NON-RENEWABLE GROUNDWATER RESOURCES

A guidebook on socially-sustainable management for water-policy makers

planned aquifer depletion

social sustainability

adaptive groundwater management

participation of groundwater users

United Nations Educational, Scientific and Cultural Organization

GW-MATE world bank

Edited by
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and Daniel P. Loucks

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بير تشرب منه لا ترمي فيه حجر

Bīr tishrab minhu lā tarmī fīhi ḥajar

Arabic Proverb
(literally)

'Into the well from which you drink do not throw stones'

[Care for the water upon which you depend]

From UNESCO

Hydrogeology is a relatively young discipline and therefore the **knowledge on** the characteristics and dynamics of different types of aquifer is still not yet fully achieved.

It is only very recently that groundwater experts have become aware of how climatic changes that took place during the various geological periods actually modified and shaped the earth and consequently the aquifer systems. Past climatic conditions made it possible to store vast groundwater resources in deep underground reservoirs. Some of these systems are the heritage of previous, more humid climatic conditions that existed thousands of years ago, and some of them are located in regions that today suffer from arid or hyper-arid climatic conditions and receive little contemporary natural recharge. The age of the water contained in these aquifers is therefore so old that it has inspired the use of terminology borrowed from paleontology; as a result these aquifers bear the nickname 'Fossil Aquifers'.

In arid zones groundwater is a source of life and as such it is difficult to find a balance between preservation and use. This is made more difficult when the necessary data required to study these systems is inaccessible, and even more complicated when such systems are transboundary and therefore shared between two or more countries.

Considering the complexity of the issue, and its political sensitivity, the UNESCO International Hydrological Programme (IHP) and the World Bank decided to call upon international experts to support the preparation of a text that could provide valuable indications on the sustainable use and management of these water resources.

This publication intends to provide a contribution not only towards the development of an improved knowledge base in the field of hydrogeology, but also to the sustainable management of groundwater resources in different regions of the world. In particular it aims to provide decision-makers with the relevant scientific information

UNESCO's IHP has been dealing with the issue of non-renewable groundwater resources since 1996. Indeed, in 1996 during its 12th session, the Intergovernmental Council of UNESCO's International Hydrological Programme, adopted Resolution XII-8 on the 'Study of fossil groundwater in Sub-Saharan and Saharan Africa' (Appendix 1). In this Resolution, the IHP Intergovernmental Council, considering that aquifer systems are often the main source of fresh water in arid and semi-arid zones, recommended to improve knowledge about Fossil Groundwater in

Sub-Saharan and Saharan Africa. Since then, UNESCO-IHP has undertaken several activities such as the International Conference on 'Regional Aquifer Systems in Arid Zones – Managing non-renewable resources' (Tripoli, 21-25 November 1999). The Conference marked a milestone in the review, discussion and analysis of the emerging concept of planned groundwater mining. One of the direct achievements of the Conference was the Tripoli Statement (Appendix 2) which recognized that in many arid countries the controlled and carefully regulated mining of non-renewable groundwater resources could provide an opportunity and a challenge for their social and economic development.

It is within this framework that UNESCO IHP in cooperation with the World Bank/ GW-MATE that UNESCO-IHP organized a seminar on the 'Socially-Sustainable Management of Non renewable groundwater resources' in Paris in September 2002. As a result of this meeting guidelines were formulated by a group of experts and the publication was initiated. It should be pointed out here that the authors contributed to this title under their own personal capacity. They were selected for their knowledge and expertise both in this specific field as well as within a specific region.

The case studies as well as the data and the indications provided in the chapters, refer mainly to situations existing in arid and semi-arid regions, although non-renewable groundwater resources are also found in humid and permafrost regions.

One such example from a temperate climate, is the Albian-Neocomian aquifer system located in France, in the Parisian basin, composed of two reservoirs, the Albian and the Neocomian, which are hydraulically linked. According to the indications provided by the French Agency 'Agence de l'Eau Seine-Normandie', the system covers 84,000 km^2 and its total estimated reserves are around 655 billion cubic meters. The Albian aquifer has very original characteristics: total protection against surface pollution, high reserves in water, and a very low natural recharge compared to its total volume. The Neocomian aquifer is still not well known, but seems to present similar characteristics. The Albian aquifer has been developed since the middle of the nineteenth century. The result was a drop in the water table of 80 meters. Public authorities reacted and in 1935 adopted a regulation imposing a licensing regime on all drillings of more than 80 meters depth in the Parisian basin. The Neocomian aquifer was developed only recently (in 1982).

Today the Albian-Neocomian system is considered an important strategic resource (Agence de l'Eau Seine-Normandie, www.eau-seine-normandie.fr/index.php), exploited mainly for drinking water purposes. In 2003, the 'Schéma Directeur d'Aménagement et de gestion des eaux du bassin Seine-Normandie' was amended in order to maintain the emergency function of the system (arrêté préfectoral n°2003-248, 24 February 2003). Indications concerning the total annual volume of water that can be extracted from the system in case of emergency are carefully provided.

Some of the aquifer systems considered in this monograph are transboundary, as already mentioned. Their management creates specific problems. The sharing of these resources implies equity of influences from all parties concerned, co-operation in development policies and plans and ideally joint monitoring. This particular issue has been considered and developed in the draft articles on the law of transboundary aquifers, in preparation since 2003 at the UN International Law Commission, with the scientific support of UNESCO-IHP.

They are also part of the inventory of transboundary aquifers around the world initiated by UNESCO-IHP since 2000 under its Internationally Shared Aquifer Resources Management project (ISARM). The aim of the project is to reach the sustainable management of transboundary aquifers.

Finally, just recently, UNESCO-IHP together with WMO submitted the chapter on the status of the resources in the second UN World Water Development Report (March 2006) recommending to decision makers and water scientists to pay greater attention to non-renewable groundwater resources.

We hope that this monograph could be useful to decision makers in addressing the environmentally and socially sustainable policies that should be set up as long as due consideration is given to the assessment and management modalities for non-renewable resources.

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From the World Bank

The World Bank, through GW-MATe its Groundwater Management Advisory Team, has been pleased to work with the UNESCO-International Hydrological Programme on the development and writing of this publication. GW-MATE also acts as the Global Water Partnership Associate Programme on Groundwater Management, and the members of GW-MATe that have been involved in this publication are Stephen Foster (Director), Marcella Nanni (Water Sector Legislation Specialist) and Karin Kemper (GWMATE Manager/Lead Water Resources Management Specialist).

The utilisation of non-renewable groundwater resources, whether on a planned or unplanned basis, implies the mining of storage reserves. As such it presents a special challenge due to the social, economic and political concerns that have to be taken into account by policy and decision makers.

In the more arid climates in general and the Middle East and North Africa Region in particular, the use of non-renewable groundwater offers an opportunity to alleviate growing water scarcity, improve social welfare and facilitate economic development. Therefore such development should be considered if certain criteria can be met and specific risks can be managed in order to ensure socially sustainable utilization of the resource. Constraining utilization of non-renewable groundwater on grounds of long-term physical unsustainability would be insufficient.

To confront the challenge posed in achieving socially-sustainable development of non-renewable groundwater an integrated approach to resource management will be essential. Integrated across the water-user sectors and integrated in a multi-disciplinary sense. It is for this latter reason that the Guidebook places strong emphasis on the socio-economic, institutional and legal dimensions of groundwater utilisation and management, and places less weight on the technical aspects of resource evaluation, which have been dealt with extensively elsewhere.

It has to be recognised that in hydrogeology, like other environmental sciences, it will always be difficult to provide black-and-white definitions for many useful concepts that are essential for communication at practical resource management level. As outlined in this publication, non-renewability of groundwater resources is not an absolute term but a relative concept – in the same way as the now widely-accepted expression 'groundwater pollution vulnerability'.

The target audience for this publication is water resource decision-makers, and the Guidebook is written in a style intended to provide easy reference for them, with a specific framework of Guidelines being presented upfront. We hope that they find the Guidebook provides a genuinely progressive, but at the same time, sensitive and practical viewpoint on this important environmental topic.

Dr Karin Kemper
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> Mr Jaroslav Vrba, Senior Consultant UNESCO-IHP, IAH Commission on Groundwater Protection, Czech Republic.

The achievement of this publication would not have been possible without the long lasting efforts of Ms Raya Marina Stephan, lawyer, expert in water law, consultant for UNESCO-IHP on the groundwater resources activities; coordinator and active member since 2003 of the UNESCO-IHP's experts group assisting the Special Rapporteur of the UN International Law Commission on the topic of transboundary groundwaters. Ms Stephan has played a central role since the beginning of the project contacting the selected authors, collecting their contributions, coordinating with the editors, considering the comments received from the peer-review process, and compiling the final text.

Contents

CHAPTER 1

Concept and importance of non-renewable resources

Jean Margat, Stephen Foster and Abdallah Droubi

'Non-renewable groundwater' as a concept

Groundwater resources are never strictly non-renewable. But in certain cases the period needed for replenishment (100s or 1000s of years) is very long in relation to the normal time-frame of human activity in general and of water resources planning in particular. In such cases it makes practical good sense to talk in terms of '**non-renewable groundwater resources**' (Table 1). Some hydrogeolgical settings which are often associated with non-renewable groundwater are illustrated in Figures 1 A-D.

In nature aquifers have a capacity for both water storage and water flow, and thus groundwater simultaneously accumulates and circulates – the volume of groundwater stored in some of the larger aquifer systems is huge and represents some 97% of our planet's freshwater resources (excluding that locked as ice in the polar regions).

Groundwater **resource renewal** is a concept that derives from a comparison between the natural flow and storage of aquifer systems (Table 2). The range in nature is extreme with **renewal periods** of less than 10 years to more than 100,000 years. In cases where present-day aquifer replenishment is very limited but aquifer storage is very large, the groundwater resource can thus be termed **non-renewable** (Table 1).

'Non-renewability' does not necessarily imply that the aquifer system is completely without replenishment or entirely disconnected from processes at the land surface (since absolutely zero recharge is extremely rare). 'Renewal periods' (Table 2) are necessarily an approximate average for the aquifer under consideration, and may conceal a large range of local variation within the hydrodynamics of the aquifer flow regime – for example with more rapid 'turnover' of groundwater in the upper horizons of a thick aquifer and 'essentially stagnant' groundwater at greater depth. Moreover, both the drainable storage of an aquifer system and its long-term average rate of recharge are difficult to estimate with precision, and thus it may sometimes be difficult in practice to distinguish between essentially non-renewable and weakly replenished groundwater resources.

Table 1. Glossary of key terms

TERM	DEFINITION ADOPTED*	EXPLANATORY COMMENTS
Non-Renewable Groundwater Resource^	**groundwater resource available for extraction, of necessity over a finite period, from the reserves of an aquifer which has a very low current rate of average annual renewal but a large storage capacity**	● possible limiting criterion sometimes suggested is that the renewal period should be more than 500 years (average aquifer renewal less than 0.2% of aquifer storage) ● some argue that a limiting average rainfall (say 300 mm/a) ought also to be included in definition ● usually expressed as the **total volume** of extractable groundwater or as an annual average **flow rate for a fixed period**, under practical field conditions (drilling accessibility and hydraulic productivity), realistic economic considerations (maximum affordable cost) and with consideration of potentially undesirable side-effects ● the absence of significant replenishment is usually a consequence of very low rainfall in the unconfined areas of the aquifer but can also result from hydraulic inaccessibility in some confined aquifer
Fossil Groundwater	**water that infiltrated usually millennia ago and often under climatic conditions different to the present, and that has been stored underground since that time**	● concept is thus both genetic and kinematic, since linked with both the mechanism of emplacement and the groundwater age (time passed since water under consideration entered aquifer) respectively ● **groundwater age** relates to period of residence of groundwater concerned within the aquifer, rather than (of necessity) the present-day absence of recharge of the aquifer system as a whole, and thus concept does not necessarily imply a non-renewable resource ● should not to be confused with **connate groundwater**, which is trapped in a geological strata since its formation and is thus often saline and frequently occurs in aquitards (rather than aquifers)
Aquifer Overexploitation (Overdevelopment)^^	**prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities exceeding its average annual replenishment, bringing about a persistent fall in groundwater levels and reduction of aquifer reserves with undesirable side-effects**	● concept of overexploitation is intended to indicate an **imbalance** within the groundwater budget of the aquifer system under consideration and the term **aquifer overdraft** is also sometimes used to indicate 'the amount of groundwater withdrawn from aquifer reserves' ● however, the **definition of time period and geographical area** over which to evaluate this budget is always subjective and interest is usually more in the **side-effects of groundwater depletion** on aquifer users, third parties and the environment (well yield reductions, saline water intrusion, land subsidence, ecosystem impacts, etc) than the process itself ● important not to confuse aquifer overexploitation with active exploitation of an aquifer as a **regulating reservoir** (between seasons or in drought years) without any rupture of its long-term equilibrium
Groundwater Mining^^	**extraction of groundwater from an aquifer having predominantly non-renewable resources with depletion of aquifer reserves**	● process distinguishable from overexploitation of an aquifer with renewable groundwater resources, since in its case the reduction of aquifer reserves (with or without side-effects) is **essentially permanent**

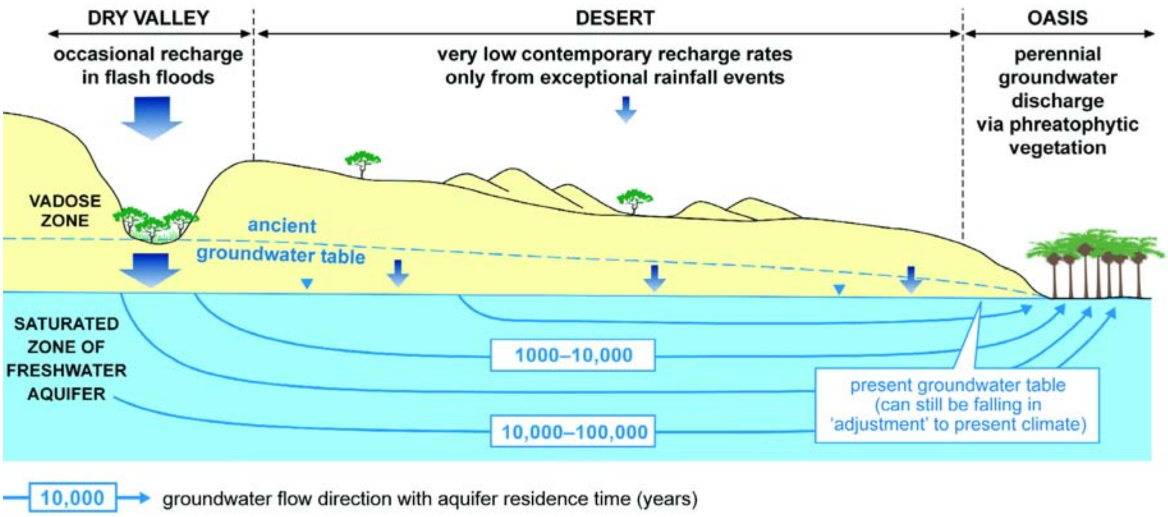
Note: * " definitions of International Glossary of Hydrogeology (1992) followed, except for terms marked ^ for which none available and ^^ for which some qualification deemed necessary (see for example Margat & Saad , 1984; Margat, 1992; Foster, 1992; Margat, 1996; Custodio, 2000; Foster & Kemper, 2002-04; Llamas & Custodio, 2003)

The main occurrences of non-renewable groundwater resources tend to fall into one or other of the following two categories :

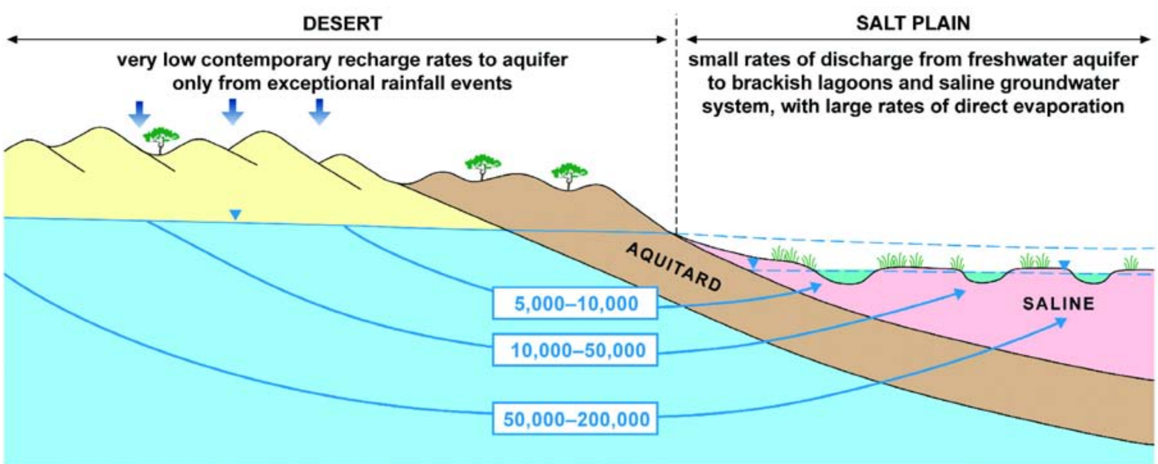
- **unconfined aquifers** in areas where contemporary recharge is of small volume and very infrequent, and the resource is essentially limited to aquifer storage reserves (Figures 1 A-C);
- **'confined sections' of some aquifer systems**, where groundwater development intercepts (or induces) little active recharge, as a result of natural geohydraulic impedance to groundwater

Figure 1

Hydrogeological settings to illustrate the occurrence of essentially non-renewable groundwater resources



(A) hyper-arid area with average rainfall of less than 100 mm/a and prolonged (up to 30 months) dry periods – occasional storms result in flash floods down otherwise dry valleys (wadi) and lead to small amounts of localised recharge, but bulk of aquifer contains fossil groundwater, which infiltrated during a Holocene humid period at least 10,000 years or more ago and still has an active residual flow to a perennial discharge area.

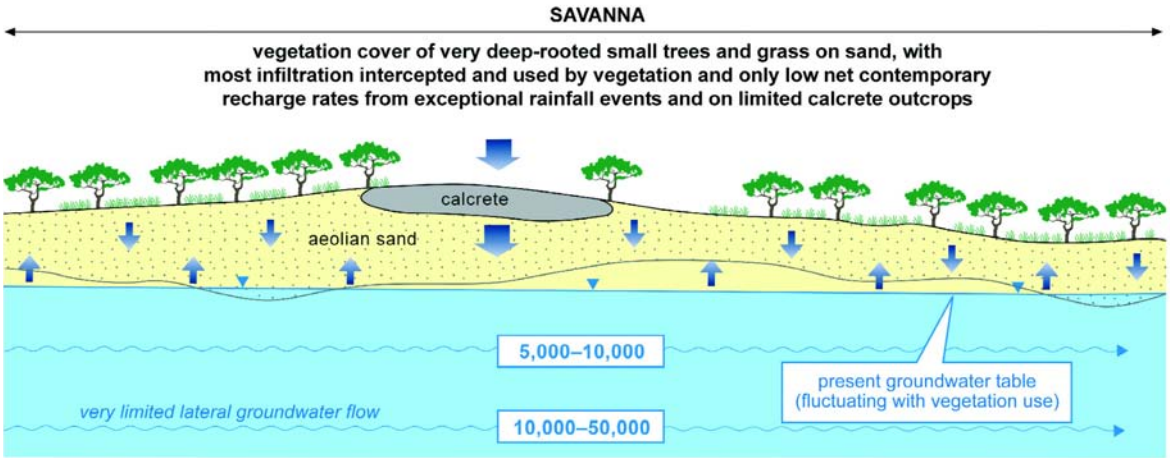


(B) similar climatic situation to above, but hydrogeological setting includes an aquitard which confines the groundwater and increases residence times of the freshwater aquifer, but allows limited leakage and discharge via an overlying shallow saline groundwater system.

