizations and other decision makers should address the interdependencies between water-, food-, and energy security. Increasing groundwater irrigation through subsidies to energy for farmers may be tricky, as it may strain the energy systems, may benefit certain population groups, and encourage unsustainable groundwater use. Decision makers need to ensure that the development of groundwater for irrigation is a sustainable endeavour and a positive development for all components of the society, and not just for one class against the interests of another.

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9.8 Exercise

Tragedy of the Groundwater Commons

Rules of the Game

Version: 19 Sep. 2013
Frank van Weert (IGRAC) and Karen G. Villholth (IWMI)

General rules

There are nine farming households and one fishing household (there are nine teams in total playing the game).

The farming households each have a farmland of 100 hectares and each have their own groundwater well (needed for groundwater irrigation). Only one type of crop is grown.

Only the fishing household is allowed and able to fish in the community lake and the lake water level is dependent on the groundwater level. The layout of the wells and the lake are shown in Figure 1. When groundwater is pumped, some wells may interfere with each other. This means that one well will be drawn down not only by that well but also by the surrounding wells (Figure 2).

The game consists of a series of simulation runs, each representing one growing season.

Each farming household can produce one harvest per simulation run and the fishermen household can produce one fish catch per simulation run.

After each simulation run, the groundwater and lake level go back to ‘normal’ (no physical memory effect in the hydrogeological system).

Performing livelihood activities have associated costs and benefits (see below) and these costs and benefits accumulate over multiple simulation runs. The team that accumulates most net benefits over the series of simulation runs has won. However, note that maximizing production (cropping area) may not optimize net incomes! Various mechanisms may limit the net outcome:

1. The drawdown of the groundwater level, which implies a larger cost of abstracting groundwater
2. The drying of the lake, which implies an environmental (health) cost
3. Climate shocks that limit the crop yields
4. Penalty costs for drafting groundwater above an upper cap that has been decided by a majority of well owners
4. All households start with an equal capital of 0€.
6. If a household reaches a debt of 250€ the household is out of business for the rest of the game.
7. Players are able to set the rules if a majority agrees: however transaction costs are involved.

Benefits (per simulation run, per household)

- 2 €/ha in case of farming
- 150 € for fish catch

Costs (per simulation run, per household)

Type	Amount	Explanation
Living cost	25 €	Note: Not playing (no livelihood activity) will cost you money anyhow!
Cost of fishing:	100 €	
Abstraction cost	Variable	is a function of volume of pumped groundwater, groundwater level and unit price per unit volume (0.002 €/m3)
Cap rule transaction cost	100 € divided by the number of players that join the rule for that simulation run	Advice: Convince others to join: it will make your transaction costs smaller; but be aware of free-riders!
Environmental (health) cost	35 €	When the lake runs dry fishing household is temporarily out of business, all households pay costs for getting sick because of protein deficit!
Social cost or benefit	20% of averaged cumulative net benefit from all the households	Paid by or accrued to all households in the subsequent run
Water saving equipment cost	150 €	Like drip irrigation kits. Implies 20% water saving and smaller farming costs. Investment is only done once during a game
Penalty cost for no compliance with cap rule		Is set by those who pay cap rule transaction costs and given to non-compliers