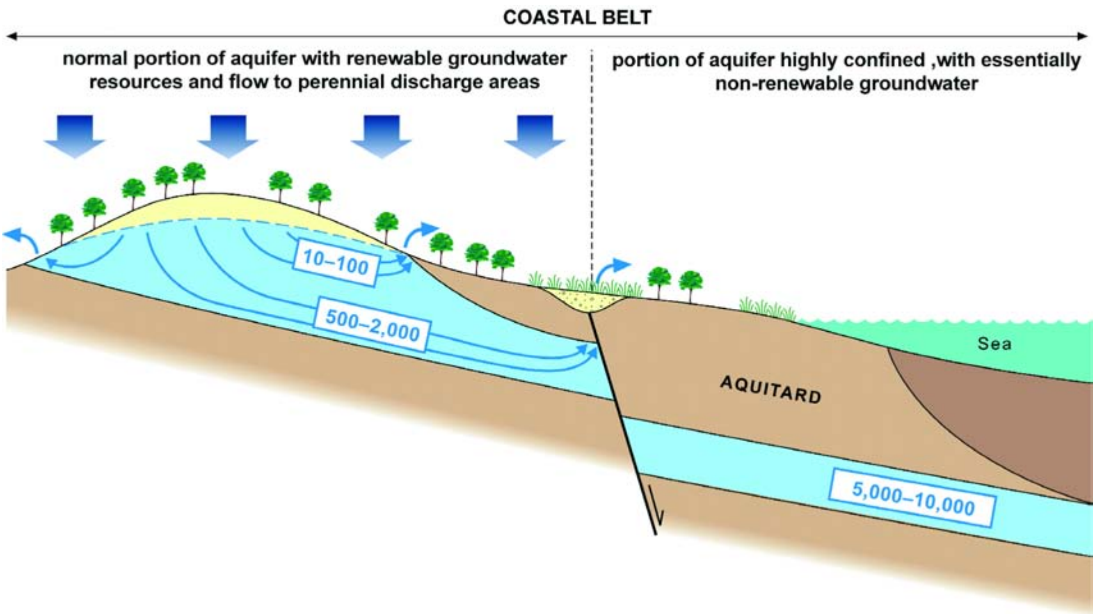
flow, and the piezometric surface thus falls continuously with groundwater extraction (Figure 1D).

They can thus occur in a wide range of present-day climatic conditions, but their occurrence and utilization is of most interest in the more arid regions.

Figure 1 (contd.)



(C) semi-arid region with average rainfall of 400 mm/a and dry periods of up to 6 months – the sand cover is stabilised by deep-rooted vegetation capable of withdrawing soil water down to depths of 30 m, which intercepts and utilises most of the soil infiltration from short-term excess rainfall, thus reducing deep infiltration to less than 10 mm/a with most of the groundwater resources also being of Holocene origin.



(D) temperate humid region with annual rainfall in excess of 1,000 mm/a normally generating renewable groundwater resources, but highly-confined portion of aquifer system contains essentially non-renewable (but fresh) groundwater as a result of geological structure and geomorphological history – and this is potentially of local strategic importance.

Table 2. **Hydrogeological concept of groundwater resource renewal**

PARAMETER	SYMBOL	DIMENSION	UNITS
"Groundwater resource renewal is the replacement or displacement of groundwater in aquifer storage through aquifer recharge"			
Total drainable aquifer storage reserves*	S	L^3	Mm^3 **
Average annual aquifer recharge rate	R	L^3/T	Mm^3/a
Rate of aquifer groundwater renewal	R/S	$L^3/TL^3 \times 100$	%/a
Renewal period of aquifer	S/R	L^3T/L^3	year
"Renewal is a comparative (not absolute) concept – relative to both aquifer storage and recharge AND thus subject to very wide variation due to geological factors (aquifer thickness and drainable porosity) and climatic parameters (especially rainfall regime)"			

Notes:

* It is recognised that the definition of the term 'drainable aquifer storage' will be rather subjective in practice.

** Mm^3 (10^6 m^3) also referred to as hm3 in many countries, and km^3 (10^9 m^3) also frequently used for large aquifers.

L = lenght, T = time.

Most importantly the development of non-renewable groundwater resources will imply the '**mining of aquifer storage reserves**' (Table 1), such that they will not be available for future strategic use. As such it has special social, economic and political sensitivity compared to other water resource development.

The occurrence of non-renewable resources in a variety of different hydrogeological settings results in a number of important consequences for their management :

- some non-renewable aquifers sustain (directly or indirectly) important aquatic ecosystems (eg. Figures 1A and B);
- non-renewable groundwater can be vulnerable to pollution from inadequately-controlled human activities at the land surface, especially the discharge of polluted and/or saline wastewater (eg. as would be the case in Figures 1 A and C);
- the clearance of natural vegetation could reactivate deep groundwater recharge under certain conditions (eg. Figure 1C), but would also be associated with the mobilisation of salts previously accumulating in the vadose zone;
- if a source of surface water is made available through a major pipeline transfer or other means, then it will be possible to artificially recharge many non-renewable aquifers but great care is needed to avoid the mobilisation of saline water.

The development of a non-renewable groundwater resource usually involves the extraction of so-called '**fossil groundwater**' (Table 1), which originated as recharge in past, more humid, climatic regimes. But to speak synonymously about 'fossil groundwater' and 'non-renewable groundwater resources' is misleading since there are many aquifer systems containing large volumes of fossil (usually Holocene) groundwater at depth which if extracted is replaced (or renewed) by more modern recharge.

Scale and distribution of non-renewable resources

The global geographical distribution of non-renewable groundwater resources is determined by two main factors:

- Hydrogeological Structure : principally the existence of extensive thick aquifer reservoirs or the presence of confining beds and flow barriers, although confined aquifers providing their yield exclusively by decompression are of much less volumetric significance
- Climatic Conditions : essentially aridity, which diminishes rainfall and runoff, and thus tends to reduce recharge of all aquifers.

The distribution of major aquifers containing non-renewable groundwater resources (Table 3), therefore, mainly reflects the occurrence of extensive deep aquifer reservoirs in the large sedi-

Table 3. Some major aquifers containing predominantly non-renewable groundwater resources

COUNTRY	AQUIFER SYSTEM	EXTENSION (km^2)	EXPLOITABLE RESERVES (Mm^3)	CURRENT EXTRACTION (Mm^3/a)	RECENT REFERENCES
Egypt, Libya, Sudan, Chad	**Nubian Sandstone**	2,200,000	14,460,000	2,170,000	UNESCO-IHP (2006) Bakhbakhi, (this volume), OSS (2003)
Algeria, Libya, Tunisia	**North Western Sahara**	1,000,000	1,280,000	2,560	Pallas and Salem (1999), OSS (2003)
Algeria, Libya, Niger	**Murzuk Basin**	450,000	60 to 80,000	1,750	Salem (1992), OSS (2003)
Mauritania, Senegal,Gambia	**Maastrichtian**	200,000	480 to 580,000	265	Khouri (1990), OSS (2003)
Mali, Niger, Nigeria	**Iullemeden Multilayer Continental**	500,000	250,000 to 2,000,000	225	Dodo (1992), OSS (2003)
Niger, Nigeria, Chad, Sudan, Cameroon,Libya	**Chad Basin**	600,000	170 to 350,000	250	Terap (1992), OSS (2003)
Botswana	**Central Kalahari Karroo Sandstone**	80,000	86,000	2,890	Carlsson (1993)
Saudi Arabia, Bahrain, Qatar, UAE	**Various**	225,000 to 250,000	500,000 to 2,185,000	13,790	Abderraman (this volume)
Jordan (only)*	**Qa Disi Aquifer**	3,000	6,250	170	Garber and Salameh (1992)
Australia	**Great Artesian Basin**	1,700,000	170,000	600	Habermehl (this volume)

Note:
* Extends into Saudi Arabia, where it is included in the entry above

mentary basins of the semi-arid and arid regions. It is here also that renewable water resources are most scarce and the interest in such aquifer systems is greatest.

Elsewhere, aquifers containing non-renewable groundwater resources are present in humid regions, but their distribution is more limited and their importance is much less, except where deep highly-confined aquifers are being tapped by high-yielding artesian overflowing waterwells. Additionally the expansion of the permafrost in some arctic areas can hinder or eliminate aquifer recharge and this can also result in the occurrence of aquifers with non-renewable groundwater resources (for example, some sedimentary basins in Russian Siberia, northwestern Canada and Alaska.

Current utilisation of non-renewable resources

Aquifer systems with recognised non-renewable resources, where significant groundwater mining has already taken place, are located principally in North Africa and the Arabian Peninsula (Table 4). In these regions large aquifer systems with non-renewable groundwater resources are often transboundary in political distribution, a factor which imposes special conditions and particular constraints on resource management.

On the basis of available statistics (undoubtedly incomplete) the global mining of groundwater is currently put at some 27,000 Mm3/a, and if this figure is compared to the current total rate of groundwater exploitation, provisionally put at 670,000 Mm^3/a (Shiklomanov, 1998), the proportion derived from groundwater mining is 4%. This production is mainly concentrated in Saudi Arabia and Libya, who have some 77% of the estimated total world extraction of

Table 4. Exploitation of non-renewable groundwater resources

COUNTRY	YEAR(S) OF ESTIMATE	GROUNDWATER (Mm^3/a)		
		Share of demand *	Total use	Non-renewable
Algeria	(2000)	54%	2,600	1,680
Saudi Arabia	1999 (1996)	85%	21,000	17,800
Bahrain	1999 (1996)	63%	258	90
Egypt	1999 (2002)	7%	4,850	900
UAE	1999 (1996)	70%	900	1,570
Jordan	1999 (1994)	39%	486	170
Libya	1999	95%	4,280	3,014
Oman	1999 (1991)	89%	1,644	240
Qatar	1999 (1996)	53%	185	150
Tunisia	2000	59%	1,670	460
Yemen	1999 (1994)	62%	2,200	700

Note:
* Proportion of total actual water demand met from groundwater.
Source: Based on Margat (1995, 1998, 2004), UN-FAO (1997), UN-ECSWA (1999).

non-renewable groundwater. In both these cases non-renewable groundwater represents an important or predominant source of water-supply (84% in Saudi Arabia and 67% in Libya), and is used for urban water-supply and for irrigated agriculture.

Certain other huge aquifers, such as the North China Plain Quaternary Aquifer System (Foster et al, 2004) occur in somewhat less arid regions with significant annual rainfall, but have also been subject to prolonged resource overexploitation. It is arguable whether these are cases of 'mining of a non-renewable resource' – the term is probably applicable to the limited groundwater extraction from highly-confined portions of these aquifer systems but not universally and thus they do not figure in the above inventory.

Exploitation scenarios for non-renewable groundwater

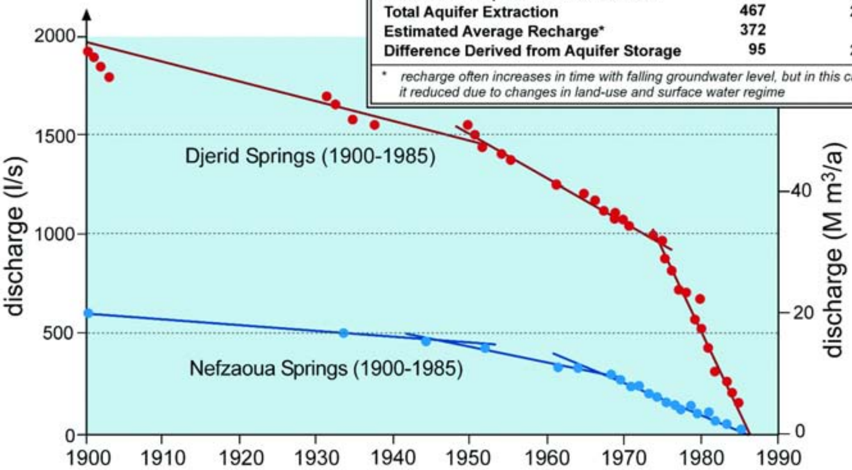
In practice non-renewable groundwater resources become available for exploitation through technical advances and economic improvements which interact to make possible the mining of groundwater from an aquifer. An example is the growth in exploitation of the groundwater storage reserves of the North Western Sahara Aquifer System (NWSAS) in Algeria, Libya, and Tunisia (Figure 2), which has led to the progressive reduction in major spring flows and for which the current groundwater extraction rate is estimated to be six times higher than the current rate of resource renewal (Mamou, 1999).

Figure 2

Groundwater resource development and environmental side-effects in the North Western Sahara Aquifer System

GROUNDWATER BALANCE ITEM	GROUNDWATER EXPLOITATION ($M\ m^3/a$) 1900	2000
Traditional Galleries ('foggaras') Extraction	353	142
Artesian & Pumped Waterwell Extraction	114	2460
Total Aquifer Extraction	**467**	**2602**
Estimated Average Recharge*	**372**	**363**
Difference Derived from Aquifer Storage	**95**	**2239**

* *recharge often increases in time with falling groundwater level, but in this case it reduced due to changes in land-use and surface water regime*



Pprogressive elimination of major springflows in southern Tunisia during the 20th century is shown, together with the status of the overall aquifer resource balance in Algeria, Libya and Tunisia for the corresponding period.

The way in which the utilisation of non-renewable groundwater arises can be conveniently classified (Foster and Kemper, 2002-04) into :

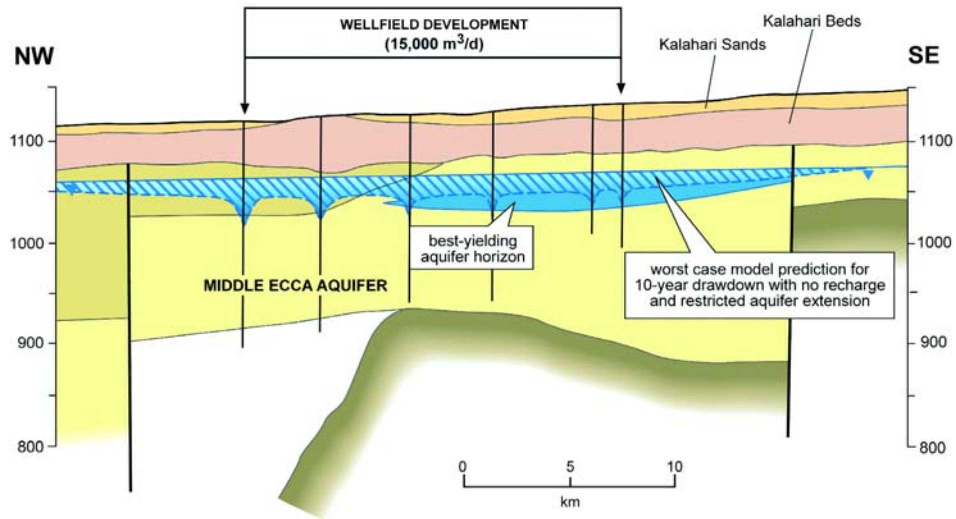
- **planned schemes**, in which mining of aquifer reserves is contemplated from the outset, usually for a specific development project in an arid area with little contemporary groundwater recharge (eg. Figure 3)
- an **unplanned basis** with incidental depletion of aquifer reserves, as a result of intensive groundwater abstraction in areas with some contemporary recharge but where this proves small or where there is limited hydraulic continuity between deep aquifers and their recharge area (e.g. Figure 4).

Unplanned depletion of non-renewable groundwater reserves can undermine, and potentially erode, the economic and social vitality of the traditional groundwater-dependent community – and instances of the collapse of such rural communities are known. Hence, there is need to plan the exploitation of non-renewable groundwater resources, and guide their utilisation with a view to making communities better prepared socio-economically to cope with increasing water stress as aquifer storage is depleted.

Unplanned depletion of non-renewable groundwater reserves can undermine, and potentially erode, the economic and social vitality of the traditional groundwater-dependent community – and instances of the collapse of such rural communities are known. Hence, there is need to plan the exploitation of non-renewable groundwater resources, and guide their utilisation with a view to making communities better prepared socio-economically to cope with increasing water stress as aquifer storage is depleted.

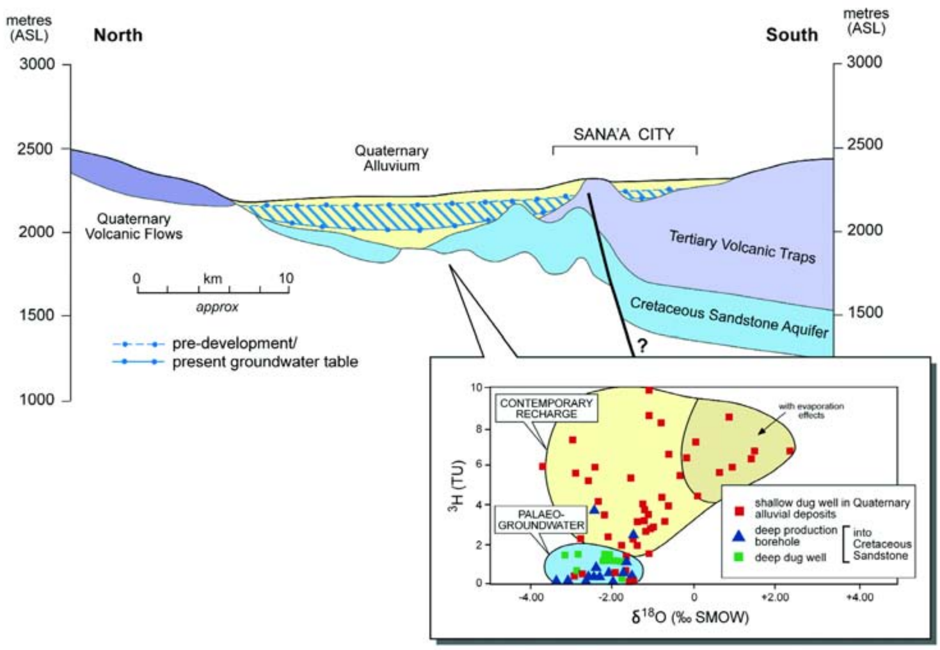
Figure 3

Planned mining of essentially non-renewable groundwater resources in the southern Kalahari of Botswana (Foster et al., 1982)



Hhydrogeological conditions in area where Middle Ecca (Karroo) Sandstone was discovered to form an excellent aquifer readily capable of supplying a wellfield yielding the 5 M m3/a required for development of a major mining complex and regional centre - the question of physical and social sustainability of the proposed groundwater extraction arose in the 1980s before the development took place, since detailed investigations revealed that most of the groundwater extraction would be non-renewable because deep rainfall infiltration to the aquifer was very limited – however worst-case predictions for aquifer drawdown (at the expected mine life of 20 years), generated by aquifer numerical modeling, were such that they would not prejudice long-term use of the aquifer for town water-supply and traditional ranching activity, and post-development monitoring has proved this to be the case.

Figure 4
Unplanned depletion of non-renewable groundwater resources in a deep aquifer beneath the Sana'a Basin-Yemen



This arid basin (average rainfall of less than 250 mm/a) possesses a Quaternary alluvial aquifer (with clear isotopic evidence of some contemporary recharge from storm runoff) locally overlying a deeper Cretaceous Sandstone aquifer for which there is no evidence of significant recharge and presently contains mainly palaeo-groundwater (Aggarwal et al, 2002) - in the absence of regulation some 13,000 waterwells have been constructed for urban and rural water-supply and to irrigate some 23,000 ha, these extract groundwater in part from the deep aquifer and its groundwater levels are falling by 3-5 m/a as a result of the imbalance between groundwater extraction and recharge (Foster, 2003)

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Chapter 2

Social and economic dimensions of non-renewable resources

Mohammed Al-Eryani, Bo Appelgren and Stephen Foster

Concept of socio-economic sustainability

There is no rigorous definition of social sustainability, although Turton and Ohlsson (1999) have defined the related concept of 'social adaptive capacity to water scarcity'. Social sustainability contemplates consideration of society needs and goals, which will vary with time, place and people. The changing nature of social sustainability and inter-related risk of resource degradation are the critical considerations when developing plans for the use of non-renewable groundwater resources. They imply periodic review and adjustment of plans, in response to changing circumstances and increasing knowledge.