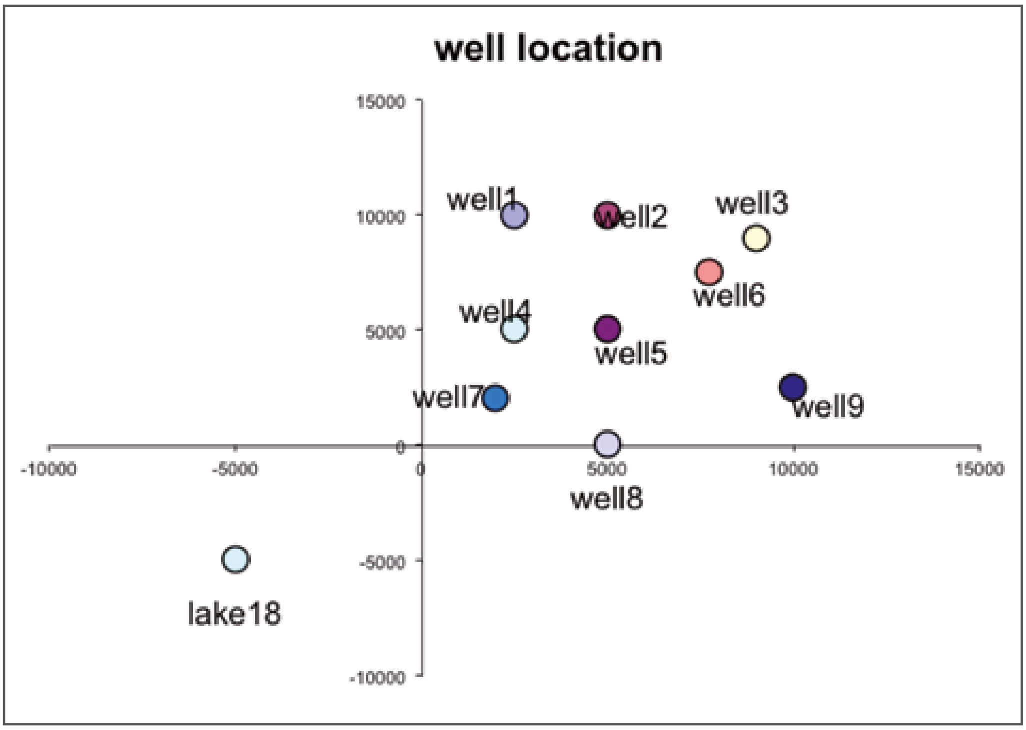

Figure 1. Location of wells and the lake

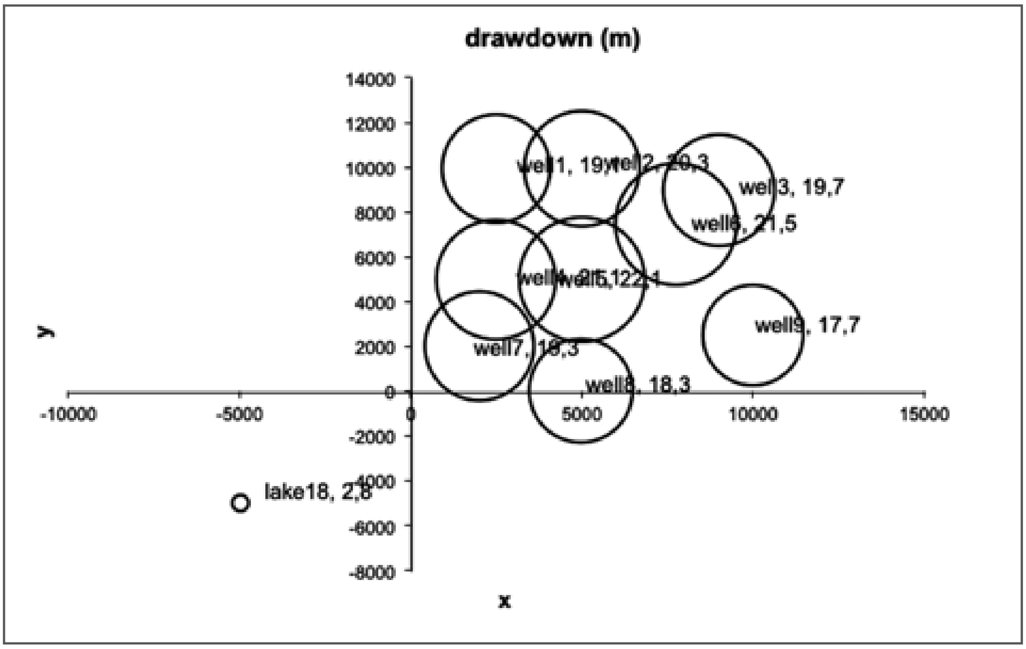

Figure 2. Illustration of interference between pumping wells

MODULE

10

GROUNDWATER AND ENVIRONMENT

CONTENT

MODULE 10

Groundwater and Environment

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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Picture: *IGRAC*

GROUNDWATER AND ENVIRONMENT

LEARNING OBJECTIVES

- To understand the link between groundwater and the environment
- To appreciate the main environmental threats that affect groundwater
- To appreciate the impacts that use or abuse of the groundwater resource can have on the environment.
- To understand the interactions between contaminants and aquifers
- To characterize groundwater-dependent ecosystems

10.1 Introduction

Groundwater is that part of the hydrologic cycle that lies below the surface of the Earth. Development of groundwater for various human uses has an impact on the environment. Similarly changes in the surface environment, whether of natural or anthropogenic origin, have the potential to affect the groundwater resource.

- There are two main interactions between the environment and groundwater: one is predicated on flows from the environment into the groundwater system and the other on flows from the groundwater system to the environment.
- The environment interfaces with groundwater by impacting on the recharge quantity and quality. Some of these interactions are entirely natural and others are modified by human activities. For example, various forms of land use and human waste management may result in groundwater contamination. Groundwater recharge may be increased or decreased by natural or human induced changes to the environment.
- Groundwater discharge to the environment occurs at Groundwater Dependent Ecosystems (GDE). A groundwater dependent ecosystem may be defined as a place where the groundwater surface intersects the land surface, giving rise to some form of usually perennial wetland environment. GDEs tend to host an entirely distinct suite of biota, and are generally highly bio-diverse and productive compared to the surrounding dry land. GDEs may arise from a number of different sets of groundwater conditions, giving rise to the differences between different types of GDEs and to their individual signatures. The varieties of GDEs are described in section 4 of this module.

10.2 Surface and groundwater interaction

Surface water and groundwater are linked as components in the hydrologic system. In humid climates, groundwater and surface water are frequently in direct contact, while in arid and semi-arid climates, the link is indirect since they are usually seperated by a thick unsaturated vadose zone. Excessive abstraction from and contamination of either one will in time most likely affect the other. Understanding the basic principles of interactions between surface water and groundwater is important for an effective management of the all water resources.

Water, whether surface or groundwater, flows in the direction of the hydaulic gradient.

Water flows from a high hydraulic head to a low hydraulic head. This fundamental principle governs all water flows. In order to determine the direction of flow, it is necessary to know the head at the either end of the flow path. Once the head dsitribution is know, it is straightforward to determine if flow is from the surface environment into the groundwater or vice versa.

Surface water and groundwater interact at many locations in all watersheds. Groundwater that is recharged from rainfall on upland interfluve areas could be discharged months or years later to streams, lakes, springs and wetlands. On the other hand, surface water that is derived from rainfall/runoff may be lost by seepage through the streambed, soil layer and fractures to mix with groundwater.

Surface water and groundwater interact on different physical scales and over long periods of time. The interactions of significant interest include (1) groundwater discharging as a baseflow to perennial streams throughout the year; (2) groundwater discharge as a source for springs, seeps, and cave systems; (3) streamflow supply of recharge to the groundwater system; (4) groundwater flow into and out of reservoirs, lakes, ponds and lagoons.

The larger-scale hydrologic exchange of groundwater and surface water in any landscape is controlled by: 1) the distribution and magnitude of hydraulic properties (hydraulic conductivity, transmissivity and storativity) 2) the relation of stream stage to the adjacent groundwater level, modified by the aquifer permeability; 3) the geometry and position of the stream channel within the alluvial plain (Woessner 2000); 4) the relative elevation of the water level in stream and groundwater table; and 5) climatic setting: high rainfall region favours abundant recharge into aquifers and rapid groundwater level fluctuation.

?

What type of surface and groundwater interaction processes are you aware of in any of the catchments in your area? List the types and identify the links?

10.3 Groundwater Contamination

Any developmental activity (urbanization, industrial activity, mining and agriculture) by humans has an impact on both surface water and groundwater.

Surface water and groundwater both originate as precipitation. However, from the moment that precipitation reaches the soil and begins to infiltrate en route to becoming groundwater, its composition begins to change. Water that infiltrates into soils and rocks attain different water quality characteristics than the original preciptation water, and from the surface water component that does not infiltrate into the ground. On the other hand, surface water is open to contamination at the surface by waste mateirals and bacteria. Thus surface and groundwater tend to have different bio-chemical compositions. When they interact, the biochemistry of the resulting water is a product of the biochemistry of the two water sources.

Urbanization: Urbanization with large population concentrations in localized areas significantly increases the pollution load due to sewage discharge and solid waste disposal and hence risk of groundwater pollution. Urban populations generate huge volumes of sewage and discard vast volumes of solid and liquid waste every day containing plastics, chemicals, grease and oil, metals, glass, paper, organic wastes etc. Lack of water borne sewerage systems in most urban centres in Africa also forces people to use pit latrines and/or dispose untreated sewage into water bodies. This then creates a huge diffuse pollution of the groundwater system. Sewage contains salts, bacteria, phosphorus and many other chemicals. Overland flow from streets and buildings also carries pollutants such as bacteria, oil, and chemicals that can enter into the groundwater.

Urbanization also brings with it waste treatment and disposal sites such as solid waste landfill sites and sewage treatment plants. These point sources of pollution are sites where potentially there are concentrations of pollution entering the groundwater.

Industrial activity: Uncontrolled disposal of industrial effluent has a tremendous impact on groundwater especially from chemical and nuclear wastes. Industrial wastes are generated during manufacturing processes. Industrial wastes may be toxic, corrosive or reactive. Some examples are: oils, solvents, chemicals, radio active wastes, scrap metals and many others. If improperly managed, these wastes can pose dangerous consequences through pollution of groundwater upon which people depend. Waste water from manufacturing or chemical processes in industries contributes a lot to the groundwater pollution. Most large scale industries have treatment facilities but many small scale industries do not.