The principles of the Brundtland Commission are :

social sustainability refers to the maintenance of well-being of the people most dependent on a resource, through regulating actions that affect the sustainability of the resource while maintaining an equitable inter-generational distribution of benefits

and a **socially-sustainable plan** for use of a non-renewable resource would thus need to be formulated to meet three main conditions (Borrini-Feyerabend, 1997):

- maintaining (or improving) **well being** of communities involved, by meeting as far as possible their social, economic, cultural and environmental needs, now and in the future,
- managing the actions of **concerned individuals or communities** that affect resource use, by strengthening their capacity to cooperate in the management of the resource and assuring appropriate financial, legal, technical, institutional and political conditions for them to adhere to the established management plan,
- address the fundamental concern about human survival not only for present and future generations, by maintaining **inter-generational equity** in terms of benefits derived from the resource and ensure economic and social opportunities to all stakeholder groups including future generations.

Socially-sustainable use of non-renewable resources

The use of the term '**sustainability**' in the context of 'mining aquifer storage' requires some clarification. It is interpreted here in the '**social context**' – and thus sustainability is not meant to imply 'preserving' the groundwater resource for generations to come, but instead reconciling the use of the non-renewable resource with the *'sustainability of human life'.* A good starting point is to set an appropriate planning horizon of a substantial number of years (at least 20 and preferably 50 – 100 years) for the use of the non-renewable groundwater resource, and at the same time pay full consideration to the questions of 'external impacts' and 'what comes after', and thus to time horizons of 100 – 500 years and to climate change implications. In reality the use of non-renewable resources can arise as a result of both planned and unplanned scenarios (Foster and Kemper, 2002 – 04), which will require a somewhat different management approach.

For groundwater resource management, the typical situation is that :

- diagnostic data are limited,
- use patterns involve a substantial number of individual abstractors,
- impacts are not very visible and often delayed,
- damage to the resource base can have far-reaching and long-term consequences.

In such situations an adaptive approach to management has to be adopted, recognising the risks and uncertainties at the outset to reduce subsequent conflicts (WWAP, 2003).

Planned depletion scenario

In the **'planned depletion scenario'** the socially-sustainable criterion requires orderly utilisation of aquifer reserves (of a system with little pre-existing development), minimising quality deterioration and maximising groundwater productivity, with expected benefits and predicted impacts over a specified time-frame. The overall goal should be to use groundwater in a manner that maximises long-term economic and social development of the community and decreases, over time, the frequency and severity of threats to society, leaving people better prepared to cope with socio-economic stresses associated with increasing water scarcity as aquifer storage is depleted. This will often entail the initiation and expansion of high added-value economic activities that are not water intensive.

An appropriate **'exit strategy'** needs to be identified, developed and implemented by the time the aquifer is substantially depleted, and this would normally imply that society will have used the mined groundwater to advance economically, socially and technically so as to enable future generations to develop substitute water sources at tolerable capital and operational cost. But it could equally mean strengthening the capacity of existing water-users to cooperate in managing water resources more efficiently.

A key challenge in the planning process is to determine the quantity of groundwater that can be pumped over the planning period to best serve the communities involved. Such an analysis involves assessment of three key components :

- The economics of groundwater mining and the progressive increase in water production costs under different exploitation options – which will have implications for the economic feasibility of the proposed uses.
- The long-term effects of the proposed exploitation of aquifer reserves on all traditional groundwater users, so that some form of compensation can be provided for predicted or actual derogation. Where the protection of indigenous people is an issue, it should be ensured that a sufficient reserve of extractable, adequate quality, groundwater is left in the aquifer system at the end of the proposed period of intensive exploitation to sustain the pre-existing activity (albeit at additional cost). Another way of achieving this end would be to restrict the 'design average drawdown' of intensive exploitation to less than a given average figure over a stated period (for example, 20 m after 20 years or 50 m after 30 years).

- The dependence of any aquatic ecosystems on the groundwater system, and whether these can be sustained (albeit in reduced form) through provision of compensation flow by local irrigation and/or aquifer recharge. This consideration will need to be realistically factored into the evaluation of the acceptability of the proposed groundwater development.

In developing the groundwater mining plan, the socio-economic analysis will require planners to look at other sectors besides water. Hence, modeling will be needed to guide the allocation of groundwater abstraction between sectors and over time, so as to determine the optimal abstraction schedule to maximise some economic criteria (often economic efficiency). However, the long-term socio-economic impacts may often be difficult to forecast accurately. But what is known is that the non-renewable groundwater used today will not be available for future use, although it is often the case that the socio-economic benefits to future generations are often greater if some of that resource is used today rather than saved for future use.

In summary the key principles that should adopted for the development of non-renewable groundwater resources (Louvet and Margat, 1999) are :

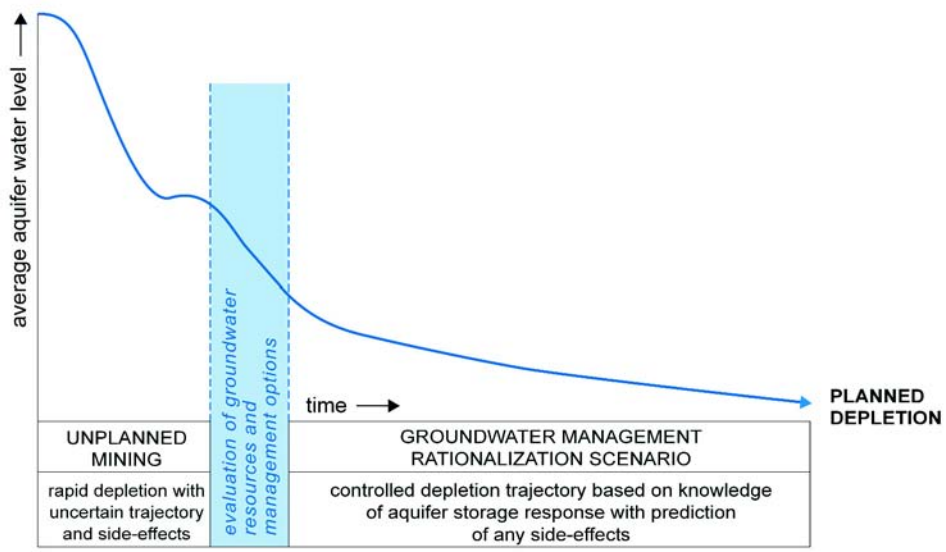
- the evaluation phase should result in estimates of the volume of groundwater that can be produced in a fixed time-horizon with reference to an acceptable groundwater level decline
- the development of non-renewable resources must be justified by socio-economic circumstances in the absence of other water resources, and that its implementation is planned and controlled.

Rationalisation scenario

In the unplanned situation the socially-sustainable criterion implies that *'rationalisation'* of groundwater extraction and use be imposed with the goal of achieving **orderly utilisation** of aquifer reserves (Figure 5), which will minimise quality deterioration, maximise groundwater

Figure 5

Targets for groundwater resource management 'rationalisation scenarios'



Concept of rationalizing previously indiscriminate, excessive, and poorly understood, exploitation through a combination of 'demand-side intervention' and 'supply-side enhancement' measures with a clearly-defined long-term management target which will allow systematic water resource and socio-economic planning.

productivity and allow time to promote **social transition** to a less water-dependent economy. In general the groundwater abstraction rate will have to be progressively reduced, and thus the introduction of demand-management measures will be needed. In the longer run potable water-supply use will have to be given highest priority and some other lower productivity uses may have to be discouraged.

Resource utilisation and aquifer management plans aimed at achieving social sustainability of groundwater use also have to vary considerably according to the stage of development at which the planning intervention is invoked. Management interventions in the case of an aquifer whose non-renewable resources are already being mined at a high rate will entail a different planning approach, and it will often be a more difficult to reconcile and integrate the interests of the various stakeholders into a rational management plan to achieve maximum useful-life of existing waterwells and the aquifer system, together with a smooth social transition to other economic activities that are less water-consumptive and/or able to support the much higher cost of alternative water-supply provision. To ease the situation, all available economically-viable opportunities should be taken of enhancing recharge in those aquifer recharge areas that experience intermittent surface water runoff.

Planning for socio-economic sustainability

The planning process for socially-sustainable mining of groundwater resources, or putting the existing mining of groundwater resources on a socially-sustainable basis, must incorporate the following key elements :

- evaluation of 'social well-being' on a periodic basis
- effectiveness of community participation in groundwater regulation
- appraisal of the extent to which 'inter-generational equity' is being met.

Specific criteria or parameters for these elements should be incorporated into the management model developed for the aquifer under consideration.

Social well-being

The planning and management of socially-sustainable mining of groundwater resources must be guided by the criteria summarised in Table 5, which will determine the well-being of communities whose livelihood depends on the associated aquifer system.

- **Security of access to water-supply**
  Based on water-use rights, regulated access and adequate monitoring over the years of the plan, taking into consideration pre-existing groundwater users – relevant instruments include : permit system for waterwell drilling and groundwater abstraction, scientifically-based spacing requirements between waterwells, monitoring of groundwater use/levels/quality, aquifer numerical modeling and periodic drawdown prediction, adjustment of authorised abstractions taking aquifer behaviour into account.

- **Economic and social opportunity**
  Planning use of groundwater resources to enhance long-term economic and social development, so as to provide opportunities to all stakeholder groups including future generations.

- **Just and effective decision-making**
  Upholding and promoting the right of communities to participate meaningfully in groundwater use decisions affecting livelihoods – including just mechanisms for participation in decision-making during planning and implementation, and resolution of conflicts, distribution of benefits/responsibilities/incentives and compensation for damages resulting from groundwater mining.

- **Social heritage and identity**
  Protection of cultural values and life-styles, but this needs to be reconciled with the need to promote economic transformation as regards reduced dependency on scarce water resources through the promotion of high added-value activities.

- **Environmental considerations**
  Inventory of ecological services provided by aquifer system concerned, with provision for protection of critical elements, safeguards against the potentially-adverse effects of land subsidence and wastewater disposal.

Table 5. Criteria for ensuring social well-being in the management of non-renewable groundwater utilisation

CRITERION	CONSIDERATIONS
Security of access to water-supply	Based on water-use rights, regulated access and adequate monitoring over the years of the plan, taking into consideration pre-existing groundwater users – relevant instruments include : permit system for waterwell drilling and groundwater abstraction, scientifically-based spacing requirements between waterwells, monitoring of groundwater use/levels/quality, aquifer numerical modeling and periodic drawdown prediction, adjustment of authorised abstractions taking aquifer behaviour into account.
Economic and social opportunity	Planning use of groundwater resources to enhance long-term economic and social development, so as to provide opportunities to all stakeholder groups including future generations.
Just and effective decision-making	Upholding and promoting the right of communities to participate meaningfully in groundwater use decisions affecting livelihoods - including just mechanisms for participation in decision-making during planning and implementation, and resolution of conflicts, distribution of benefits/responsibilities/incentives and compensation for damages resulting from groundwater mining.
Social heritage and identity	Protection of cultural values and life-styles, but this needs to be reconciled with the need to promote economic transformation as regards reduced dependency on scarce water resources through the promotion of high added-value activities.
Environmental considerations	Inventory of ecological services provided by aquifer system concerned, with provision for protection of critical elements, safeguards against the potentially-adverse effects of land subsidence and wastewater disposal.

Effectiveness of community participation

Facilitation of effective social cooperation will be a crucial element in the elaboration and implementation of plans for the utilisation of non-renewable groundwater resources. Such capacity of people to cooperate over the management of a shared resource has been termed 'social capital' (Ostrom, 1994). By assessing this social capital and the incentives which groundwater users receive for the rational use of the resource, it is possible to predict the likelihood of sustainable management. Building on ideas of common property resource management (Ostrom, 1994; Turton and Ohllson, 1999; Ward, 1999), the criteria and conditions summarized in Table 6 are identified as being necessary for effective community participation in the sustainable use of non-renewable groundwater resources.

Table 6. Criteria for promoting community participation in the management of non-renewable groundwater utilisation

CRITERION	CONSIDERATIONS
Proactive government role	Absolutely essential and must ensure appropriate cross-sector consultation for plan elaboration, implementation, evaluation and revision; needs to facilitate equitable 'grass-root' stakeholder participation within an integrated policy framework that treats water as a socio-economic good.
Organisational structure	Partnership between government and stakeholder/social/non-governmental organisations in overall aquifer management organisations for policy development, mobilization of investment and other decision-making; provision of opportunity for social organisation into smaller 'nested' groups for regular communication.
Financing management	Levying some kind of 'water resource abstraction fee' will provide an important signal to users and help generate the financial resources needed for effective user participation in groundwater resource administration, and demand and supply side management.
Capacity building	Necessary to ensure that the communities involved have access to appropriate education, technology and information for implementation – and the plan itself must address the inputs required and provide insight on ways to secure them.
Accessibility of groundwater resource data	To ensure transparency the aquifer management boundaries (both spatial and vertical) need to be well defined, and information on all relevant technical parameters (which determine aquifer storage, yield and quality risks) must be accessible in a 'friendly format'.
Demand management and water conservation	Awareness campaigns and incentives to promote improved water-use efficiency, treatment and recycling of wastewater, and constrain overall demand especially in relation to crop cultivation; promotion of a 'water rights market' could be considered as one possible instrument in this regard.

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Inter-generational equity

The inter-generational distribution of benefits focuses on the improvement of social equity over time. It should be a core requirement for successful planning of the mining of non-renewable groundwater resources, and has the following indicators:

- **Improvements in well-being** : the improvement of people's well-being is a good indicator of inter-generational social equity, and hence of the sustainability of the socio-economic development arising from groundwater resource mining, and the plan must define the related parameters and appropriate points for measurement.
- **Enhancement of 'social capital'** : the evolution of capacity of stakeholders to cooperate effectively on resource utilisation is another important indirect indicator of the potential for inter-generational distribution of benefits.
- **Opportunities to younger generations** : an additional factor that needs to be taken into account is the likelihood of younger generations having opportunities created by technology breakthroughs that positively impact on the availability of alternative water supplies – amongst these developments advances in desalination technology (reducing desalinated water cost and environment impact) is likely to be the most significant for the more arid regions.

Broader policy issues

Groundwater resources in many of the more arid countries are being mined in an uncontrolled and unplanned manner, usually as a result of a public policy and institutional failure to enforce regulations to control groundwater abstraction. Planned and socially-sustainable mining of groundwater resources represents a change in policy that will require strengthening social capacity to cooperate in managing common resources through appropriate financial, legal, technical, institutional and political provision.

Experience of some water-scarce countries provides valuable lessons on improving the social- sustainability of groundwater development and use. Jordan, whose overall renewable water resource amounts to less than 200 m^3/capita/a, is transforming its agriculture to a high-income economic activities with large value-added dominated by market garden crops grown under plastic with drip irrigation. This has been made possible by good market organisation and by the availability of the appropriate technology, the required training, and the necessary capital investment. At the same time, the Jordanian agriculture sector has progressively released labour into other sectors, and this has been made possible by high levels of investment in human resources and enterprise development (Ward, 1998).

A number of countries have large groundwater reserves in remote sparsely-populated areas, but are suffering water-stress in their more densely-populated areas. These reserves of largely non-renewable groundwater often represent the only remaining unused freshwater resource, and one of few development options currently available. While the use of these non-renewable groundwater resources cannot go on forever, the mining of fossil groundwater should not be considered per se as non-sustainable and undesirable (Llamas, 1999). Government programmes that encourage migration to such groundwater-abundant areas will help in coping with over-population in water-stressed areas, but require a concomitant political commitment to the planning and control of the groundwater mining operation with adherence to the principles of social-sustainability, which for effective implementation will require significant political, social and economic inputs.

The management of fossil aquifers is subject to a wide range of factors beyond the immediate hydrological issue of water balance. Numerous of these aquifer systems are internationally-shared and their transboundary character implies the need for the prevention of international conflicts over socio-economic and environmental objectives. The need for strategic choice is well illustrated by the example of the Nubian Sandstone Aquifer System. Given that exploitable groundwater storage is estimated to be 6,500,000 Mm^3, the planned development over the next 50 years for the Egyptian New Valley Project (540 Mm^3 from the Dakhla sub-basin) and the Libyan Great Man-Made River Project (750 Mm^3 from the Kufra sub-basin) equates to a very small percentage of the stored volume and this can be used as a justification for development (Khouri, 1999). The 'common pool' issues associated with large transboundary non-renewable aquifers (such as the Nubian Sandstone) suggest the need for a new paradigm (Alghariani, 1999) – one which shifts from considering sub-basins to consider the whole system. While on a 50–100 year planning horizon non-renewable groundwater resources are available from the Nubian Sandstone Aquifer System the main question is about their optimised use for social development which requires socio-political cooperation among countries that share the resource. In contrast Attia (1999) argues that the proposed schemes are so small that regional impact is not very significant and development can proceed according to national and local social priorities, although there is a clear need for exchange of monitoring data among countries that extract groundwater from the same aquifer system.

Modifications to land and water use, as well as accelerated climatic change, can impact the available groundwater resources, in both a quantity and quality sense. Political cost and institutional capacity are the ultimate constraints to groundwater management. As water-policy paradigms evolve, and the importance of water governance that can accommodate multiple risks and political/ economic uncertainties is recognised, there will be need to ensure that water management instruments are politically and institutionally realistic.

Political economies are generally focused more on distributional issues and on short-term objectives (including national food security and rural welfare), rather than on economic efficiency and longer-term issues Thus within a plan for sustainable groundwater management it becomes critical to promote the legitimacy, rights, obligations and participation of individual users at the operational level. Aquifer management plans must be based on effective local institutions, which have the political will and institutional capacity to act.

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Aquifer characterisation techniques

Shaminder Puri, Jean Margat, Yucel Yurtsever and Bill Wallin

Key needs for characterisation

For the utilisation of non-renewable groundwater to be managed effectively (Lloyd,1999, special emphasis must be put upon aquifer system characterisation to provide adequate predictions of:

- groundwater availability, and the distribution of wells to abstract it over a given time horizon;
- the impact of such abstraction on the aquifer system itself, on third parties (especially traditional users) and on related aquatic and terrestrial ecosystems;
- anticipated groundwater quality changes during the life of intensive aquifer development.

Such characterisation requires special hydrogeological investigations to evaluate certain key factors such as :

- quantification of aquifer storage reserves (especially the three-dimensional variation of specific yield);
- assessment of contemporary recharge rates (which are likely to be small);
- appraisal of depletion trends and the risk of quality deterioration (especially salinity increase)
- prediction of potential ecological impacts.

In contrast to the characterisation of renewable groundwater resources, a critical component will be assessment of the storage of those parts of the aquifer system that will be (or are being) drained by groundwater pumping, together with the susceptibility of the aquifer system to saline intrusion. Incomplete data can result in significant aquifer development problems and related financial losses (Foster. 1987). Hydrogeological field investigation including geochemical and isotopic techniques, coupled with the construction and application of numerical aquifer modelling, are essential to provide a sound scientific basis for planning the use of non-renewable groundwater resources.

The long-term effects of exploitation of aquifer reserves on all traditional groundwater users need to be assessed, sufficiently accurately so that some form of compensation can be provided for actual and/or predicted derogation. It will be equally important to identify all aquatic and/or terrestrial ecosystems that may be dependent on, or actively using, the aquifer concerned and to make predictions of the likely level of interference that will occur as a result of the proposed development. A degree of doubt over impact assessment is likely to arise (Foster, 1989) for two reasons:

- hydrogeological uncertainty in the prediction of groundwater drawdown, especially at large distances from the proposed centre of extraction;
- difficulties in estimating how the given ecosystem will react to a certain level of drawdown.