Mining: Prospecting and developing mineral and energy resources in Africa involve activities with the potential to significantly affect both the quantity and quality of groundwater resource associated with those areas.

Chemical pollution is often associated with mining. The main pollutant in both active and abandoned mining areas is acid mine drainage which is rich in heavy metals. Oxidation of sulphide minerals, such as pyrite, produces highly acidic water which then dissolves heavy metals and carries them into the aquatic environment, including the groundwater.

Dewatering of underground workings is a normal component of all mining. Dewatering around mine areas will significantly lower the water table, affecting surface water flows and drying out shallow aquifers. At a local scale, there may be water shortages for communities due to drying up of surface water bodies (streams, rivers, ponds, wetlands, lakes) and springs.

The impacts from mining can last for many decades. As a result, environmental impact assessment, environmental monitoring, contingency planning and financial assurance have to be in place for management. Geochemical conditions within the ore body, waste rock, and tailings can change over time and must be tracked. Flexibility, therefore, is needed to make necessary changes in water control and water treatment after mine closure.

Active management of the mine site and water management may be necessary for years or even decades after closure, depending on the type of mine, the size and nature of the area of disturbance, and the type of ore processing used. Permanent closure routinely includes some or all of the following: removal/disposal of chemicals; structure demolition; removal of unnecessary roadways and ditches; waste detoxification; capping of tailings and waste rock; backfilling pits; and active water management, including assuring that all applicable water-quality standards are met. In numerous cases, this has meant operating and maintaining a water-treatment facility in order to remove toxic chemicals. At sites where acid mine drainage is a problem, post-closure water treatment is necessary for several years, and in some cases, permanently.

Agriculture: Farming has direct and indirect impacts on groundwater quality. Direct impacts include dissolution and transport of excess quantities of fertilizers, pesticides, herbicides, antibiotics, hormones and associated materials and hydrologic alterations related to irrigation and drainage. Indirect impacts include changes in water–rock interactions in soils and aquifers caused by increased concentration of major ions and metals. Many studies indicate that agricultural practices have resulted in nitrate (NO3–) and pesticide contamination of groundwater with localized concentrations in shallow aquifers.

Sustainable agriculture is one of the greatest challenges to attain in the fast developing economies in Africa. According to FAO, sustainability implies that agriculture not only secures a food supply, but that its environmental, socio-economic and human health impacts are recognized and accounted for within national development plans. However, this is not priority in poor areas due to the attention to attain food security.

The potential groundwater contaminants due to agricultural activity are:

Nutrients: The risk of nutrients such as nitrogen and phosphorus reaching groundwater depends on the nutrient application method and extent, type of plantation and the type of soil. Phosphorus is not very soluble in water and rarely reaches groundwater except in highly permeable soil. In contrast, nitrogen is water soluble and rapidly converts to nitrate, which can contaminate groundwater unless it is used up by plants. High nitrate levels can lead to euthrophication of water bodies.

Pesticides are most likely to leach through sandy soils that contain little organic matter. Pesticide absorption and breakdown is inefficient in sandy soils with little organic matter because there are fewer microbes, and leaching can be rapid through the large soil pores. Since pesticides are designed to kill pests, excessive use will have far-reaching impact on people who consume groundwater underlying agricultural areas.

Microorganisms live in animal and human intestinal tracts and are excreted in faeces and manure. When they reach surface water, they can cause disease in humans and livestock. Groundwater is largely protected from such contamination because of the physical (filtration), chemical (adsorption) and biological (natural die-off) processes.

10.4 Groundwater-dependent ecosystems (GDEs)

Groundwater-dependent ecosystems (GDEs) vary from being marginally or only occasionally dependent on groundwater to being entirely groundwater dependent.

GDEs are communities of plants, animals and other organisms whose extent and life processes depend on groundwater. The following are some ecosystems that may depend on groundwater:

- Riverine environements where baseflow discharge maintains perennial streamflow.
- Wetlands in areas of groundwater discharge or shallow water table
- Terrestrial vegetation and fauna, in areas with a shallow water table or in riparian zones along streams/ rivers
- Aquatic ecosystems in groundwater-fed streams and lakes
- Karst systems
- Springs
- Estuarine and near-shore marine ecosystems

Threatening activities to GDEs:

The major threatening activities are:

- extensive groundwater resource development
- changes in land use – particularly change from indigenous vegetation to agricultural land
- agricultural development and expansion
- dewatering and acid mine decant associated with mining
- river diversion and daming
- commercial, urban or recreational developments.

?

What are some of the threatening activities on GDEs in your watershed?

These activities have potential to alter the groundwater levels and the water quality enjoyed by GDEs. GDEs are, to a significant extent, reliant on groundwater and those that occupy a very narrow ecological range and those in arid and semi arid areas could be completely eliminated by even relatively small changes in water regime or water quality. In dry seasons, especially in less humid and semi-arid areas in Africa, the base flow of rivers is maintained entirely from groundwater. This makes management of this groundwater very important for both human and environment where wildlife, flora and people depend on surface water availability.

Many GDEs exist in environments that have been modified by human activity. Some have come into existence due to human activities, such as wetlands that may occur downstream of sewage treatment plants or mine decant sites. Others have dried up as a result of one or more threatening activities indicated above.

Some GDEs are vulnerable to slight groundwater declines due to excessive use and / or a decrease in recharge. Groundwater extraction by humans can lower groundwater levels in unconfined aquifers and the piezometric head in confined aquifers. The result can be alteration of the timing, availability, and volume of groundwater flow to GDEs.

Some of the planning and coordinated implementation methodologies that are appropriate to minimize adverse impacts on GDEs ecosystems are (1) maintaining natural patterns of recharge and discharge; (2) minimizing disruption to groundwater levels that are critical for ecosystems; (3) protecting groundwater quality by preventing the addition of toxic contaminants; and (4) rehabilitating degraded groundwater systems where possible.

Environmental flows

Environmental flows are the quantity and timing of surface and ground water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and the services they provide to people. Environmental flows are intended to mimic the patterns and ecological outcomes of the natural flow regime. In order to maintain a healthy environmental flow, coordinated management of surface water and groundwater is essential. There are flexible and iterative frameworks that can help in the environmental flow assessment in a given river basin. The following framework includes three levels of assessment: 1) Comprehensive hydrologic assessment: desk top and field (identifying hydrologic indicators, ecological limits of hydrological alterations); 2) Scientific interpretation of the processes and impacts: focus group discussion; and 3) examining trade-offs and prediction of impacts and recommendations.