Armoury of investigation tools

The outcome of scientific evaluation will be a 'conceptual model' of the aquifer system. This conceptual model should be considered as dynamic, evolving in complexity with increasing levels of information and confidence of interpretation. A 'systems approach' should be adopted to the use of hydrogeological tools for evaluation of non-renewable groundwater resources, and Table 9 is designed to enable resource-managers and policy-makers to appreciate how the same tools can be used progressively in accordance with the state of aquifer development. Although all of the investigation tools described are standard hydrogeological practice, they are summarised for convenience in this chapter with examples of their application to non-renewable groundwater resource evaluation. In any case, basic hydrogeological field methods would also be used.

Field mapping and remote sensing

All groundwater assessment must start with field topographic and geologic mapping, which is the foundation of all spatial assessment of natural resources. Various forms of satellite imagery can provide vital supporting data for better definition of the geographical extension and geological character of the aquifer system.

The exploration of groundwater basins of the eastern Sahara relied heavily upon the analysis of digital satellite images (El Baz, 1999), including multi-spectral data from the Landsat Thematic Mapper, radar images from the Spaceborne Imaging Radar – many buried channels containing groundwater resources were identified.

Hydrogeomorphological mapping of the Luni Basin of Rajasthan-India was effectively carried out using Landsat Band 5 and 7 images (Bajpal et al., 1999). Image analysis revealed geological units forming significant potential aquifers – image interpretation defined 'rocky tracts' underlain by fractured rock aquifers while 'valley fill' deposits and buried pediments contains alluvial aquifers.

Once the basic hydrogeological configuration has been established, sub-regional reconnaissance will need to be carried out – combining satellite imagery and aeromagnetic surveys with ground observations of hydrogeological features. Some of the most extensive surveys of groundwater resources have been conducted through the USGS-RASA Program, which has produced a wealth of information for aquifers in the arid areas of California (Sun and Johnson, 1994).

Waterwell drilling and geophysical logging

Aquifers are 3-D water bodies which contain groundwater flowing under hydraulic gradients which often have important vertical components. Consequently surface hydrogeological mapping is not sufficient, and exploratory drilling to define the vertical dimension – in terms of aquifer depth and thickness, and vertical variations in groundwater hydraulic head, aquifer hydraulic properties and groundwater quality – is absolutely essential.

Although relatively expensive, the cost of such investigations do not generally exceed those for dam site investigation. However, there has been reluctance on the part of some agencies to finance regional exploration drilling (which is sometimes erroneously compared to 'wildcat drilling') and in consequence some major non-renewable aquifer systems still remain only partly explored.

Table 9. Summary of hydrogeological tools to guide groundwater development and management

TOOLS	EXPLORATION Groundwater use only for rural subsistence	DEVELOPMENT Introduction of improved drilling and pumping technology	MANAGEMENT Groundwater level decline and possible quality deterioration
Field mapping and remote sensing	Definition of aquifer extension/ structure and potential recharge areas	Identification of areas for intensive resource development and possible impacts of reduced aquifer natural discharge	Checking groundwater production from agricultural crop-use and status of natural discharge areas
Regional geophysical surveys	Complements mapping of surface geology	Improves identification of more productive aquifer zones (include use of aeromagnetic techniques)	Further refinement possible but not widely used
Waterwell drilling	Exploratory for reconnaissance level data on hydrostratigraphy	Production wellfield construction with associated infrastructure (usually either for urban water-supply or irrigated agriculture)	Refining production system to provide maximum energy efficiency; in some cases waterwell rehabilitation and pump replacement
Downhole geophysical logging	Improves hydrostratigraphic analysis	Improves correlation between waterwells and refines aquifer conceptual model	Aids diagnosis of waterwell yield and quality problems, and thus facilitates rehabilitation
Geographical information systems	At best simple manual databases of geo-referenced hydrogeological data	GIS-based information systems for well records and aquifer data – output well-suited for input to numerical aquifer models	GIS transformed into MIS for data on aquifer production performance and socio-economic indicators
Groundwater chemical and isotopic analysis	Reconnaisance-level determination of groundwater genesis and chemical variations	More detailed evaluation of groundwater genesis and evidence of contemporary recharge	Evaluation of rates of contemporary recharge and prediction of groundwater quality changes threatening wellfields
Analytical radial groundwater flow models	Analysis of pumping test data for estimation of aquifer properties	Prediction of drawdowns for waterwell design	Analysis of causes of well deterioration and rehabilitation planning
Lumped-parameter aquifer models	--------------------	Basic aquifer water balance to confirm conceptual model	Mass-balance type checks on issues such as 'life of resource' or 'bulk impact of production'
Numerical distributed-parameter aquifer models	--------------------	Testing conceptual model validity, optimising wellfield design/production and determining potential long-term impacts	Improving operational efficiency and evaluating long-term sustainability of wellfields
Groundwater development risk assessment	--------------------	Assessment of risks of premature failure/quality deterioration of wellfields	Assessment of risks to groundwater-based economic development related to externalities, such as changes in energy costs and crop prices

Phases of aquifer modelling followed by exploration drilling have been carried out from the mid-1970s in southern Jordan. In the final phase of exploration (before the implementation of a major, and very costly, groundwater transfer scheme) an extensive exploration drilling programme was employed to allow a critical re-evaluation of the Rum-Saq aquifer, shared by Jordan and Saudi Arabia (Puri et al., 1999). The programme involved some 18,000 m of drilling and was complemented by a host of other measurements and analyses. These included detailed downhole geophysical logging, laboratory testing of aquifer rock-cores, long-term pumping tests and groundwater quality analyses – which were synthesized into a regional numerical model of the aquifer over 70,000 km^2.

Geographical information systems

Many thousands of data-points can be collected in the evaluation of a large regional aquifer system – from waterwell drilling, geophysical logging, pump testing, groundwater quality analyses, etc. Quality assurance of these data can become unmanageable unless a well-suited geographical information system (GIS) is used. There are various commercially-available suites of computer programmes marketed as packages for this purpose. Numerical models of aquifer behaviour have to be based on data collated within reliable and interactive information systems. The nature and type of data stored in a GIS has to evolve with time and the level of aquifer exploitation.

Approaches to resource evaluation

By definition the assessment of the non-renewable groundwater resource potential of a specific aquifer system requires the evaluation of its storage reserves – or more specifically its extractable storage reserves – and two complementary approaches will need to be pursued.

Bulk storage estimation from hydrogeological structure

As a first approximation, the calculation of aquifer storage reserves can be made using structural hydrogeological data (geometry/volume of the aquifer reservoir and aquifer specific yield or unit drainable storage), providing that the possible presence of groundwater of inferior quality is also considered (Margat, 1991). The total storage reserve thus calculated (see Table 10 for examples) remains theoretical, however, since any estimate of extractable groundwater reserves must also reflect the technical and economic limits on aquifer exploitation. In the case of a confined aquifer system, the calculation of exploitable storage reserves must be based exclusively upon the confined storage coefficient (and not on aquifer specific yield) and thus will be relatively small in volume – although complex multi-layer aquifer systems with interbedded aquitards can also contain large exploitable storage reserves.

Dynamic storage computation by aquifer modelling

The use of numerical hydrodynamic simulation of the aquifer system under consideration is a powerful tool to estimate the availability of aquifer storage reserves. This approach normally uses a computerised model of the aquifer system to calculate and compare the feasibility of

Table 10. Estimation of groundwater storage in Nubian Sandstone Aquifer of North Africa

COUNTRY	UNCONFINED SECTION*		
	Area (km^2)	Thickness (m)**	Storage (km^3)***
Egypt	311,862	839	52,299
Libya	350,733	1,786	125,310
Chad	232,977	1,026	47,807
Sudan	373,102	454	33,878
TOTAL	1,268,674	––	259,294

Notes:
* Large extension of confined aquifer (mainly in Egypt and Libya) but confined storage not included in calculation.
** Average saturated thickness of unconfined aquifer calculated from GIS mapping.
*** Based on an estimated average sandstone specific yield of 0.20 derived from laboratory and field testing.

different long-term aquifer development scenarios inferred from demand projections related to specific socio-economic development plans. The objectives of the assessment are not only the determination of exploitable groundwater storage volumes but also the number of production wells needed, the probable pumping lifts and thus approximate water production costs. Wellfields can be designed that optimise yield while respecting practical feasibility constraints (maximum permissible drawdown, tolerable operating costs and even groundwater quality constraints). Thus the assessment of the exploitable non-renewable groundwater resources can be tied in with the choice of development strategy.

Special role of environmental isotopes and chemistry

The application of environmental isotope analyses is particularly valuable for interpretation of the genesis of both fresh and saline groundwater in aquifer storage and the quantification of any contemporary recharge (Table 11). By use of a multiple isotope approach (^{2}H, ^{18}O, ^{3}H, ^{14}C), combined with conventional chemical analyses and supplemented (where necessary) with more recently developed techniques (CFCs, ^{36}Cl, noble gases), groundwater systems can be better characterised. Isotope and chemical techniques are combined with hydrological methods. Environmental isotopes have been widely incorporated in numerous multi-disciplinary case studies and have provided unique information on the origin and age of groundwater in aquifer systems (Edmunds, 1999). Moreover, isotopic data can be an important indicator of changes in the aquifer system consequent upon groundwater extraction or recharge enhancement, and therefore assist in groundwater management and protection.

The unique characteristic of environmental isotopes is that they provide time and space integrated information, and may be used as indicators for the characterisation of groundwater system dynamics and recharge origin. The use of a suite of isotopes is advisable initially, but a specific isotope technique is often found to provide the most robust results in a given aquifer system. Environmental isotopes are a vital tool for the elaboration and/or validation of conceptual and numerical aquifer models. Another important roles for isotopes is to act potentially as an 'early warning indicator' before the quantitative or qualitative status of an aquifer system is irreversibly damaged. Certain specifically targeted tasks can be evaluated by the use of isotope techniques, including the evaluation of aquifer-system response to increased groundwater withdrawal and water-level decline, and potentially associated deterioration of groundwater quality.

Table 11. Summary of principal isotopic techniques used in groundwater investigation and their status of development and application

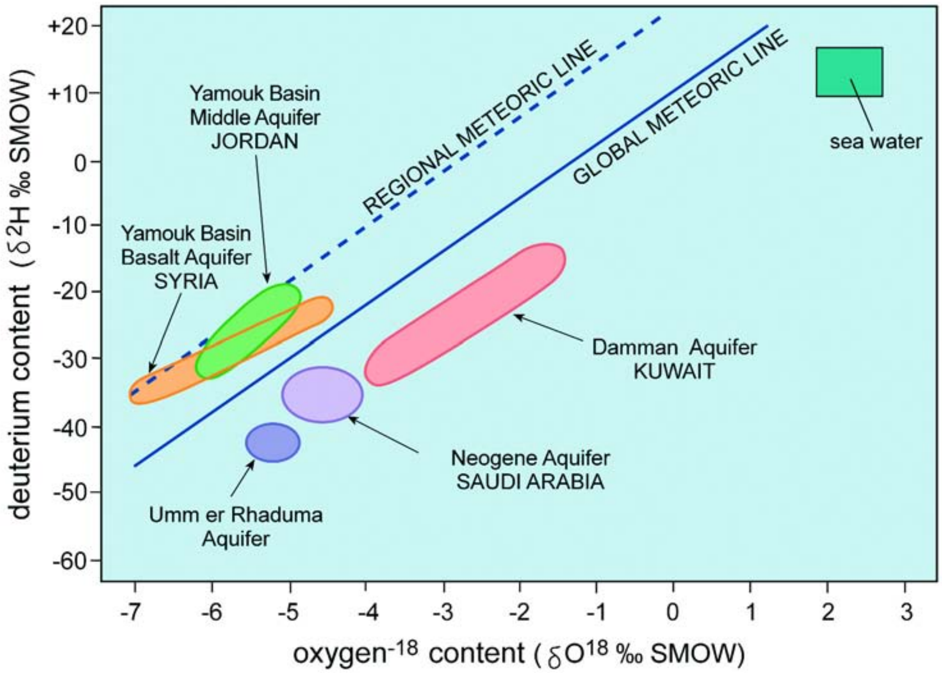
ENVIRONMENTAL ISOTOPE	MAIN APPLICATIONS	STATE OF DEVELOPMENT
Oxygen-18 (^{18}O) and Deuterium (^{2}H) (in H_2O)	Origin of groundwater (identification of recharge areas and palaeowaters); interconnection with surface water; salinisation mechanisms	Routine application
Carbon-13 (^{13}C in HCO_3)	Correction for C-14 dating and identification of paleowaters	
Sulphur-34 (^{34}S) and Oxygen-18 (^{18}O) (in SO_4)	Identification of pollution sources	Research deployment
Nitrogen-15 (^{15}N) and Oxygen-18 (^{18}O) (in NO_3 and N species)	Identification of pollution sources and microbial denitrification processes	
Boron-11 (^{11}B) (in $B(OH)_4$ and $B(OH)_3$)	Identification of pollution sources and origin of salinity	
Krypton-85 (^{85}Kr)	Groundwater transport mechanisms and delineation of protection zones	Development stage
Tritium (^{3}H)	Identification of recent aquifer recharge and vadose zone tracer	Routine application
Helium-3 (^{3}He)	Dating of young groundwater	Research deployment
Carbon-14 (^{14}C)	Dating of old groundwater	
Argon-39 (^{39}Ar)	Dating of very old groundwater	Development stage
Krypton-81 (^{81}Kr)		
Uranium-234 (^{234}U)		
Chlorine-36 (^{36}Cl)		

Genesis of groundwater in large aquifer systems

The genesis of groundwater in relation to present-day and paleoclimatic conditions is an important aspect of resource characterisation in the more arid regions. An assessment in this respect can be made through incorporation of isotopic and hydrochemical techniques into hydrogeological investigations. Determination of the proportions of the common stable isotopes (^2H and ^{18}O) (Figure 6), together with radiometric dating (through ^{14}C, ^3H, ^3He and other determinations), can be usefully deployed for this purpose.

Figure 6

Characteristic isotopic composition of groundwater from some major Middle East aquifers



The stable isotope composition characteristic of groundwater from some of major aquifer systems in the Middle East (Yurtsever, 1999) – for example, the Umm Er Rhaduma and Neogene aquifers in Saudi Arabia, together with the Dammam aquifer in Kuwait and the Qatar aquifers, all have low excess ^2H in relation to the present meteoric line, which is a classic palaeo-groundwater indicator, and it has been confirmed by radiometric dating that these aquifers were mainly replenished during a humid Pleistocene episode.

The composition of certain radioisotopes (^{14}C, ^3H, ^3He) can provide a specific indicator that, under favourable conditions, allows estimation of the age distribution of groundwater in the aquifer system, and the potential age differentiation between shallow aquifer inputs, aquifer natural discharge and groundwater abstracted by waterwells. The residence time of groundwater in aquifer systems can range from months in very shallow aquifers of humid regions to many thousands of years for the deep thick aquifer systems in arid areas with low recharge. Exceptional cases of fossil groundwater flow with residual flow patterns still reflecting palaeoclimatic patterns can be seen in the extensive groundwater basins of some desert areas (notably in North Africa), reflecting their huge groundwater storage and the large distances between their paleo-recharge and discharge areas. For such cases ^{14}C can be a powerful investigation tool, under favourable geochemical conditions.

It has been conclusively proven, through the use of environmental isotopic indicators, that the last major replenishment of the principal aquifers in many of today's more arid regions occurred in humid climatic episodes in the Holocene and Pleistocene. The stable isotopic (^2H and ^{18}O) signature displays consistent and significant depletion in the groundwater from these aquifers, and this groundwater has been widely dated (using the evidence of ^{14}C content) as having been recharged during at various intervals during the period 10,000 – 40,000 years BP.

It should be noted, however, that groundwater ages, flow rates and residence times derived from isotopic data can vary widely according to the position and structure of sampling points within an aquifer system. Isolated values thus should not be used to derive the overall average renewal period for an aquifer system, since the aquifer can contain groundwater of very different ages due to complex flow trajectories between areas of recharge and discharge. This can restrict the practical application of groundwater dating methods.

Estimation of contemporary recharge rates

Quantification of natural contemporary aquifer replenishment rates is also an important aspect of groundwater resource evaluation for management strategy in the more arid regions. An in-depth review of available physical, chemical and isotopic methodologies for quantitative evaluation of groundwater recharge was provided by Allison (1988), and the applicability and limitations of different approaches is presented in a more recent publication (IAH, 2002).

Assessment of the processes involved in natural groundwater recharge (by both direct and indirect mechamisms) requires consideration of the climate, soil profile, morphology and vegetation. In more arid climates in particular, quantification of contemporary recharge fluxes presents significant difficulty and often involves substantial uncertainty because of :

- wide spatial and temporal variation of rainfall and runoff events;
- widespread lateral variation in soil profiles and hydrogeological conditions.

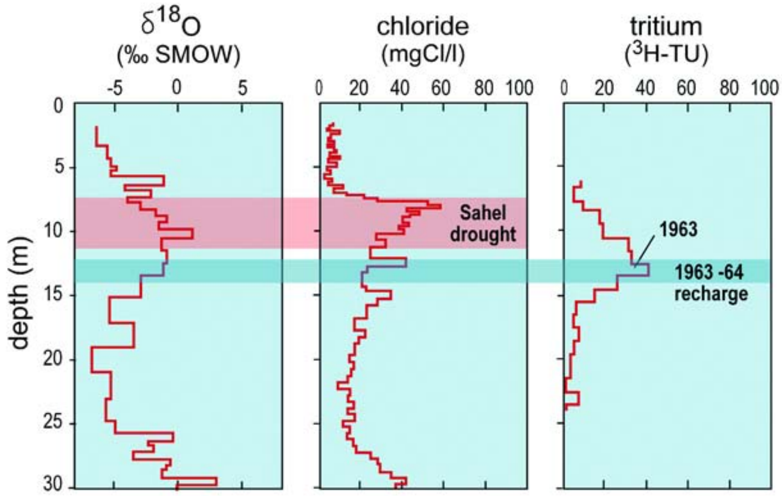
In contrast to humid regions, recharge to groundwater under arid and semi-arid conditions is much more intermittent (taking place only during short-duration, high-intensity, rainfall events of infrequent recurrence), with direct rainfall recharge generally becoming progressively less significant than indirect recharge via surface runoff. Furthermore, such rainfall events usually have only limited areal distribution and thus often do not permit the application of regional approaches, whose resolution would be too low to quantify a small component of contemporary recharge. Most practical applications in arid and semi-arid regions, therefore, are restricted to study of the recharge process and replenishment rate at the local scale. Such 'point information' is not easy to extrapolate to regional scale, but advances in satellite and airborne remote-sensing techniques offer potential in this respect.

Among the different methodologies available for quantitative recharge estimation, the use of isotopic and chemical properties of soil moisture down a vertical profile through the vadose (unsaturated) zone is probably the most effective in providing data at site-scale (Edmunds, 1999) (Figure 7). Numerous studies from the semi-arid zone have been reported in the literature during the last two decades in which the use of :

- tritium (3H) usually involves determination of the depth of the 1963 thermonuclear fallout peak (in the northern hemisphere), with the volume of water above the peak representing the total recharge since 1963;
- stable isotopes (^2H and ^{18}O) to provide evidence on the extent of evaporation and characterise the pattern of recent recharge episodes;
- chloride (Cl) depends upon knowledge or assumptions on the input from local atmospheric (aqueous and solid) deposition, which are conserved in the soil and concentrated through moisture loss by evapotranspiration, but sites in coastal areas (with aerosol deposition) and in cultivated areas (where agricultural fertilisers may have been added) are best avoided.