Even though environmental flow assessment focuses on river water, the management solution will surely address sustainable use of groundwater in order to maintain base flow to streams.

Some goals for the management of GDE’s are suggested below:

- Manage GDEs to satisfy various legal mandates, including, but not limited to, those associated with floodplains, wetlands, water quality and quantity, acid mine drainage and decant, endangered species, and cultural areas.
- Manage GDEs under the principles of IWRM, while emphasizing protection and improvement of groundwater.
- Delineate and evaluate both groundwater and GDEs before implementing any project potentially adversely affecting the resources. Determine geographic boundaries of GDEs based on site-specific characteristics of water, geology, flora, and fauna.

- Establish maximum limits to which water levels can be drawn down at a specified distance from a GDE in order to protect the character and function of that ecosystem.
- During borehole development, establish a minimum distance from a connected river, stream, wetland

?

What measures would you recommend?

10.5 Groundwater over-abstraction

Groundwater depletion is the inevitable and natural consequence of withdrawing water from an aquifer. Groundwater over-abstraction has a potential to affect the water balance in catchments of rivers and wetlands in hydraulic connection with groundwater and may lead to reductions in baseflow. However, ‘over abstraction’ is a value judgement. How much is ‘over abstraction’? Over abstraction may be considered to occur if there are any irreversible impacts on the aquifer. Of course by this stage, it is already too late because permanent environmental damage has already taken place. Over abstraction might be considered to occur when the benefits of groundwater abstractions are overshadowed by the negative impacts arising from reduction to baseflow and spring flow.

Granting licenses for groundwater abstraction in sensitive areas requires comprehensive understanding of the interrelationship of the surface water and groundwater bodies. Such information will not be readily achieved without a suitably designed monitoring system and a good time series of data to assist in assessing this interrelationship, which may then be used as a basis for adjusting abstraction limits.

The response of the aquifers to over-pumping depends on characteristics of the aquifer, such as aquifer transmissivity and specific yield (if unconfined) or storativity (if confined) and the rate of recharge. Confined or leaky aquifers will show the most rapid and most significant head response to pumping and this can induce the most significant head differences and fluxes at a river. Land subsidence adjacent to developed aquifers can result from fluid pressure declines because of groundwater withdrawals.

It is important to be flexible when developing management solutions to such environmental challenges. Conserving groundwater by reducing pumping can be accomplished through administrative, legislative, or management controls, including economic incentives to reduce demand. It is important to target reductions that actually save water. In agricultural areas, for example, improved efficiency is sometimes sought through lining irrigation canals to reduce seepage. While this saves irrigation water, it also reduces return flows to the groundwater. A more effective strategy might be to plant a different crop that uses less water.

Conjunctive management of surface water and groundwater could help to reduce the pressure on both resources. Conjunctive management of surface and groundwater may be predicated on the feature that surface water abstraction, daming, diversion etc. have very significant upstream / downstream impacts. With groundwater abstraction, the impacts are centred around the abstraction points with much less significant upstream / downstream effects. Optimization methods may be used to position pumping centers to maximize withdrawals while minimizing upstream / downstream detrimental effects such as stream baseflow depletion. This may lead future water managers to implement appropriation zoning or to require well permits in which allowable pumping rates vary with location because of hydrogeological properties, distance from boundaries, and unit responses of surface water.

Reallocation between also economic sectors provides opportunities to optimize conjunctive use. For example potable groundwater resources may be substitued for untreated surface water, which may then be directed to irrigation demand.

10.6 Environmental aspects of groundwater management

Groundwater management is an important part of water resources management in order to sustain the livelihood of vast rural populations, rapidly growing urbanization, irrigation and industrial activity. The three main considerations for environmentally sound groundwater management are the following:

(i) Groundwater development must be sustainable on a long-term basis. This means that the rate of abstraction should be equal to or less than the rate of recharge. If the rate of abstraction is higher than the rate of recharge, it will result in groundwater mining, which may be carefully considered for some specific cases. If mining occurs, groundwater levels will continue to decline, which will steadily increase pumping costs, and then at a certain level it would no longer be economic to pump it for many uses such as agricultural production.

(ii) Human activities which could impair the quality of groundwater for potential future use should be controlled. This would include leaching of chemicals like nitrates and phosphates from extensive and intensive agricultural activities, contamination by toxic and other undesirable chemicals from landfills and other environmentally unsound waste disposal practices, bacterial and viral contamination due to inadequate sewage treatment and wastewater disposal practices, and increasing salinity content due to inefficient or improper irrigation practices, and salinization due to overpumping in coastal areas.

(iii) Improper groundwater management often contributes to other adverse environmental impacts such as dessication of wetlands, decrease in baseflow etc.

Environmental impact assessments may be considered to be as a planning tool to assist planners in anticipating potential future impacts of alternative groundwater development activities, both beneficial and adverse, with a view to selecting the ‘optimal’ alternative which maximizes beneficial effects and mitigates adverse impacts on the environment. It can be used not only for groundwater development projects but also for plans, programmes and policies (Biswas, 1992).

10.7 The role of basin organizations in environmental management of groundwater.

What are the roles that basin organizations can assume to make sure that the groundwater management carried out is sensitive to environmental needs?

Water availability:
This module has discussed the impact of groundwater abstraction on baseflow and on groundwater dependent ecosystems. BO's may carry out river hydrograph analyses to determine how much of total river flow in the catchment may be attributed to baseflow. Comparisons between river flow in areas with heavy groundwater use and similar rivers in areas without groundwater abstraction can provide some answers. However monitoring of both groundwater pumping, time series of groundwater levels and river stage levels will be essential to manage these interactions. Without data, such management becomes just guess work, and can have a negative economic impact without providing any benefits to river flow.

BO's may carry out an inventory of groundwater dependent ecosystems and quantify their economic and environmental value. If such ecosystems are potentially threatened by groundwater resource development or changes in land use, then the BO may institute monitoring and issue groundwater abstraction permits of short duration with regular review. A priority ranking system can be helpful to ensure the most vulnerable and the most valuable GDEs are protected. GDE's may start to change in unacceptable ways long before complete dessication, and thresholds for such changes need to be understood and defended.

BOs should also assess the economic and environmental value of maintaining baseflow. Groundwater that discharges as baseflow has significant downstream impacts, a factor that needs to be considered when allocating permits to abstract groundwater.

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MODULE

GROUNDWATER AND CLIMATE CHANGE

CONTENT

MODULE 11

Groundwater and Climate Change

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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Picture: *IWMI*

GROUNDWATER AND CLIMATE CHANGE

LEARNING OBJECTIVES

- To become familiar with the basic concepts of the impacts of climate change on groundwater
- To explore the link between climate change impacts and groundwater resources
- To understand the potential for climate adaptation through groundwater management

11.1 Introduction

Groundwater is the major source of drinking water in Africa and has a rapidly expanding role in irrigation to combat growing food insecurity. This module deals with both the impact of climate change on groundwater resources and the role that groundwater can play in adapting to the impacts of climate change. Although the focus is on Africa, it is important to recall the global extent of climate change, and to consider the impacts on the scale of the global hydrologic cycle.

Of Africa's population of 1 billion, roughly 60% live in rural areas and most – perhaps 80% – rely on groundwater-based community or household supplies for domestic and other water needs (JMP, 2008). Currently there are more than 300 million people in Africa without access to safe drinking water, many of whom are amongst the poorest and most vulnerable in the world (MacDonald et al. 2012). Climate variability and change influences groundwater systems both directly through replenishment by recharge and indirectly through changes in groundwater use. These impacts can be modified by human activity such as land-use change (Taylor et al. 2013).

Climate change will manifest itself by modifying rainfall and evaporation patterns in the river basins thus altering the hydrological balance. Changes in mean annual rainfall, as well as in its temporal and spatial distribution, would be expected to influence the water balance as a whole, including groundwater recharge.

River basins incorporate the interaction of environmental changes and human activities at different spatial and temporal scales. Regional temperature trends presented in IPCC (2001) show trends for grid boxes located in Sudan and Ethiopia in the order of +0.2-0.3 ºC/decade from 1946 to 1975. Hulme et al. (2001) found an African mean trend of about 0.5 ºC/century. According to Conway (2005), there is high confidence that temperatures will rise in the Nile basin, leading to greater losses to evaporation. Higher evaporation rates will increase aridity and hence desertification due to the loss of soil moisture.

Even though much attention is given to the negative effects, it should not be forgotten that some areas will benefit from lower temperatures and increase in the mean rainfall amount that facilitates an increase in groundwater recharge and hence storage.

11.2 Groundwater as part of hydrologic cycle

The hydrologic cycle represents the continuous movement of water within the atmosphere, the earth's surface (glaciers, snowpack, streams, wetlands and oceans) and soils and rocks. The term groundwater refers to water in soils and geologic formations that are fully saturated. Groundwater is part of hydrologic cycle, which is recharged from precipitation. The hydrologic cycle primarily governed by the balance between input (Precipitation/rain) and output (Evapotranspiration, runoff and discharge) (Fig. 11.1).

The components of the groundwater balance are displayed in the figure and consist of recharge (direct recharge and inter-aquifer flows) and discharge (groundwater flow to streams, springs, lakes, wetlands, oceans; groundwater abstraction; evapotranspiration). The difference between recharge and discharge determines the change in the volume of groundwater.

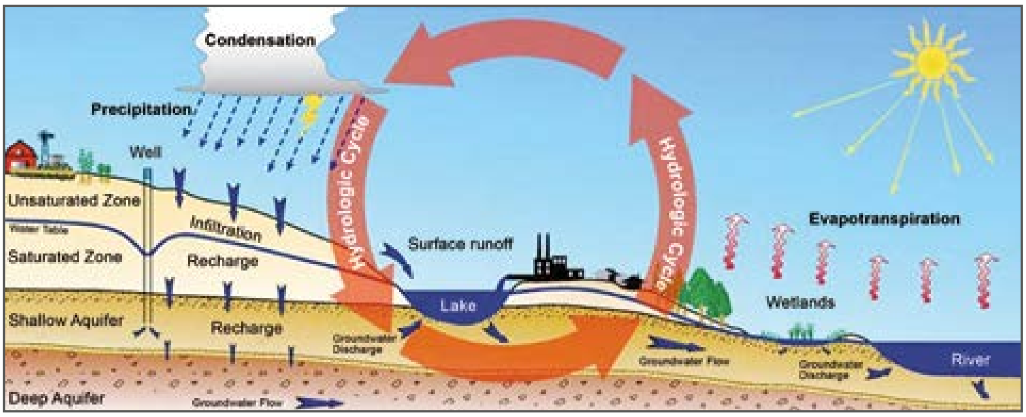

Figure 11.1: Hydrological components
[Precipitation (Rain)- ET- Runoff - Recharge= change in storage]

Any variation in climate has the potential to affect input into the groundwater (recharge) and output into surface water bodies as baseflow and springs (discharge), either directly or indirectly as vapour return into atmosphere.

An example of a direct impact would be reduced recharge due to a decrease in precipitation. An indirect impact would be salt-water intrusion into coastal aquifers due to sea level rise, which represents a major threat to coastal groundwater quality.

However probable impacts of land use change and groundwater abstraction on groundwater quantity and quality are expected to be the most significant indirect impacts of climate change on groundwater. These changes may include increased irrigation from groundwater to offset declines in rain-fed crop production.

11.3 Climate variability and climate change

Climate variability refers to a deviation of climate from the long-term meteorological average over a certain period of time, e.g. a specific month, season or year. These variations are a natural component of the climate caused by changes in the system/s that influence the climate such as the general circulation system.

On the other hand, 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 forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use” (IPCC, 2007).

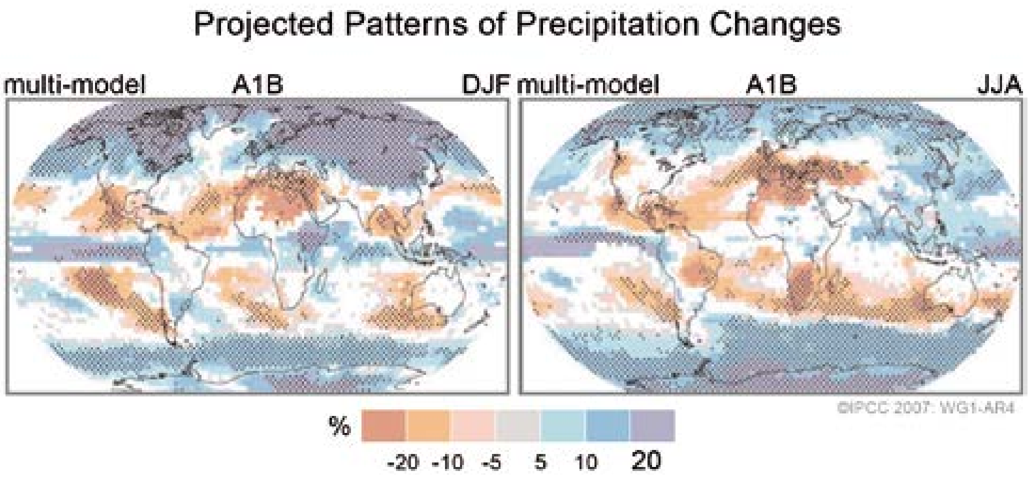

Figure 11.2: Relative changes in precipitation (%) for the period 2000-2099, relative to 1980-1999. Values are multi-modal averages based on the SRES A1B scenario for Dec-Feb (left) and June-Aug (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change (IPCC, 2007).