Figure 7

Vadose zone isotopic and chemical investigations of groundwater recharge in arid regions



An estimation of local contemporary recharge rates and an indication of the severity of the Sahel drought in the late 1960s can be obtained from these deep vadose zone profiles from northern Senegal (Edmunds, 1991 and Enrich, 2001). The ^{3}H peak corresponds to 1963 infiltration and the enrichment in ^{18}O, together the high Cl concentrations at shallower depth are a consequence of very low recharge rates and soil fractionation during the drought years.

Detailed field research on the applicability of isotopic and geochemical methods in the vadose (unsaturated) zone for groundwater recharge estimation was coordinated by the International Atomic Energy Agency during 1995-99, with results being obtained from 44 sites mainly in arid climates (IAEA, 2001). Detailed information on the physiography, lithology, rainfall, vadose zone moisture content and chemical and isotopic determinands were collected at each profiling site and reliable contemporary recharge estimates obtained (Table 12).

Table 12. Summary of physical, isotopic and geochemical investigations of contemporary groundwater recharge at sites with arid climate

COUNTRY Region	MEAN PRECIPITATION (mm/a)	VADOSE ZONE DEPTH (m)	RAINFALL Cl CONTENT (mg/l)	MEAN RATE OF RECHARGE (mm/a)
JORDAN				
Jarash	480	21	10	28
Azraq	67	7	61	2
SAUDI ARABIA				
Qasim	133	18	13	2
SYRIA				
Damascus Oasis	220	21	7	2–6
EGYPT				
Rafaa	300	20	16	18–24
NIGERIA				
Mfi	389	10	—	<1

Geochemical and isotopic techniques can also be applied to the study of groundwater in the saturated zone to identify recharge processes and sources. Age dating through radiometric methods can provide the groundwater age-gradient down the vertical profile in the saturated zone which have been used to estimate recent recharge rates. Such an approach using tritium (^3H) was reported to give an estimate of 3–7 mm/a for the average natural direct recharge to the main aquifer system in Qatar (Yurtsever, 1999), but one of the main assumptions inherent in the lumped parameter modelling approach needed for interpretation is steady-state flow conditions in the aquifer system and this is often likely to be invalid.

Aquifer numerical modelling

Lumped-parameter aquifer models can provide useful bulk assessments of aquifer systems – as their name suggests they lump each set of aquifer parameters by a single averaged value. Their application to reconnaisance-level investigation of non-renewable groundwater resources is generally for rapid assessment of the 'resource life' or an indication of the bulk response which can serve as a cross-check for more detailed numerical modelling.

Another category of aquifer models are the **analytical groundwater radial flow models**. These are of great utility at the scale of waterwell testing for local aquifer properties and well hydraulic diagnosis. They can include consideration of complexities, such as aquifer anisotropy and vertical property variations.

In general, however, when reference to aquifer modeling is made it relates to the application of **distributed-parameter numerical aquifer models,** since these are readily capable ofrepresenting the spatial variations of the aquifer system. The simulation of groundwater flow involves iterative solution of the relevant partial differential equation, using either finite difference or finite elements. There is an extensive scientific literature on numerical aquifer modelling and a large number of modelling codes/programmes are available, both free and as commercial packages. The user has a very large choice, but the selection of an appropriate code requires a considerable appreciation of the hydrogeological problem to be solved, and the pros and contras of the various packages.

Initially numerical aquifer models are used to examine the validity of the conceptual model of the aquifer system. As additional data become available and the aquifer is better characterised, the model can be used to identify regions of greatest uncertainty where exploratory drilling is most needed. At the aquifer development stage, models are first used to test potential wellfield configurations and subsequently to optimise their performance (Chaleb, 1999). System characterisation will inevitably be subject to considerable initial uncertainty and it is thus recommended that 'worst-case parameter values' be selected if numerical aquifer modeling is used as a basis for planning. Once reasonably calibrated there is potential for the outputs of numerical aquifer models, which have been subjected to appropriate sensitivity analysis, to be used by water regulatory agencies for resource administration , providing they are capable of withstanding legal challenges on the validity of their basic assumptions.

In general aquifers respond only slowly to groundwater extraction. And this is well demonstrated through numerical modelling analysis of a shared aquifer system in Jordan and Saudi Arabia. The model study (Schmidt et al., 1999), which considered the aquifer response to climatic change over the 5000-year period following the last pluvial recharge in the region, showed that the aquifer could have been discharging to the Dead Sea at rates of almost 500 Mm^3/a,

Further field data are awaited to confirm or refute this finding, but it shows how modelling can be used to challenge (and perhaps modify) the basic conceptual model of an aquifer system.
A quasi-three dimensional finite element numerical model of the Western Jamahiriya Aquifer in Libya has been constructed to guide the de velopment of the Great Man-Made River Project - Phase II ((Pizzi and Sartori, 1984 and Pizzi, 1999). Model calibration was carried out using historical data for the period 1970–90, and the model was then used to optimise the design of wellfield layout, which consisted of 440 waterwells with production rates of 45– 56 l/s. Aquifer modelling was based on extensive surveys and field observations programmes since the mid-1960s. Even then it had many initial flaws concerning the choice of boundary conditions, and was later improved by incorporating the physical limits of the aquifer system and adopting the prevailing hydrodynamic conditions at those limits. In general terms, it can be said that 'one-time modelling' of an aquifer system is insufficient. It will always take several iterations before a numerical aquifer model is robustly calibrated and fully reliable as a tool for operational management. The modelling of this aquifer system is a good example of the need to carry-out repeated model audits and upgrades. The original modelling of the mid-1970s was revised in the early 1980's and in the mid-1990s, each supported by new hydrogeological data from additional exploratoration/observation wells. In each phase the outcome was an improvement in understanding and ability to predict wellfield performance and aquifer response.

Risk assessment of long-term resource reliability is an important component of aquifer management modelling, where non-renewable groundwater resources are involved (Puri et al., 1999). This involves the identification of all potential hazards, ranking them in terms of their probability of occurrence and testing their significance in the numerical aquifer model. Such analysis permits the identification of the key hazards and allows management to focus on risk control and mitigation.

In summary, non-renewable groundwater resource assessment should include the following phases :

- construction and verification of a hydrodynamic simulation model, adequately representing the structure and storage parameters of the aquifer system and predicting its non-steady state response to long-term groundwater extraction;
- design of possible production wellfields, compatible with potential demand from urban, industrial or agricultural development, including (as one option) maximising long-term groundwater output;
- simulation of long-term groundwater extraction scenarios, for the purpose of examining their practical feasibility and identifying their respective impacts.

Importance of groundwater monitoring

A high-level of uncertainty is inherent in the interpretation of groundwater resource investigations in more arid climatic conditions. But the level of confidence in hydrogeological prognosis will increase greatly with the availability of some years of monitoring data on aquifer response to large-volume abstraction (Foster 1989). Thus a carefully-designed and systematically-operated monitoring program is essential.

The monitoring programme should be based on systematic periodic groundwater sampling and analyses, and commence as early as possible in the aquifer development cycle. A long-term perspective must be taken since balanced interpretation will necessitate more than a <handful>

of data. There is always need to formalise and strengthen the interface between monitoring activities and groundwater resource decision-making, such that monitoring data acquisition becomes an iterative part of aquifer development and management. This is essential to be alert to unexpected changes in aquifer system response to groundwater extraction.

The monitoring programme should be tailored to fit specific management objectives, but the incorporation of selected isotopic determinants can provide a useful tool for interpretation of such factors as induced recharge from surface watercourses, increasing salinity levels, etc. In the longer term, isotope monitoring data can provide further insights into the rates of aquifer storage depletion or aquifer recharge renewal. In some areas where fossil groundwater is used extensively for agricultural irrigation there is risk that irrigation returns (with elevated levels of leached salts and nutrients) will contaminate aquifers. Isotopic monitoring data can act as an indicator and provide 'early warning' of such processes. Also in many arid regions, 'check dams' are constructed across surface watercourses as a means of enhancing aquifer recharge, and isotopic monitoring data can be useful to assess their effectiveness.

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CHAPTER 4

Legal and institutional considerations

Marcella Nanni, Stefano Burchi, Kerstin Mechlem and Raya M. Stephan

Introduction

As was mentioned in Chapter 1, dealing with the management of non-renewable groundwater resources is not just a matter of allocating available flows and preventing conflicts between users, but also about planning their exploitation.

Many countries still lack coherent policies and strategies for the management of groundwater resources. However recently enacted legislation specific to the control of groundwater abstractions and quality - or comprehensive water resources legislation with a specific focus on groundwater - suggests that efforts are being made towards achieving the goal of a more sustainable development, use and management of these resources. Efforts are also being made to devise adequate institutional arrangements to administer this legislation.

On the other hand, a number of large aquifer systems containing predominantly non-renewable groundwater resources span multiple countries (Table 3 (Chapter1)). As their development on one side of the border may have adverse effects on the other side, the issue of co-operation over their management is to be considered. So far the international law of transboundary aquifer systems (whether containing renewable groundwater or not) is little developed and there are very few examples of international cooperation in the management of these aquifer systems.

The national dimension

Legal aspects

National legislation generally makes no distinction between renewable and non-renewable groundwater resources. At the domestic level, a major issue is the legal nature of groundwater resources, or in other words its ownership. When these are legally owned or held in trust by the state on behalf of the national community it is easier, in principle, to introduce regulatory management measures that restrict individual freedom to develop and use the resources (Caponera, 1992). Until recently, groundwater was privately owned in many countries, among which European civil law countries such as France, Italy and Spain. A regime similar to private water ownership is present in common law countries like England, the USA and Australia. However there have been major legal reforms in these countries, and groundwater is now state-owned or subject to superior state use rights (Burchi and Nanni 2003). In arid countries of

Northern Africa and the Middle East, groundwater – like all water resources – belongs to the state or is held in trust by it, and may be subject to management measures whenever the need arises. In other words, the definition of the legal status of groundwater resources is the natural starting point for the introduction of management measures such as those illustrated in Table 7 (GW-MATE 2002-2004 – Briefing Note 4). These measures range from minimum regulatory requirements to more complex systems of groundwater management. It is also worth noting that provisions on groundwater management are to be found not only in water legislation, but also in legislation relating to land-use planning, public works, agricultural development and environment protection, among others.

However, national groundwater legislation will not generally provide on its own a sufficient basis for addressing management needs for non-renewable resources. Since non-renewable aquifers are storage-dominated and therefore should not be dealt with in the same way as (flowing) rivers, specific provisions should be made through regulations for given aquifer units to provide guidance in the depletion (or recovery) plan implementation process, and to adapt the above mentionned tools and measures to the specific case of non-renewable groundwater. The regulations should be supported by administrative and technical guidelines. The two planning scenarios relevant to non-renewable groundwater resources are described in Chapter 2 and summarized in Table 8 (GW-MATE 2002-2004 – Briefing Note 11).

Thus, the provisions of a national (ground)water law enabling the authority responsible for groundwater to identify and declare critical areas, normally corresponding to hydrogeological units (aquifer sub-units), will be of particular importance. Based on the declaration, the authority will proceed to the development of strategic management plans tailored to the specific conditions of the units under consideration. Water uses will be dealt with differently, depending on the storage reserve available in each specific unit, on the unit management goal and on the allowable decline rate over a given period of time. In any case, it is essential to limit the duration of groundwater abstraction/use rights (to, say, five years), so as to facilitate the periodical review process and the adjustment or reduction of these rights, as needed. Finally, in some hydrogeological units, new permit applications for irrigation or other purposes may have to be ruled out, while water suppliers may be required to have conservation plans.

If this is normally the situation in technologically advanced states such as the western states of the USA, which are in a position to base strategic choices on reliable data and information, in most countries the knowledge of groundwater resources is limited. Thus, legal provisions are often confined to the banning of certain types of crops, or to prescribing the conversion to crops requiring less water than others, or a reduction of farming grounds. In some countries, emphasis is placed on the prohibition of the construction of new wells. To be able to make strategic choices, the countries in which data are scant should make efforts, in particular, to introduce legislation requiring groundwater-related institutions to coordinate data-gathering activities and pool data into unified groundwater data-bases s at the national level. In parallel with this, it is indispensable to introduce systems of water rights which are time-limited and adjustable under given circumstances.

Finally, with a view to the recovery of an aquifer water legislation may provide for artificial aquifer recharge with surface water, stormwater or wastewater. In this case, the legislation will require that certain conditions as to the qualifications of the operators in the sector and to water quality are met. Therefore, artificial aquifer recharge will be subject to a permit, and the operators to registration with the administration.

Table 7. Typical range of legal provisions on groundwater resources

Groundwater resources planning	*General trends*	• Incorporates key strategies and the means to implement them. • Possibility of compensation for those who lose their entitlement on groundwater use. • Public records : registration of all licensed groundwater uses.
	Specific measures ■ In case of groundwater decline ■ Efficiency measures ■ Use of non-conventional resources ■ Penalties for offences	• Temporary rationing of the available supplies. • Suspension, reduction or banning of certain groundwater uses. • Implementation of 'codes of good agricultural practices'. • Controlled recycling and reuse of wastewater, and use of sea-water. • Range from administrative sanctions to imprisonment, and to the obligation to restore the original state. • Sanctions may include the seizure of the equipment used to execute unlawful works (drilling rigs).
Groundwater abstraction control	*Permit system (permits, licenses, authorizations, concessions, entitlements, water rights)*	• May cover groundwater exploration, well construction and groundwater use. • Terms and conditions are set for: (a) volume, rate and period of abstraction; (b) location of well; and (c) modalities of abstraction and use. • Enables the water administration to control groundwater abstraction. • Ensures that groundwater is used as needed. • Protects the entitlement of registered water users (recorded in specific registers). The legislation specifies the cases in which a permit may be suspended, modified and revoked. Groundwater permits should be consistent with the hydrogeological reality of aquifers.
	Registration of certain wells	The construction of a well not exceeding a certain depth and/or a certain rate of flow is subject to a simple declaration, followed by registration by the water administration.
	Licensing of drillers	• Serves to ensure that drilling contractors are sufficiently qualified. • Through sampling and reporting obligations, ensures that drillers supply groundwater data to the administration.
	Water charges	Groundwater use is subject to charges which may increase progressively, depending on the volumes abstracted.
	Metering of wells	Serves to (a) quantify the amounts of water extracted, and (b) charge the users accordingly.
Groundwater quality protection	*Declaration of protected areas*	To protect groundwater supply wells and wellfields, vulnerable aquifers against pollution, aquifers at risk of overexploitation.
	Environmental Impact Assessment (EIA)	Required for projects/activities with potentially negative impact on aquifers.
	Control of land uses	A number of measures may be introduced to ensure that land uses do not adversely affect groundwater: • Restrictions of certain cropping patterns; • Reduction of animal-grazing intensity; • Land reclamation and drainage; • Prohibition or limitation of certain water-using activities; • Prohibition or limitation of certain polluting activities; • Limitations of the use of fertilizers and pesticides.

Table 8. Planning scenarios and key management instruments

SCENARIO 1: PLANNED DEPLETION (Mining of the resource)	SCENARIO 2: PLANNED RECOVERY (Rationalization scenario)
(a) a depletion plan including an 'exit' strategy, i.e., an indication of what to do the day after: - resorting to alternative water sources (conventional or non-conventional); - relocating uses and users (wherever feasible). (b) permits containing conditions as to: - well siting; - the depth of drilling; - abstraction rates; - abstraction volumes. (c) water charges to be so structured as to (at least) contribute to the cost of implementation of the exit strategies.	(a) a long-term stabilization or recovery plan containing priorities as to demands that must be satisfied first and the uses that must be scaled down/ banned. (b) Zoning, based on aquifer vulnerability. (c) Sealing of certain wells. (d) Permits containing conditions as to (as sub scenario 1). (e) Demand management measures.

Institutional aspects

The successful implementation of the measures outlined above requires an institutional set-up facilitating the management of non-renewable groundwater resources. This includes:

- consistent policies,
- legislation,
- strategic management planning,
- resource administration capability at government and decentralized levels,
- an informed and participating groundwater users,
- capacity for monitoring and assessment.

At the national level

A single authority

The ideal solution for addressing groundwater management issues at the national level would be to place the entire range of functions relevant to groundwater in the hands of a single ministry or authority, which should also be in charge of surface water. This, however, is not always possible. In spite of the existence of a 'water resources' institution in a number of countries, many ministries and government agencies usually have a stake and a say in groundwater development and use.

An interministerial coordination mechanism

Therefore, legislation provides in some cases for the participation of these stakeholders in groundwater resources planning and management at the national level through interministerial coordination mechanisms, such as a council, commission or committee. In Tunisia, for instance, a Water Council provides advice on all matters relating to policies and plans. In Algeria, a similar institution was created in 1996.

At the aquifer level : Aquifer Management Organisations (AMORs)
The participation of stakeholders and users in groundwater management is indispensable for the successful implementation of planning determinations and management measures. Its importance has been recognized, and many countries are beginning to provide, through their legislation, for the establishment of Aquifer Management Organizations (AMORs). AMORs are particularly useful for aquifers at risk of being degraded or 'mined', i.e., exploited to the point where abstraction becomes economically un-attractive, whether abstraction rates exceed natural recharge, or regardless in the case of non-recharging aquifers. AMORs may comprise representatives of central government agencies, water users and other stakeholders, and of the local authorities. They may perform an advisory role with regard to aquifer management planning and the measures required to address the negative impacts of development on the condition of an aquifer, including measures entailing a limitation to individual water rights. Furthermore, they may be called upon to monitor the implementation of an aquifer management plan.

AMORs exist in Spain, Mexico, Australia, and western states of the USA, among others. In particular, a remarkable example of AMOR is offered by the Australian states sharing the Great Artesian Basin (GAB) – Queensland, New South Wales, South Australia and Northern Territory. Each of these states has established an advisory committee for its respective portion of the GAB. The committee represents all stakeholders and provides advice to the water administration on the granting of groundwater abstraction licenses. At the GAB level there is a GAB Consultative Council comprising representatives of the Commonwealth, the states, the users and various associations of stakeholders. In the year 2000, the Council adopted the GAB Strategic Management Plan, which sets guidelines for groundwater management at the Commonwealth and state level. The Council is in charge of monitoring the implementation of the Plan at the basin level and of facilitating the exchange of information among basin states, amongst other things.

Local and users' level

For groundwater management to be successful, it is essential, that users' representatives participate, through their groupings or associations, in any decision that might affect their interests. This has been acknowledged by the legislation of some countries, which has provided for users' representation in AMORs. It is also important that the local authorities have a say in groundwater management when AMORs are established. Therefore, the water legislation of some countries requires their representation in these organizations.

The specific case of non-renewable groundwater

Since management measures in this case are aquifer-specific, it is important to establish or designate an institution that will coordinate the implementation of plans and management measures at the aquifer level, with the participation of groundwater users and stakeholders. That of the AMOR would be the most appropriate form for such an institution.

International groundwater law

A number of aquifers in the world containing non-renewable groundwater are transboundary (Table 3, Chapter 1). Among these are, for example, the Nubian Sandstone Aquifer System

(NSAS), which is overlain by parts of Chad, Egypt, Libya and Sudan; and the North-Western Sahara Aquifer System, better known by its acronym in French as SASS (Système Aquifère du Sahara Septentrional), shared by Algeria, Libya and Tunisia. Case studies on these two aquifer systems are attached to this monograph. (case studies).

International law has only sparsely taken account of transboundary aquifer systems (UNESCO 2001), be whether they contain renewable or non-renewable water as it appears in the following.

International instruments

While a number of treaties and other legal instruments address groundwater, few do so exclusively or specifically (Burchi & Mechlem, 2004). In many instances groundwater is only nominally included in the scope of a legal instrument. There are, however, both in treaty as well as in non-treaty law tendencies to develop more groundwater specific rules (Mechlem, 2004).

At the bi-lateral level, one exception is the 1977 *Arrangement relatif à la protection, à l'utilisation et à la réalimentation de la nappe souterraine franco-suisse du Genevois (Agreement on the protection, utilization and recharge of the Franco-Swiss Genevese aquifer)* dealing with groundwater quality, quantity, abstraction and recharge. This is a rare example of a treaty dealing exclusively with a transboundary aquifer and establishing a joint commission for the management of the aquifer. Other treaties deal specifically with groundwater, among other subject matters, such as the 1973 agreement between Mexico and the United States on the Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River, known as Minute 242. The latter concerns mainly surface water, but contains one provision (paragraph 5) that limits groundwater pumping of the Yuma Mesa aquifer by both countries in the immediate vicinity of the Arizona-Sonora boundary near San Luis. It is notable that this provision covers only one of at least 15 shared aquifers between the United States and Mexico, and was adopted 'pending the conclusion' between the two governments 'of a comprehensive agreement on groundwater in the border areas'.

On the regional level, mention is to be made of two framework agreements tha apply to both surface and groundwater: the 1992 UN ECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes andthe 2000 Revised Protocol on Shared Watercourses in the Southern African Development Community (Revised SADC Protocol).

For the Member States of the European Union the Water Framework Directive (Directive 2000/60/EC) provides a very detailed and ambitious regime of groundwater quantity and quality control, which is directed at both domestic and transnational situations. A proposal for a directive on the protection of groundwater against pollution has been submitted in September 2003 (COM (2003) 550 final). While the Water Framework Directive provides a general framework for groundwater protection, the purpose of the Groundwater Daughter Directive is to establish specific measures to prevent and control groundwater pollution.

At the global level, the United Nations Convention on the Non-navigational Uses of International Watercourses (Watercourses Convention), prepared by the International Law Commission (ILC) (the United Nations body in charge of codifying and progressively developing international law), was adopted on 21 May 1997 by the UN General Assembly after State negotiations. The Convention constitutes a major step in the development of international water law. It includes in its scope groundwater that is part of a 'system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus' (article 2a). Hence, it does not extend to non-renewable groundwaters as they are not part of a system of surface and groundwaters.

In view of the lack of legal and institutional arrangements in the case of transboundary aquifers, a multi-disciplinary group of experts felt the need to draft and propose a model treaty, the Bellagio draft treaty (Hayton and Utton, 1989). The draft treaty remains as a result of their work.

And finally mention should also be made of the 2004 Berlin Rules on Water Resources of the International Law Association (ILA) that build on the earlier Helsinki and Seoul Rules.. The Berlin Rules apply to renewable and non-renewable, domestic and international groundwater. According to the Rules, the general principles of international water law apply to all groundwater. In addition, they contain specific provisions, inter alia, for the precautionary and sustainable management of aquifers and their protection. These Rules represent a scholarly opinion.

International law principles

Treaty law has mainly developed for groundwater related to surface water, and tends to apply to groundwater the general principles of international water law, which were developed for the management of surface water.. Shared water resources have to be utilized in an equitable and reasonable manner. States also have a duty to take all appropriate measures to prevent the causing of significant harm to other states. Finally, they shall cooperate to attain optimal utilization and adequate protection of groundwater. In particular, they shall exchange data and information and provide advance notification of planned measures when managing aquifers in a way that could cause significant adverse effects on another state. While these principles provide some legal basis to the management of transboundary groundwater resources, there is a need to develop the law further to do full justice to the specific characteristics of aquifers, the particular challenges of their management and the need to protect them from degradation.

The paucity of treaties and other legal instruments dealing specifically with groundwater in general, and especially with non-renewable aquifers, makes it difficult to determine the relevant customary international law, i.e., the law that binds all states as a result of state practice carried out in the conviction of a corresponding legal duty, in particular with respect to the latter type of aquifer.

The specific issue of non-renewable aquifers

At the bi- and multilateral level, efforts are ongoing among states sharing transboundary non-renewable aquifer systems to cooperate and agree on joint management mechanisms.

A case in point is the NSAS. Egypt and Libya, two of the states concerned, established a joint Authority for the study and development of the aquifer system in the early 1990s. Chad and Sudan have become members of the Authority subsequently. Amongst other things, the Authority is responsible for collecting and updating of data, conducting studies, formulating plans and programmes for water resources development and utilization, implementing common groundwater management policies, training technical personnel, rationing the aquifer waters and studying the environmental aspects of water resources development. The Authority has a board of directors consisting of three members for each state, an administrative secretariat and a director who is appointed by the board. A representative of each member state chairs the board of directors on a rotation basis. The board meets twice a year and takes its decisions by a majority vote. An integrated regional information system was developed with the support of the Center for Environment and the Development for the Arab Region and Europe (CEDARE). On 5 October 2000 the four Member States signed two agreements on procedures for data collection, sharing and access to the data system.

Since 1999, cooperation efforts have also been ongoing with regard to the SASS. Recently the three countries have agreed to set up an institutional mechanism for cooperation consisting of a small secretariat attached to the inter-governmental *Observatoire du Sahara et du Sahel (OSS).* Such a secretariat will ensure continuity of cooperation in hydrogeological data collection and aquifer modelling, in support of domestic planning and decision-making by the concerned countries.

Groundwater on the agenda of the ILC

Also at the global level there are encouraging indications regarding the development of international groundwater law. The ILC incorporated in 2002 the topic of 'Shared Natural Resources', comprising groundwater, oil and gas, in its long-term programme of work.. Three reports were already submitted on the sub-topic of transboundary groundwater (2003, 2004, and 2005). In his last report (UN Doc. A/CN.4/551), which was well received by the members of the ILC, the Special Rapporteur proposes a full set of draft articles for the management of transboundary aquifers. He introduces the equitable and reasonable use principle, the no-harm rule, a provision on monitoring, and a series of articles on the protection, preservation and management and on activities affecting other States. A specific provision on non-renewable groundwater is presented identifying the obligation on aquifer States to 'aim to maximize the long-term benefits derived from the use of the water ...' Aquifer States 'are encouraged to establish a development plan' for their non-renewable groundwater, 'taking into account agreed life span of such aquifer or aquifer-system as well as future needs of and alternative water sources for the aquifer States.' (draft article 5)

Recent efforts of cooperation over transboundary aquifers and the work being achieved at the ILC may be the sign of a slow evolution and concern in the international arena on the sustainable management of such water resources. Specific attention is being given to non-renewable gourndwater resources. However, successful international cooperation requires the availability of a functioning domestic legal and institutional framework in the countries concerned, including adapted regulatory and economic tools for pollution control and demand management of non-renewable groundwater resources.

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- Groundwater resources whose replenishment takes very long in relation to the time-frame of human activity are conveniently termed '**non-renewable groundwater resources**' – and the volume of such groundwater stored in some aquifers can be huge. In these cases one is usually dealing with '**fossil (or palaeo) groundwater**', recharged in past, more humid, climatic regimes, but not all aquifer systems containing fossil groundwater are non-renewable.

- Development of non-renewable groundwater resources implies the **'mining of aquifer storage reserves',** and as such takes on particular social, economic and political sensitivities. But especially in many of the world's more arid regions, the use of non-renewable groundwater offers an opportunity to alleviate growing water scarcity, improve social welfare and facilitate economic development. To constrain resource utilisation on grounds of not being 'physically sustainable' in the long-term is simplistic and insufficient, since such development can (and should) be considered **socially-sustainable** if certain criteria can be met and specific risks can be managed.

- To meet the requirement of 'social sustainability' in respect of development of the non-renewable groundwater resource, the following criteria need to be addressed :
  - it should lead to clear **improvements in social well-being and livelihoods;**
  - the balance between short-term socio-economic benefits and longer-term 'negative impacts' must be positive;
  - an '**exit strategy**' should exist, with an answer to the question 'what comes after the aquifer becomes seriously depleted';
  - the issue of **inter-generational equity** has to be considered.

- Concomitantly, it should be recognised that predicting the longer-term evolution of any given case of groundwater mining will be subject to **significant uncertainty** (as a result of incomplete hydrogeological understanding, innovations in water technology, changing global agriculture and food markets, accelerated climate change, etc), which places limits on conventional resource management. This dictates the need to incorporate more **flexible and adaptive risk-based approaches**, which need to find political acceptance.

- In practice the utilisation of non-renewable groundwater tends to occur in two scenarios :
  - '**planned aquifer depletion**' – whose management goal is orderly utilization of aquifer reserves (of a system with little pre-existing development) with expected benefits and predicted impacts over a specified time-frame;
  - '**excessive unplanned exploitation**' – with incidental depletion of aquifer reserves as a result of intensive groundwater abstraction in areas with limited contemporary recharge.

- In cases of unplanned exploitation, management action is needed to 'rationalise' the situation, and this will have much in common with 'planned depletion scenarios' since the goals will be more orderly utilisation of aquifer reserves – minimizing quality deterioration, improving groundwater productivity and promoting social transition to a less water-dependent economy. In one sense it will be more difficult – because greater vested interest and social inertia will have to be confronted, but the availability of data on aquifer response should mean that numerical aquifer models can be calibrated from historic trends and sounder predictions of future trajectory and impacts be made.

- **Government** has to play the key role in facilitating socially-sustainable use of non-renewable groundwater, but unacceptable political cost and inadequate institutional capacity can represent major impediments. The preferred arrangement is for responsibility to rest with a **single ministry or agency** – but if not possible a 'special lead unit' should be established with all ministries having a stake in groundwater development and environmental management being involved through a '**multi-sector coordination committee**'.

- Policy decisions on mining of aquifer reserves (or priority for rationalisation of an aquifer subject to uncontrolled mining) should be referred to high-level in government – in countries with a non-sectorial water resources ministry the decision could rest with the corresponding minister, but in others it would be better taken by a **high-level authority in the government hierarchy** (president's or provincial governor's office).

- These days most nations have **legal groundwater codes** which treat groundwater in aquifer storage as a public-property (or common-property) resource, but the perception of groundwater being private property may still pervade. However, national legislation will not generally provide a sufficient basis for addressing the management of non-renewable resources, and specific provision will have to be made through supplementary regulations which declare the non-renewable aquifer as a 'reserve area' subject to special development and management arrangements.

- Full **participation of groundwater users** will be equally vital to successful implementation of management measures. This will be best approached by establishment of an aquifer management organisation, which should include representatives of all main sector-interests and geographically-based user groups, together with those of government agencies, local authorities and other stakeholders. **Public awareness campaigns** on the nature, uniqueness and value of non-renewable groundwater resources will be essential to create social conditions conducive to improving water-use productivity and to effective aquifer management.

- A high priority will be to put in place a **groundwater abstraction rights system** (permits, licenses or concessions). These must be consistent with the hydrogeological reality of continuously-declining groundwater levels, potentially- decreasing well yields and possibly-deteriorating groundwater quality. Thus the rights should be time-limited in the long term, and subject to initial review and modification every 5–10 years. In the process, customary water-rights prevalent in many rural areas of the world must be reckoned with and reconciled with the proposed development.

- Focused administration of non-renewable groundwater, and the vital step of effective communication with stakeholders, will greatly benefit from the application of various key management tools :
  - **aquifer system characterisation and numerical modelling** to facilitate adequate prediction of groundwater availability, the impact of abstraction on the aquifer itself, third parties (especially traditional users) and related aquatic and terrestrial ecosystems, and potential groundwater quality changes during development;
  - **socio-economic assessment of options** for mining aquifer reserves, including consideration of potential alternative uses, the value of the proposed or existing use(s) in relation to the in-situ value of groundwater and the probable 'exit strategy' when aquifer reserves are depleted;
  - an acceptable **system of measuring or estimating volumetric abstraction** will be the cornerstone for both realistic charging and enforcing regulations to discourage inefficient and unproductive uses.

- The value of **detailed monitoring of groundwater abstraction and use**, and the aquifer water-level and quality response to such abstraction, cannot be overemphasised. This should be carried out cooperatively by the water resource administration, stakeholder associations and individual users. The existence of time-limited permits subject to periodic review will normally stimulate permit holders to provide regular data on wells. It will be incumbent upon the water resources administration to make appropriate institutional arrangements – through some form of aquifer database (databank or data-center) – for the archiving, processing, interpretation and dissemination of this information.

- Many 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, and there will much to be mutually gained through :
  - formation of a high-level steering group and a joint technical group;
  - operation of joint or coordinated groundwater monitoring programmes;
  - establishment of a common groundwater database or mechanism for information sharing;
  - adoption of coordinated policies for groundwater resource planning, harmonization of relevant legislation and regulations, and procedures for joint resource management and conflict prevention and resolution.

Development and management of groundwater: regional cases

Saudi Arabia aquifers

Walid A. Abderrahman

Introduction

Most of Kingdom of Saudi Arabia (Figure 1) is arid. The average annual rainfall ranges from 25 mm to 150 mm (MAW 1988) compared to the average annual evaporation that ranges from 2,500 mm to about 4,500 mm. The country's socio-economic development has been supported in large measure by its intensive use of groundwater including non-renewable fossil water.

This paper focuses on the country's management and use of non-renewable groundwater for satisfying its national water demands and the tools it uses to minimize negative impacts on the aquifers. Also discussed are issues of sustainability and the possible impacts of climate change on water demands and thus on the continued development of the country.

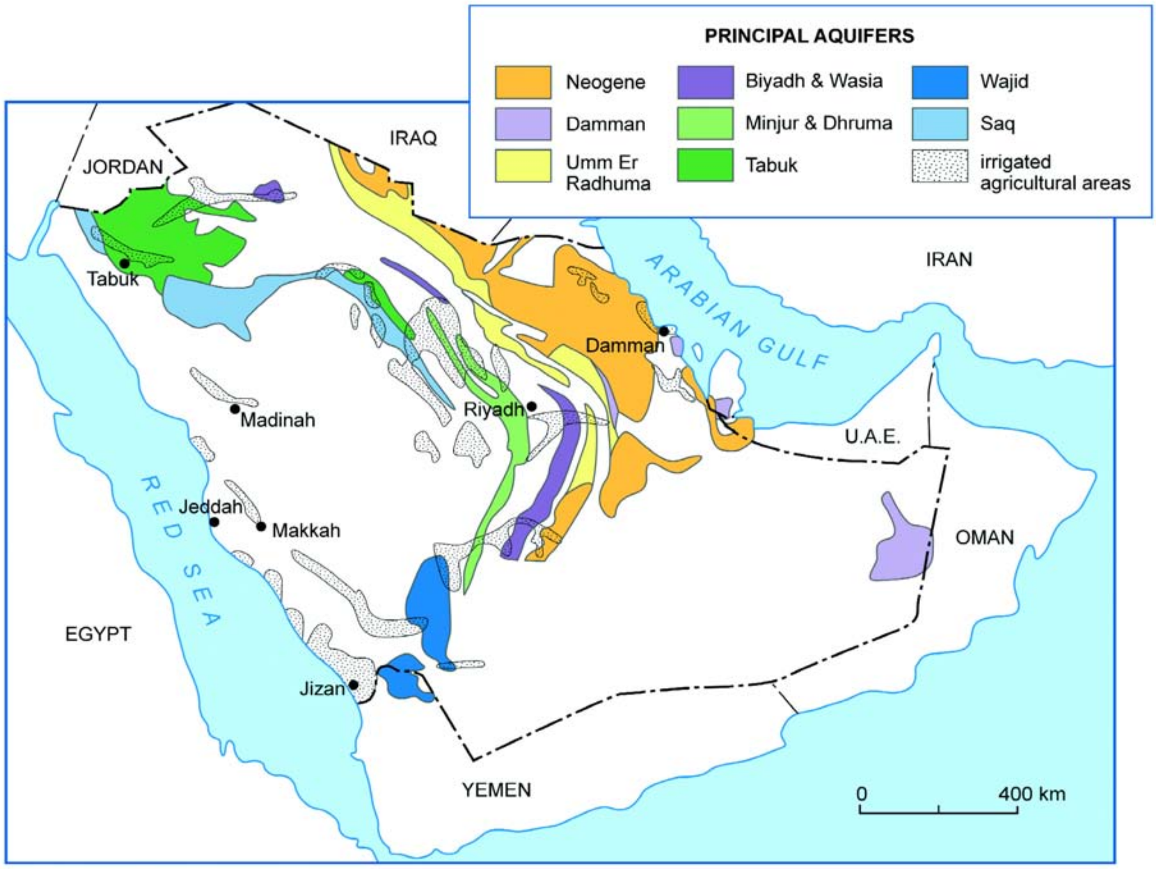
Water resources in Saudi Arabia

Groundwater in Saudi Arabia is found almost entirely in the many thick, highly permeable aquifers of large sedimentary basins of the Arabian Shield (Figure. 1), (Burdon 1982; MAW 1984). The estimated groundwater reserves down to a depth of 300 meters below ground surface are about 2,185 billion cubic meters (BCM). The average annual recharge is about three orders of magnitude less than that, or about 2,762 million cubic meters (MCM).

Groundwater is supplemented by desalinated water and treated wastewater. Saudi Arabia has become the largest desalinated water producer in the world. The total annual water production from desalination plants has increased from about 200 MCM in 1980 to over 1,000 MCM today (Al-Husayyen 2002). The present production represents about 50% of the total current domestic and industrial demands, and most of the rest is met from groundwater resources.

Figure 1

Principal aquifers of Saudi Arabia showing relation with main irrigated agricultural areas



Growth in water demands

The population of the Kingdom has increased from about 7.7 million in 1970 to about 21 million in 2000, and is expected to reach about 40 million by 2020. The urban population, about 15 million in 2000, is expected to reach about 32 million in 2020 or about 80% of the total population of the country. The annual domestic and industrial water demands have grown from about 220 MCM in 1970 to about 2030 MCM in 2000, and is expected to reach 6,450 MCM in 2020. The annual irrigation water use has increased from about 6,108 MCM in 1970 to about 19,074 MCM in 2000. These growing water demands are mainly satisfied from desalination plants and from the non-renewable groundwater resources.

Non-renewable groundwater resources supplied about 66% of the total national needs in 2000. The total consumed volume of nonrenewable groundwater resources for agricultural, domestic and industrial purpose from 1980 until the end of 2000 was about 260,000 MCM or about 11.5% of the total groundwater reserves in the top 300 meters below ground level. Under current development policies, the total national demands are expected to be about 24 billion cubic meters by 2025. Half of the expected increases in demands will likely come from non-renewable groundwater.

Impacts of intensive use of groundwater and adopted measures

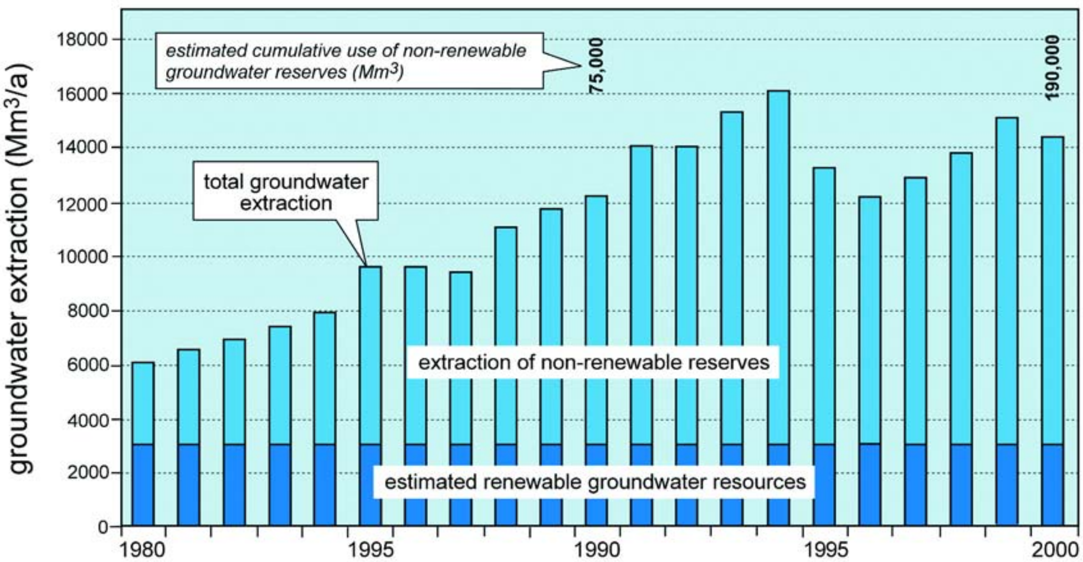
In Saudi Arabia, groundwater use has been supervised by the Ministry of Agriculture and Water. The management goal has been oriented towards recovery of the aquifer or an orderly use of aquifer reserves, minimizing quality deterioration, maximizing groundwater productivity and promoting social transition to a less water-dependent economy. The government has established regulations for the proper use of water resources and for the protection of groundwater resources. Considering factors related to regional water needs and human and economic conditions together with the availability of water, these regulations include:

- requirement of special permits from the Ministry for well drilling including site, aquifer, depth, design, development and production,
- supervision of well drilling and development by the Ministry,
- control of the purposes of water use by the Ministry,
- prohibiting well drilling in over-pumped areas or in aquifers which suffer from water level declines and quality degradation, and
- the right to establish water protected zones for special uses such as for domestic purposes.