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) and it has an impact on mean annual precipitation (Fig. 11.2). Climate also varies in response to natural phenomena, on seasonal, inter-annual, and inter-decadal scales such as the El Nino Southern 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 11.1 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.

Table 11.1 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.
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 are 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), SKM (2009)*

11.4 Climate change scenarios

There is considerable uncertainty surrounding the future of Africa's climate as reported in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Christensen et al., 2007).
First, average temperatures are likely to increase. Hulme et al. (2000) show that for Africa as a whole, warming in the 20th Century occurred at a rate of about 0.5 ºC across the century, and that the rate of warming increased in its last three decades. In future, based on predictions under the medium-high greenhouse gas emissions scenario, annual mean air temperature between 2080 and 2099 is expected to be 3-4ºC higher than it was between 1980 and 1999.

Second, annual rainfall is likely to fall in the northern Sahara and in southern Africa, and is likely to increase in the Ethiopian Highlands. Wider predictions are difficult to make as changes in precipitation are much less certain than those for temperature, particularly for the Sahel and the West African coast. Downscaling to the level of large river basins with current circulation models may produce more hydrological 'noise', rather than clearer insight (Calow and MacDonald, 2009).

Finally, rainfall is likely to become increasingly unpredictable in terms of both intensity and duration, with increases in the frequency of extreme events - droughts and floods. Mean annual rainfall is already highly variable across Africa, ranging from almost zero over parts of the Sahara to around 10,000 mm in the Gulf of Guinea. Inter-annual and seasonal variability is likely to increase.

11.5 Impacts of climate change on groundwater

Introduction

Groundwater will be less directly and more slowly impacted by climate change than surface waters. This is because rivers get replenished on a shorter time scale, and drought and floods are quickly reflected in river water levels. Groundwater, on the other hand, will be affected more slowly.

The key areas where climate change affects groundwater is through recharge, discharge and storage. Irrigation dominates current groundwater use by volume, and the effects of future climate variability and change on groundwater may be greatest through indirect effects on irrigation-water demand (Taylor et al., 2013).

However domestic groundwater use is the most widespread use of the resource, covering over 2 billion people. Although groundwater is generally regarded as a 'drought resistant' resource, many of the shallow aquifers that supply rural populations are vulnerable to annual and longer droughts. It is the deep and confined aquifers that tend to exhibit declining trends only after prolonged droughts (BGR, 2008).

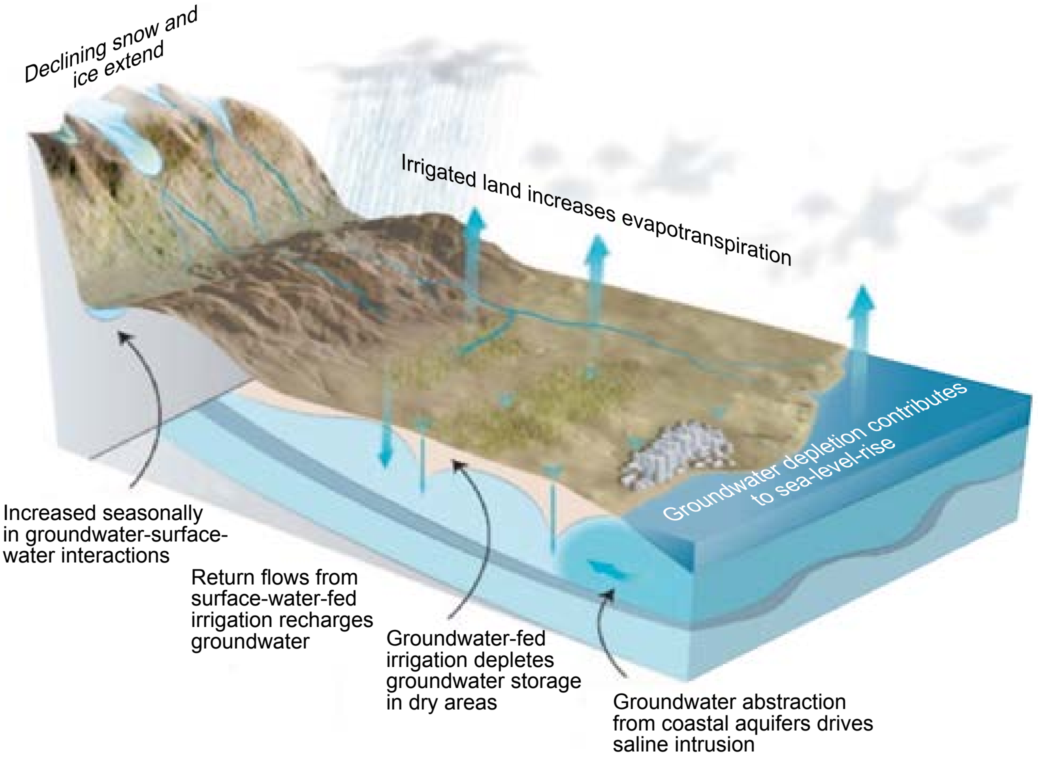

Figure 11.3: Conceptual representation of key interactions between groundwater and climate (source: Taylor et al., 2013)

Recharging of groundwater from precipitation, increase in irrigation to meet food security and groundwater pumping are interlinked through the impact from climate change (Fig. 11.3).

Groundwater recharge

Groundwater is the major source of water across Africa both in rural and urban areas. In major metropolitan areas in Africa, surface water plays a leading role. Groundwater recharge can occur locally from surface water bodies or in diffuse form from precipitation via the unsaturated soil zone. Recharge is not only influenced by the magnitude of precipitation, but also by its intensity, seasonality, frequency and changes in land use.

Natural replenishment of groundwater occurs from both diffuse rain-fed recharge and focused recharge via leakage from surface waters (that is: streams, wetlands or lakes) and is highly dependent on prevailing climate as well as on land cover and underlying geology. Climate and land cover largely determine precipitation and evapotranspiration, whereas the underlying soil and geology dictate whether a water surplus (precipitation minus evapotranspiration) can be transmitted and stored in the subsurface (Taylor et al., 2013).

This water may reach the aquifer rapidly, through fractures, or more slowly by infiltrating through micro-pores in the soils overlying the aquifer. A change in the amount of effective rainfall will change the recharge into the groundwater.

Global warming due to temperature increase is important in directly controlling evapotranspiration and thus the portion of precipitation that may drain through the soil profile into aquifers. Other factors affecting groundwater recharge include land cover, soil, geology, slope and aquifer type.

Increased variability in rainfall may decrease groundwater recharge in humid areas because more frequent heavy rains result in the infiltration capacity of the soil being exceeded, thereby increasing surface runoff and hence flooding. In semi-arid and arid areas, however, increased rainfall variability may increase groundwater recharge, because only high-intensity rainfalls are able to infiltrate fast enough before evaporating, and alluvial aquifers are recharged mainly by inundations during floods (BGR, 2008).