The above policies have been implemented to various levels of success in different regions due to different reasons especially organizational factors, and fragmentation and overlapping of responsibilities among several agencies before the establishment of the Ministry of Water in 2001. The result is shown in Figure 2.

Figure 2

Growth in consumption of non-renewable and renewable groundwater resources in Saudi Arabia during 1980–2000



Additional management actions for sustainable groundwater resources

To secure more effective water management and national planning, and a higher level of sustainability and continuity of development and progress of the country, in 2002 all water agencies and authorities were placed under the Minister of Water (MW). The specific objectives of the new Ministry as stated in the Royal Decree No 125 on 25/4/1422 (16 July 2001) are to:

- supervise the management, monitoring and organization of the water sector and its facilities,
- carry out all related studies needed to assess the country's water supplies and storage volumes,
- prepare a comprehensive water plan defining policies for water resource development, protection and conservation,
- prepare a national program to expand the drinking water and wastewater networks in all urban areas of the Kingdom,
- suggest the required organizations needed for water resources protection,
- study and propose new water tariffs for all users of water,
- determine how to improve the performance of wastewater collection systems.
- develop mechanisms, frameworks and implementation strategies for private sector involvement in water sector investments, operation and maintenance.

In addition to those responsibilities of the MW listed above, measures are also needed to:

- reduce the irrigation water consumption to increase the long-term productivity and quality of the aquifers,
- control leakage and minimize water losses from water supply networks,
- augment groundwater resources from non-conventional resources such as desalination, wastewater reuse, and
- implement artificial aquifer recharge.

In September 2003, responsibility for the electricity sector was added to the mission of the MW and its name was changed to the Ministry of Water and Electricity. This decision was made to achieve better coordination between the water and power sectors as most of seawater desalination plants produce both water and electricity. The Ministry has adopted an Integrated Water Resources Management tools to implement its short term and long-term water strategies, which are presently under development. This approach is aimed at achieving the coordinated development and management of water, land and related resources in ways that will maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of of valuable groundwater resources and vital ecosystems.

Conclusions

Saudi Arabia is an arid country that has been relying, and to a great extent is expected to continue to rely, on non-renewable groundwater resources to support its comprehensive socio-economic, agricultural and industrial developments. Understanding the characteristics of its aquifers, the country has attempted, with varying levels of success, to manage the use of groundwater resources by controlling aquifer development, well licensing and control of drilling, agriculture policy modification, and production of non-conventional water resources. To avoid additional negative impacts on aquifers from excessive groundwater withdrawals, corrective demand management measures are needed in addition to augmentation of water supplies by seawater desalination and the reuse of treated wastewater effluents. New institutions under the newly established Ministry of Water and Electricity have been created to better manage the Kingdom's water sector. Other arid countries can benefit from the experiences of Saudi Arabia in groundwater management to support its socio-economic development.

Acknowledgement

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North Western Sahara Aquifer System (NWSAS)

A. Mamou, M.Besbes, B. Abdous, D.J. Latrech and C. Fezzani

Introduction

The North Western Sahara Aquifer System (NWSAS) is shared by Algeria, Libya and Tunisia. It contains considerable reserves of non-renewable water. During the last thirty years 0.6 to 2.5 billion m^3/year of water has been abstracted from this system. This continued exploitation is associated with many risks, including salinisation, loss of the artesian flow, drying up of outlets, and conflicts among countries.

Model simulations have highlighted the areas where shared resources appear to be the most vulnerable. They also have identified new withdrawals zones that can result in increased withdrawals while controlling the risks through improved agreements among the three countries.

This paper documents the principal results obtained through the implementation of the various components of the NWSAS project.

The North Western Sahara Aquifer System

The Sahara Aquifer System consists of the superimposition of two principal deep aquifers: a) the Continental Intercalary (CI), the deepest; and b) the Complex Terminal (CT). This System, as shown in Figure 1, covers an area of more than one million square kilometers, 69% of which is in Algeria, almost 8% in Tunisia, and 23% in Libya.

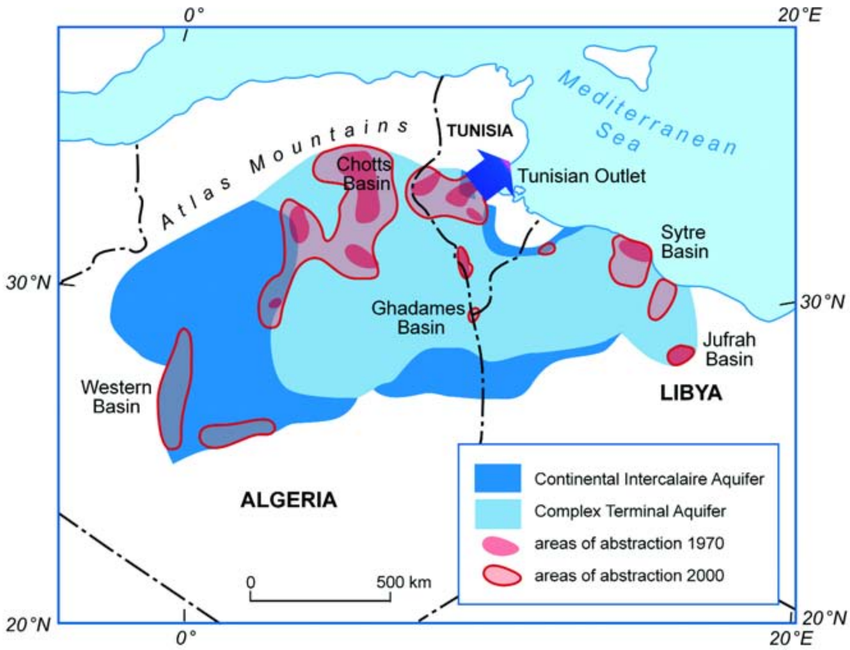
These aquifers are only slightly recharged by around one billion m^3/year in total. The little rainfall that occurs infiltrates mainly into the piedmonts of the Saharan Atlas in Algeria, as well as into the Jebel Dahar in Tunisia and the Jebel Nafusa in Libya. Nevertheless, the expanse of the system and the thickness of the aquifers supported the accumulation of considerable reserves.

The question, of course, is how, in a sustainable way, might the Saharan aquifers be exploited beyond their rate of recharge, and hence drawing from the accumulated reserves? How might a maximum of withdrawals of water for the best development of the region be secured, without at the same time risking the irreparable deterioration of the state of the resource? Answers to these questions will define the sustainable use of the exploitable resources of the North Western Sahara Aquifer System.

The Saharan Aquifer System is exploited by almost 8,800 water points, drillings, and sources: 3,500 in the Continental Intercalary and 5,300 in the Complex Terminal. These points include 6,500 in Algeria, 1,200 in Tunisia, and 1,100 in Libya. The number of drilled wells and accompanying system of exploitation has substantially increased during the last 20 years. Today, the annual

Figure 1

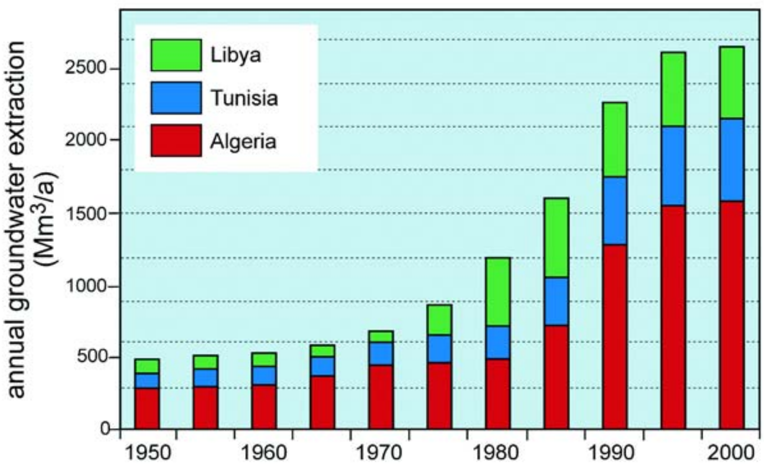
Hydrogeological sketch map of the North-West Sahara Aquifer System



exploitation reaches over 2.2 billion m^3, 1.3 billion in Algeria, 0.55 in Tunisia, and 0.33 in Libya (Figure 2). If this rate of extraction, shared among three countries, were to be prolonged, undoubtedly, there will be serious reasons for concern about the future of the Saharan regions. One can already observe the first signs of deterioration of the state of water resources, including increased potential for conflict among countries, water salinization, disappearance of artesian flow well drilling, outlets drying up, and excessive drawdown in pumping wells. The three

Figure 2

Growth in groundwater extraction from the North-West Sahara Aquifer System



countries concerned with the future of the system need to come together and find a way to jointly manage the Saharan Basin.

Authorities in these three countries, well aware of these risks, have begun joint studies under the supervision of Observatoire du Sahara ET du Sahel (OSS). In 1998 the OSS obtained support from the Swiss Agency for Development and Cooperation, the International Fund for Agricultural Development (IFAD) and the UN Food and Agricultural Organization (FAO) for a first three-year study that continued up until December 2002.

The objectives and activities of these studies focus on improved hydrogeology, an information system, a mathematical model, and a consultation mechanism. There now exists a fifty-year (1950–2000) historic record of the piezometry, water salinity, and its exploitation.

The results of this improved knowledge of the basin's hydrogeology is a schematization of the aquifers needed for a mathematical model. The Saharan basin is a large multilayered, sedimentary entity. The combined representation of the individual aquifers – permeable and semi-permeable – makes it possible to account for the hydraulic and chemical connections and exchanges among all of the basin's aquifers and thus, the performance of the system in the medium and long terms.

The NWSAS database and model simulations

The implementation of a shared database permits studies to be carried out simultaneously at each of the project's head offices and by each of the respective administrative authorities for water within each of the three countries. Creating this database involves multiple diverse operations at over 9,000 water points, including collecting, homogenizing the systems for classification and identification, reviewing, detecting faulty data, correcting, and validating. This management tool contains data of high quality and is now available for use.

Management with full factual knowledge of the Aquifer System is facilitated by the availability of a mathematical simulation model. This model provides predictions given various management scenarios. The reference period chosen for the simulations is the historical period 1950–2000, assuming the initial situation as existed in 1950.

Many alternative policies in each country have been simulated to predict their combined effects on the aquifer. A reference pattern, named scenario zero, was also defined. It consists in holding constant the withdrawals from drilled wells carried out in the year 2000, and calculating the system's corresponding evolution over 50 years.

Other policies included:

- In *Algeria*, two patterns:
  - A so-called **strong** policy representing an additional withdrawal of 101 m^3/s, which would increase Algerian withdrawals from 42 to 143 m^3/s during the first 30 years.
  - A so-called **weak** policy assumption for an additional withdrawal of 62 m^3/s, which would increase the withdrawals from 42 to 104 m^3/s.
- In *Tunisia:* the contemplated policy anticipates that the savings realized from improvement in the efficiency of irrigation will compensate for the additional demand of the new irrigated areas, which corresponds to the maintenance of the present withdrawals.
- In *Libya:* the exploratory simulations concern two programmes of the Great Man-made River Project (GMRP): an additional flow of 90 km^3/year from the pumping field of Ghadames-Derj with the collecting field of Djebel Hassaounah.

In the Continental Intercalary, CI, the scenario zero will result in drawdowns more than 40 meters within the Algerian Sahara lower part over the 50-year period. In Tunisia, the drawdowns are approximately 20 to 40 meters and in Libya they are approximately 25 meters. In the Complex Terminal, CT, in Algeria and in Tunisia, the drawdowns exceed 30 meters and in Libya they reach 60 meters. The disappearance of all artesian flow in the Algerian-Tunisian Chotts region, with the risk of saline waters intrusion from the Chotts recharge into the CT's aquifer. Hence the continuation of the current withdrawal schedule, scenario zero, constitutes a major potential danger within the region.

Assuming the strong policy in Algeria, the CI drawdowns are 300 to 400 meters within the Algerian Sahara lower part, with the complete disappearance of artesian flow. Libya is not affected by this policy but in Tunisia the drawdowns are from 200 to 300 meters and the disappearance of artesian wells and the Tunisian outlet are notable. For the CT, there is no effect in Libya, little effect in Algeria, and recharge may occur in the Chotts region.

Assuming the weak policy in Algeria, the effects in Algeria and Tunisia are very strong and quite unacceptable with respect to the CI and the CT.

Libyan scenarios of the GMRP in Ghadames resulted in CI drawdowns of 100 meters to the collecting field, around 50 meters within the deep southern region of Tunisia and in Deb Deb, Algeria. For the collecting field of the Jebel Hassaounah, its impact on the CI remains negligible.

These exploratory simulations have highlighted the harmful effects and the risks to which water resources in this basin are exposed. Continued exploitation of the CI and CT aquifers will require managing these risks, which may be summarized, as:

- disappearance of artesian flow,
- excessive drawdowns in pumped wells,
- drying up of Tunisian outlet,
- excessive interferences of drawdowns among countries,
- potential recharge in the Chotts.

A coordinated extraction policy

At the completion of the exploratory simulations, the adopted principle has been to seek the building of extraction patterns founded upon NWSAS output capacities while minimizing the identified risks of harmful effects at the sites close to the places where present or future demand might be expressed. At the same time sites that would be favorable for exportation in the future are being identified. The first stage for such a process has consisted in making an inventory of all the potential sites for pumping. The NWSAS Digital Model, which is suited to such a function, has been used to simulate the newly identified patterns.

The simulations concerning the future of the NWSAS have highlighted the most vulnerable regions. The sector most exposed is the Algerian-Tunisian Chotts basin in the CT. This is the region where the aquifer is most vulnerable. It is there where the strongest density in population can be found, where the pressure on resources will be the strongest. The simulations have clearly shown that the simple continuation of the present rates of withdrawals, over the next 50 years, would bring about additional drawdowns of approximately 30 to 50 meters on each of the two aquifers, with respect to all of the four interdependent sectors – the Oued Rhir, the Souf, the Djerid, and the Nefzaoua. Such a situation would be unacceptable for the Complex Terminal: the risk of salinity due to the chott's water percolation toward the layer would be inevitable. The simple continuation of the existing rates, at least within the CT, thus, would be completely unacceptable for the Chotts region. There, the reduction of withdrawals must be seriously contemplated now and on into the future. Salinity intrusion in the CT would be very harmful.

Simulations considered the possibility of bringing the level of exploitation up to 7.8 billion m^3/year within 50 years. This can be done only at the cost of dispersing new fields. 80% of the additional withdrawals will have to be done within distant areas, i.e., the CI's Western Basin and the CT's Oued Mya in Algeria. This will provide a total exploitation, by country, of 6.1 billion m^3/year in Algeria, 0.72 billion m^3/year in Tunisia, and 0.95 billion m^3/year in Libya. This possibility would cause exploitation of the NWSAS to climb to a level equivalent to eight times its renewable resources. Such an operation is realizable only by considerable drawing upon the system's reserves. Nonetheless, the necessity of confirming the results obtained must be stressed. In spite of the progress realized by the NWSAS project, uncertainties remain and these will require new investigations.

The new hydrogeological knowledge together with the simulation model makes it possible to predict the capacities of the NWSAS to supply appreciable quantities of water while minimizing risks concerning the resource. The results obtained show that it is advisable to manage this resource jointly. The intention of planning this joint use has been advocated by the OSS since the launching of the project: to promote a **basin consciousness** and to implement a **dialogue mechanism.**

Consultation and cooperation mechanisms

The simulations carried out have highlighted the areas where shared resources appear to be the most vulnerable. The exploitation of the Complex Terminal today, and of the Continental Intercalary tomorrow, will undoubtedly lead the three countries Algeria, Tunisia and Libya to consider sometime in the future the joint control, and reduction, of the pumping. How to control these flows through a concerted policy of preserving the water resources for the mutual benefit of all the countries over time is the central question that needs addressing today. This dialogue has begun.

Everyone acknowledges the major risk of a deteriorating resource as a consequence of overexploitation. This has forged a partnership throughout the NWSAS of technical teams convinced that common action increases the effectiveness of solutions, and the certainty that information exchange is not only possible but also necessary.

As such, the OSS, through the NWSAS project, has developed a database containing all present and historical information on all water points, their levels, and their flows. This database is operational and accessible to the three countries. In this respect, the goodwill of the three water authorities in the communication of information has been exemplary. Moreover, the NWSAS Model is available and operational within each of the three countries. A mechanism is needed to guarantee the maintenance, the development and the permanent updating of two tools – the Database and the Simulation Model.

In addition to the maintenance of the database and model, the three countries have agreed to the regular exchange of data and information. This data exchange serves as a basis for the formulation of common policies and strategies, including:

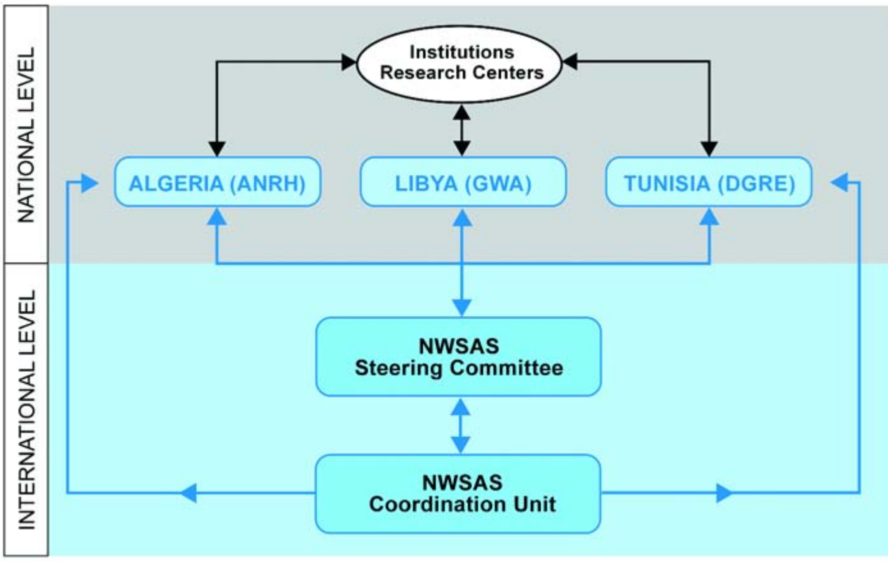
a) the necessary continuation of the NWSAS project's work on improving knowledge of the system and of its exploitation,

b) the setting up of a mechanism for continuing dialogue and its institutional anchoring within an international organization – the OSS,
c) the progressive and evolutionary nature of the consultation mechanism, meeting the growing needs for cooperation and collaboration in the management of the NWSAS water resources.

The structure of the consultation mechanism is composed of a steering committee, a coordination unit, and an ad hoc scientific committee for scientific evaluation and orientation, as shown in Figure 2.