Recharge is very important in regulating the volume of groundwater. Reduction in recharge will reduce the volume of renewable groundwater.

Output

Extreme climatic variation has a control over the hydrologic balance through reduction or increase in input and output components. Output components include evapotranspiration, runoff, groundwater discharge into streams and springs, and groundwater pumped from boreholes.

The impact of climate change on groundwater discharge is related to lowering of the groundwater table, which is linked to baseflow to rivers and springs. The impact can be most readily observed through changes to groundwater dependent ecosystems. Another cause for decrease in discharge is the over-pumping of renewable groundwater in order to cope with the water stress as a result of climate change. Increased pumping lowers the water table, and thus reduces discharge to baseflow.

The impact of climate change on output parameters may not be the same. Due to the increase in temperature, evapotranspiration will increase, but there is no guarantee of an increase in precipitation. If precipitation decreases, runoff will decrease, and in addition groundwater recharge will decrease, thus leading to a decrease in groundwater baseflow into streams and springs.

For evapotranspiration, direct climate change impacts include:

- Changes in groundwater use by vegetation due to increased temperature and CO2 concentrations, and
- 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 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 the relative head levels between groundwater and surface water. If groundwater falls below surface water levels, groundwater discharge as baseflow or spring discharge may no longer occur. Similarly, if surface water has been flowing to the groundwater system, for example from a losing stream, this recharge may cease if surface water levels decline below the local groundwater levels. 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 over-pumping is an indirect climate change impact and 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, groundwater will become a critical facet for communities to adapt to climate change.

Groundwater storage

Groundwater storage is the balance between input and output over a given period of time. Aquifers provide water that was recharged over centuries and millennia. Storage is controlled by the intrinsic aquifer properties such as storativity, transmissivity and aquifer geometry. Regionally extensive aquifers receive recharge from extensive catchment areas and hence do not react to short term climatic variability while shallow unconfined aquifers are more responsive to smaller scale climate variability. The impact of climate change on storage depends on whether or not groundwater is renewable or non-renewable (fossil) resource. Even though there is no direct climate change impact on fossil groundwater, the impact would encourage over-abstraction of fossil water during the stress period. Shortage of recharge due to climate change results in reducing the renewable storage.

Water quality

In many areas, aquifers provide an important source of freshwater supply. Maintaining water quality in these aquifers is essential for the communities. In shallow aquifers, groundwater temperatures may increase due to increasing air temperatures. In arid and semi-arid areas increased evapotranspiration may lead to soil salinization, which will affect the quality of soil moisture and associated groundwater system. In coastal aquifers, sea level rise and storm surges are likely to lead to sea-water intrusion and salinization of groundwater resources especially in areas with over-abstraction of groundwater resources.

In areas where rainfall intensity is expected to increase, pollutants (pesticides, organic matter, heavy metals, and pit latrines) will be increasingly washed into water bodies, including the groundwater. In addition, recharge from polluted surface water bodies will further compromise groundwater quality.

11.6 Climate change and population growth

Population growth has intimate relation with climate change. Increased population leads to increased water demand both for domestic use, and for production for food and industry. The associated land use changes and socio-economic factors are likely to influence the capacity to appropriately manage the groundwater resource.

Especially in Africa, groundwater has been poorly managed. Low investment in groundwater investigations and management has placed groundwater under stress either through pollution or over abstraction. Increased groundwater use associated with population growth has also been a factor, particularly in arid and semi-arid areas where water is scarce.

African population will grow by about 154% between 2000 and 2050 under the UN medium variant and by 119% to 193% under low and high variants according to UNFPA (2000, 2008 cited in Carter and Parker, 2008). It is well-established that demand for water grows over time as a consequence of both increasing population and changing water use patterns (Carter and Parker, 2008).

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 groundwater table rise over the same period.

11.7 Implications for groundwater dependent sectors

As a result of climate change and scarcity of surface water, dependence on groundwater especially in Africa is expected to be high. Climate change and population increase 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.

Shallow wells often provide an important source of drinking water for dispersed rural populations in Africa. The predicted increase in demand and increased severity of droughts may cause many of these shallow wells to dry up. The drying up of shallow groundwater has a tremendous negative impact on the rural livelihood. With limited alternatives for safe drinking water supplies and long distances between such water points, the loss through drying out of these well would force people to use unsafe water resources (Fig. 11.4). Small-scale irrigation, usually reliant on shallow groundwater, would also be affected.

Where increases in heavy rainfall events are projected, floods can wash away sanitation facilities, spreading wastewater and potentially contaminating groundwater resources. Flooding is linked to increased risk of diarrhoeal disease. The risk 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.

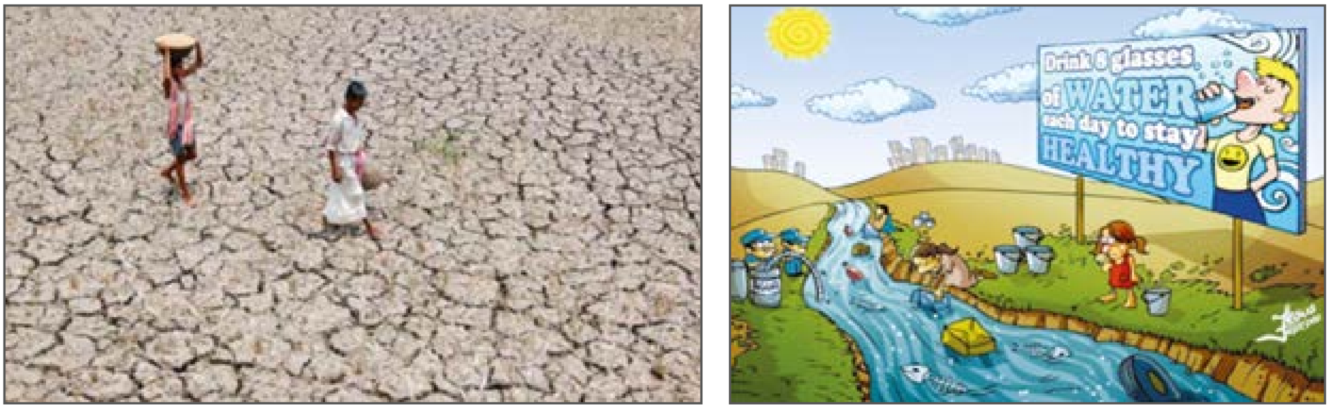

Figure 11.4: Water stress challenges

11.8 Adaptation to climate change

What is adaptation?

In order to cope with climate change, an integrated approach is needed. Such an approach embraces both mitigation, which addresses the drivers of climate change, and adaptation, which considers the measures necessary to accommodate such changes.

Adaptation is adjustments made to natural and human systems in response to experienced or projected changes in climatic conditions and their beneficial and adverse impacts (Fig 11.5). In the context of groundwater they are concerned with reducing the vulnerability of groundwater dependent systems to climate change and hydrological variability. However adaptation to climate change is also likely to increase the use of and dependence on groundwater in response to declines in surface water resources.

How can basin organizations adapt to climate change?

Adaptations are essentially management responses to risks associated with climate variability and climate change. With regards to water resources, it is the basin organizations that will have to implement strategies and policies to mitigate the risks associated with water stress and to adopt water management suited to the changing water resources conditions.

Every basin will be different due to differences in the water storage in the basin, whether surface or groundwater, and due to the changes bought about by climate change. In addition, demand for water in each basin differs due to a variety of socio-economic issues. Basin organizations can be proactive towards climate change by carrying out risk assessments for their own basins and then building their adaptation strategies accordingly. This can be an important exercise for basin organizations to carry out before crises surface.

Figure 11.5: Adapt to the changing condition

Importance of groundwater in a changing climate

Groundwater plays a critical role in adapting to hydrologic variability and climate change (Clifton et al. 2010). Groundwater provides options for enhancing the reliability of water supply for domestic, industrial, livestock watering and irrigation. Some adaptations that can be accessed using groundwater include:

- **Integrating the management of surface water and groundwater resources –** including conjunctive use of both groundwater and surface water to meet water demand. Integrated management aims to ensure that the use of one water resource does not adversely impact on the other. It involves making decisions based on impacts for the whole hydrologic cycle, and on the spatial distribution of surface and groundwater resources and the demand distribution for water.
- **Managing aquifer recharge (MAR)** – including building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge. MAR is among the most promising adaptation opportunities for developing countries. It has several potential benefits, including storing water for future use, stabilizing 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.
- **Land use change** – changing land use may provide an opportunity to enhance recharge, to protect groundwater quality and to reduce groundwater losses from evapotranspiration. Changes in land use should not result in adverse impacts to other parts of the environment. Lower water demand crops and salt tolerant crops are potentially useful land use changes to adapt to different water stresses.

Building adaptive capacity for groundwater management

Building adaptive capacity is a crucial cross-cutting theme and applies, at least partially, to multiple themes. Adaptive capacity building 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 Clifton et al. (2010) are given in Table 11.2.

Table 11.2. Adaptation options: building adaptive capacity

Adaptation option	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 paleo-climate 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 trading of water within a groundwater system. Market to determine the price for water. ■ Property rights – establish clear title and property rights to groundwater.

Managing groundwater recharge

Groundwater recharge areas may be managed to protect or enhance water resources and to maintain or improve water quality. One method would be through managed aquifer recharge. Managed aquifer recharge (MAR) involves building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge (Fig. 11.6). 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 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. Aquifer conditions must be appropriate and suitable water sources (e.g. 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.

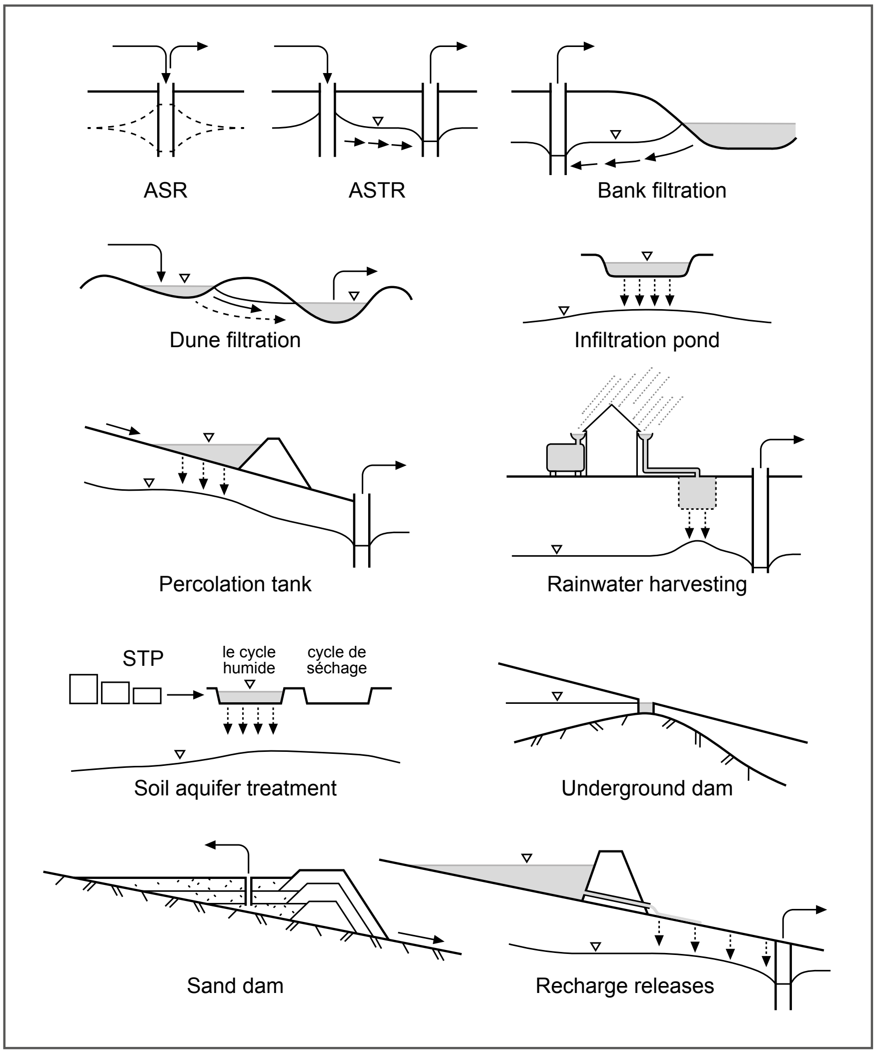

Figure 11.6: Examples of managed aquifer recharge (MAR) approaches.

ASR: aquifer storage and recovery; ASTR: aquifer storage, treatment and recovery, STP: sewage treatment plant. Source: Peter Dillon cited in Clifton et al., 2010

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 MAR using storm water or treated waste water) 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 storages

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 reservoirs as storage space 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 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.

11.9 Summary:

Climate change results in further straining already stressed water resources, eco-systems, and derived systems, which are used to service society. Groundwater needs to be protected, and its use and maintenance adapted to climate change. Groundwater can enhance the resilience of domestic, agricultural and industrial uses of fresh water in the face of climate variability and change. As the only perennial source of fresh water in many regions, ground water is of vital importance to the water security of many communities, including, most critically, rural dwellers in low-income countries. Groundwater-fed irrigation provides a buffer against climate extremes and is consequently essential to global food security (Taylor et al., 2013).

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