Figure 2

Institutional arrangements for the evaluation and management of the transboundary North-West Sahara Aquifer System



The main functions of the consulting mechanism are:

- managing and updating the tools developed by the 'NWSAS' project, including the NWSAS model,
- establishing and maintaining observation networks,
- analyzing and validating data concerning the resource,
- developing databases on the socio-economic uses of water,
- identifying and publishing indicators concerning the resource and its uses,
- promoting and performing studies and research conducted in partnership,
- developing and implementing training and improvement programmes, and
- reflecting on the mechanism's evolution.

Conclusions: sustainable management of the NWSAS

Constraints on the aquifers making up the North Western Sahara Aquifer System (NWSAS) limit their exploitation potential. These constraints are both economic and environmental. The fact that three countries share the aquifer complicates the problem, especially since these countries have not had the same outlook as to the future of the Saharan aquifers.

Thorough improved knowledge of the hydrology of the region, together with the constitution of a shared database, the elaboration and use of a mathematical simulation model, the NWSAS project has shown that:

- the simple continuation of the present withdrawals can constitute a serious danger for the Complex Terminal's layer within the Chotts region,
- outside of the Chotts region, the Tunisian outlet and the Syrte gulf, slight increases in exploitation can still be endured without serious damage,
- simulations based upon high extraction rates (strong assumptions) lead to unacceptable situations,
- appreciable increasing of the present withdrawals is possible, however, it is at the cost of dispersing additional pumping fields to distant areas: the Western Great Erg and the confines of the Eastern Erg,
- in spite of the efforts made through the project, uncertainties remain concerning knowledge of the system, as well as defining the options for development, which will require new investigations.

In conclusion, this initial, first phase presents a rather optimistic outlook concerning the exploitation of water within the Northern Sahara if the three countries take into account all of the risk factors highlighted by the NWSAS study. Recognizing the considerable remaining uncertainties, one may conceive the NWSAS Model as a powerful teaching tool and an instrument around which dialogue can be organized.

Nubian Sandstone Aquifer System

Mohamed Bakhbakhi

Introduction

The Nubian Sandstone Aquifer System (NSAS) covers approximately 2.2 million km^2 of North East Africa (Figure 1). It is shared by Egypt, Libya, Sudan and Chad. No recent significant groundwater recharge is detectable (Thorweih, 1986), thus planning the use or mining of these resources should be based on the expectation that sometime in the future the water in the aquifers will be fully depleted. A policy for progressive aquifer depletion, i.e. mining of the groundwater in storage, is needed.

The demands for using this groundwater are considerable and are growing. As a result of population growth, food demand and economic growth the pressure on groundwater in the region has increased rapidly during the past three decades. Consequently exploitation of these non-renewable resources is currently occurring. To more effectively manage the withdrawal and use of this groundwater over time it is important to assess the aquifer storage capacity and to tentatively calculate the effective recoverable groundwater volume that can be used for development in the four sharing countries.

Assessment of the groundwater resources

The Nubian Sandstone Aquifer System is considered to be one of the most important groundwater basins in the world. The Nubian Sandstone Aquifer System can be divided into two major reservoirs as shown in Figure 1. The oldest and the most extended reservoir, the **Nubian Aquifer System** (**NAS**), is largely unconfined. It includes a number of aquifers that are hydraulically connected. The other reservoir includes parts of Libya and Egypt. It is referred to as the **Post Nubian Aquifer System** (**PNAS**). Low permeability layers separate the two reservoir systems.

The Nubian Aquifer System

The Nubian Aquifer System (Figure 1) extends over a vast area in Egypt, Libya, Sudan and Chad. It is bounded in the east by the impervious mountain ranges of the Red Sea and northwards by the Suez Canal. The system's eastern western and southern boundaries are assumed to be no-flow boundaries. The southeastern boundary of the Nile at Nasser Lake and Dongola is a fixed head boundary, as is the northern Mediterranean coastline boundary. The western boundary is a groundwater divide extending from Tibesti Mountains in the south and northwards along the 19° Meridian.

Figure 1

Hydrogeological sketch map of the Nubian Sandstone Aquifer Systems

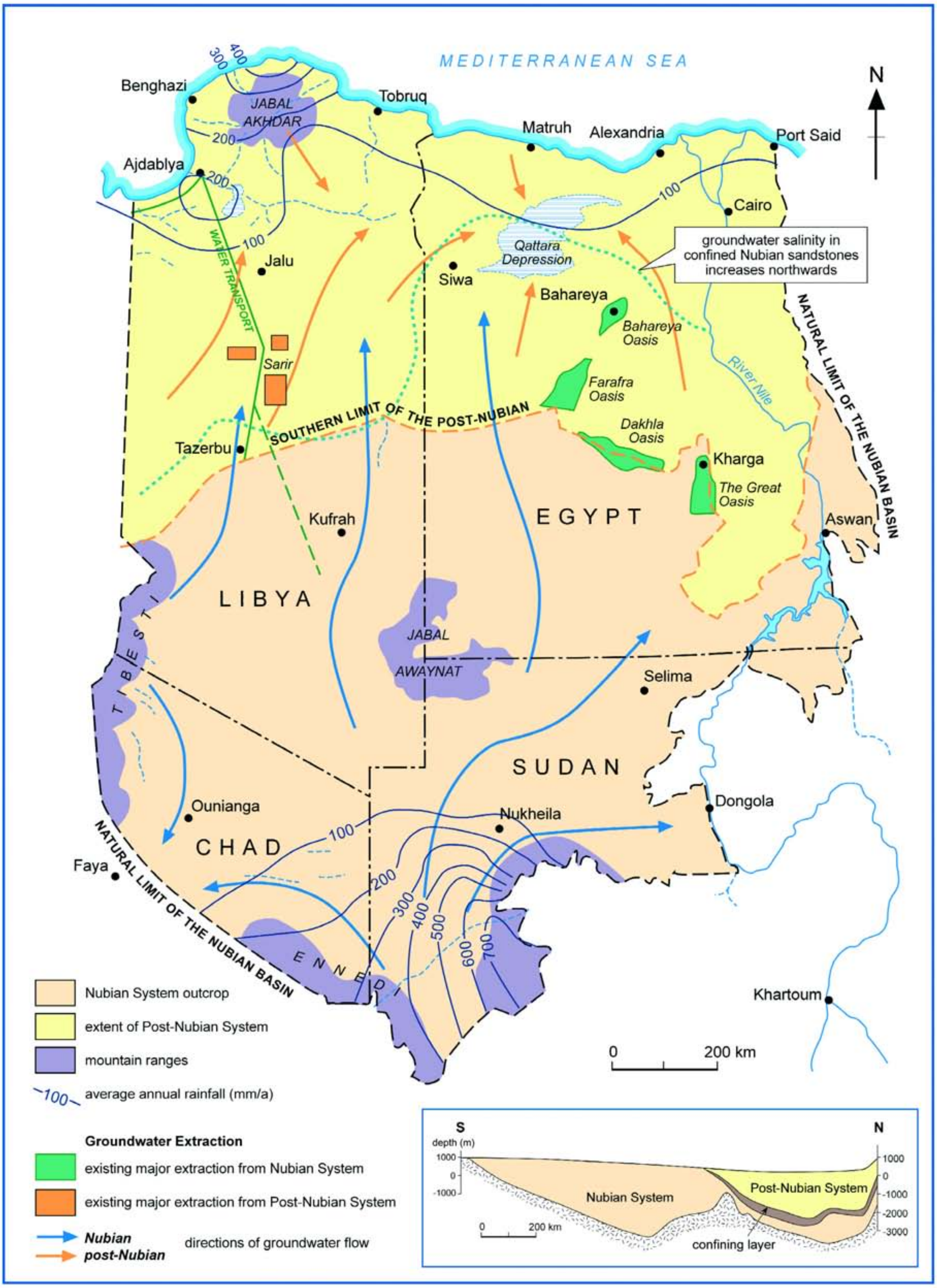


Table 1 shows the calculated storage capacity of the total Nubian Aquifer System (NAS) in both its unconfined and confined parts, within the four sharing countries, exceeding 520,000 km^3. The groundwater resources of the Nubian Aquifer System are not all fresh groundwater. The water quality, as measured by its total dissolved solid content, changes from excellent (500 ppm) in the southern part of the system to hyper saline in the Northern part (CEDARE, 2002). Eliminating this hyper saline water, the total volume of fresh groundwater in storage is approximately 373,000 km^3.

Table 1. Total recoverable fresh groundwater volumes from the Nubian Sandstone Aquifer System (NSAS)

REGION	AQUIFER UNCONFINED PART		
	Area (km^2)	Saturated thckness (m)	Volume in storage (km^3)
Egypt	311,861.87	838.5	52,299.24
Libya	350,732.68	1786.4	125,309.77
Chad	232,977.04	1026	47,806.89
Sudan	373,102.44	454	33,877.70
Total	—	—	259,293.60

REGION	AQUIFER CONFINED PART						
	All occurrence			Part with saline water			Volume of fresh water in storage (km^3)
	Area (km^2)	Saturated thickness (m)	Water * volume in storage (km^3)	Area (km^2)	Saturated thickness (m)	Water * volume in storage (km^3)	
Egypt	503,813.93	1,498.8	151,023.26	128,793	1,887	48,606.48	102,416.78
Libya	403,356.88	1,407.48	113,543.35	350,835.24	1,458	102,303.56	11,239.79
Chad	—	—	—	—	—	—	
Sudan	—	—	—	—	—	—	
Total	—	—	264,566.61	—	—	150,910.04	113,656.57

* Based on average formation bulk porosity of 20%

REGION	Egypt	Libya	Chad	Sudan	Total
Total volume of fresh water in storage (km^3)*	154,716.02	136,549.56	47,806.89	33,877.7	372,950.17

* Total volume of fresh water in storage is equal to the sum of the fresh water in the aquifer confined and unconfined parts.

The Post Nubian Aquifer System (PNAS)

The Post Nubian Aquifer System is bounded by no-flow boundaries in the south by the 26th parallel, in the west by the 19 Meridian north of Tibesti, and in the east by the Red Sea basement mountains and the Suez Canal. In the north Post Nubian Aquifer System is bounded by the fixed head Mediterranean sea. Based on average formation bulk porosity of 10%, the total volume of groundwater in storage is in excess of 84,600 km^3 (refer to Table 2). If we limit the freshwater occurrence to the north by the depression marked by several sabkhas along the parallel 30°N, the fresh ground water stored in the Post Nubian is 72,767.17 km^3.

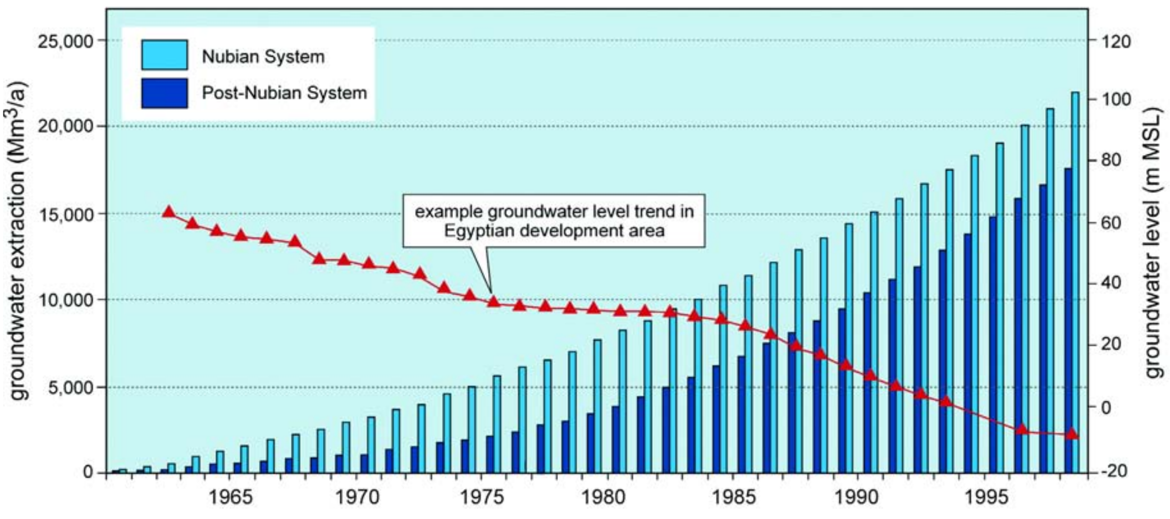
Table 1. Storage capacity of the Post Nubian Aquifer System

REGION	Area (km^2)	Saturated thckness (m)	Groundwater volume in storage (km^3)	Stored volume South of the 30°N (km^3)
Libya	426479.32	1143.00	48746.586	39427.5
Egypt	494039.44	726.00	35867.263	32839.67
Total	920518.76		84613.849	72767.17

Determining exploitable volume of groundwater

Exploitation of groundwater reserves in the Nubian Sandstone Aquifer System is currently taking place. As shown in Figure 2, this exploitation is increasing each year. In the past 40 years over 40 billion m^3 of water has been extracted from the system in Libya and Egypt. This has produced a maximum drawdown of about 60 m. All but 3% of the free flowing wells and springs have been replaced by deep wells. Most of the present water extracted is used for agriculture,

Figure 2
Growth of groundwater extraction from the Nubian Sandstone Aquifer Systems



either for large development projects in Libya or for private farms located in old traditional oases in Egypt. Quantifying the exploitable remaining volume depends on many factors. These factors include the changing cost of pumping water, the uses to which the water is put, quantitative and qualitative reactions of the reserves to exploitation and ecological repercussions. In the case of shared aquifers, groundwater withdrawals from the shared resource in each country may produce negative reciprocal externalities. These and other factors should be considered in quantifying the volume of exploitable groundwater.

Table 3 shows that the remaining volume of freshwater that can be exploited or recovered from the system is about 14,500 km^3. A relationship between annual extraction and duration of production has been worked out for each country and for the total exploitable volume as shown in Figure 3.

Table 4. Total recoverable fresh groundwater volumes from the Nubian Sandstone Aquifer System (NSAS)

REGION	NUBIAN			POST NUBIAN		NSAS
	Maximum allowed water level decline (m)	Area (km^2)	Recoverable groundwater volume * (km^3)	Area (km^2)	Recoverable volume South of the 30°N * (km^3)	Recoverable volume * (km^3)
Unconfined part						
Egypt	100.00	311,861.87	2,183.03	494,039.44	3,166.36	
Libya	100.00	350,732.68	2,455.13	426,479.32	2,403.61	
Chad	100.00	232,977.04	1,630.84			
Sudan	100.00	373,102.44	2,611.72			
Total		1,268,674.03	8,880.72	920,518.76	5,569.97	
Confined part						
Egypt	200.00	375,020.93	7.50			
Libya	200.00	52,521.64	1.05			
Total		427,542.57	8.55			
GRAND TOTAL		1,696,216.60	**8889.27**	920,518.76	**5,569.97**	**14,459.24**

* Based on aquifer storativity of 10^{-4} for the confined part and 7×10^{-2} for the unconfined part.

Figure 3

Relationship between production rate and duration of Nubian Aquifer System in various countries

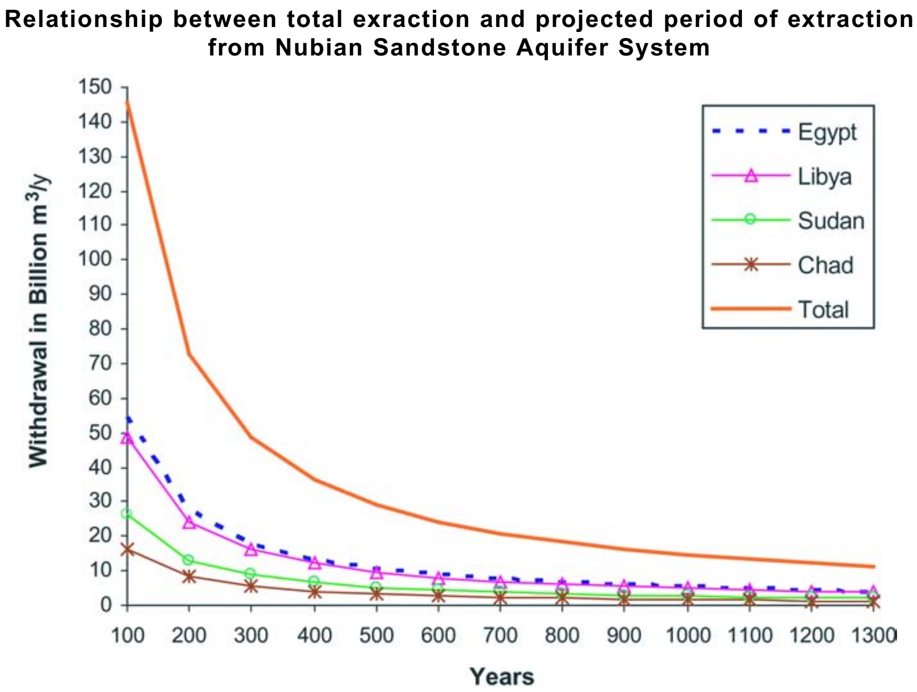


Table 4 shows a summary of the stored and the recoverable fresh groundwater and the presently extracted in each country from the two aquifer systems, based on tables and assumptions presented previously.

Table 3. Comparison between the present extraction and the recoverable groundwater in the NSAS

REGION	Nubian System (Paleozoic and Mesozoic sandstone aquifers)		Post Nubian System (Miocene aquifers)		Total volume of fresh water in storage (km^3)	Total recoverable ground-water volume (km^3)	Present extraction from the Post-Nubian system (km^3)	Present extraction from the Nubian system (km^3)	Total present extraction from the NSAS (km^3)
	Area (km^2)	Fresh water volume in storage (km^3)	Area (km^2)	Fresh water volume in storage (km^3)					
Egypt	815,670	154,720	494,040	35,867	190,587	5,367	0.306	0.200	0.506
Libya	754,088	136,550	426,480	48,746	185,296	4,850	0.264	0.567	0.831
Chad	232,980	47,810	—	—	47,810	1,630	—	0.000	0.000
Sudan	373,100	33,880	—	—	33,880	2,610	—	0.833	0.833
Total	2,175,838	372,960	920,520	84,614	457,570	14,470	0.570	1.607	2.170

Conclusions

In light of the results of this assessment of the exploitable reserves, planners could choose the period of production in accordance with national water policies. Relationships between annual extraction and duration of production has been worked out for each country and for the total exploitable volume. Mining of this non-renewable resource will eventually lead to rise in extraction costs as water levels fall and if and as water quality deteriorates. It is vital that the extracted groundwater is used with the maximum possible hydraulic efficiency and economic productivity.

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The Great Artesian Basin, Australia

M.A. Habermehl

Introduction

The Great Artesian Basin, underlying 1.7 million km^2 of semi-arid regions of Australia, is one of the larger artesian basins in the world. It is Australia's largest and most important groundwater resource (Habermehl, 2001). This confined basin is up to 3,000 m thick. It includes parts of the States of Queensland, New South Wales, South Australia and the Northern Territory (Figure 1). The mining of the artesian pressures and groundwater in storage during the last 125 years has affected the Basin to varying degrees. It has produced large-scale drawdowns and reduced discharges from flowing artesian water boreholes and springs. Flowing waters from boreholes are important for the pastoral industry in the Basin and flowing waters from springs are essential for the maintenance of their ecosystems.

Recent programs aim to rehabilitate water boreholes in poor condition, equip boreholes with control valves, and replace with polyethylene piping systems the inefficient open earth drain distribution systems that cause up to 95 percent wastage of the water. These measures will benefit groundwater and rangeland management and assist to alleviate land degradation and plant and animal pest problems. A reduction of the uncontrolled discharges, a halt in the diminution of the artesian pressures and a partial recovery of the artesian pressures are being achieved. A Strategic Management Plan for the whole of the Basin was developed by the Great Artesian Basin Consultative Council in 2000. It addresses basin-wide management issues, sustainable development and use of artesian groundwater.

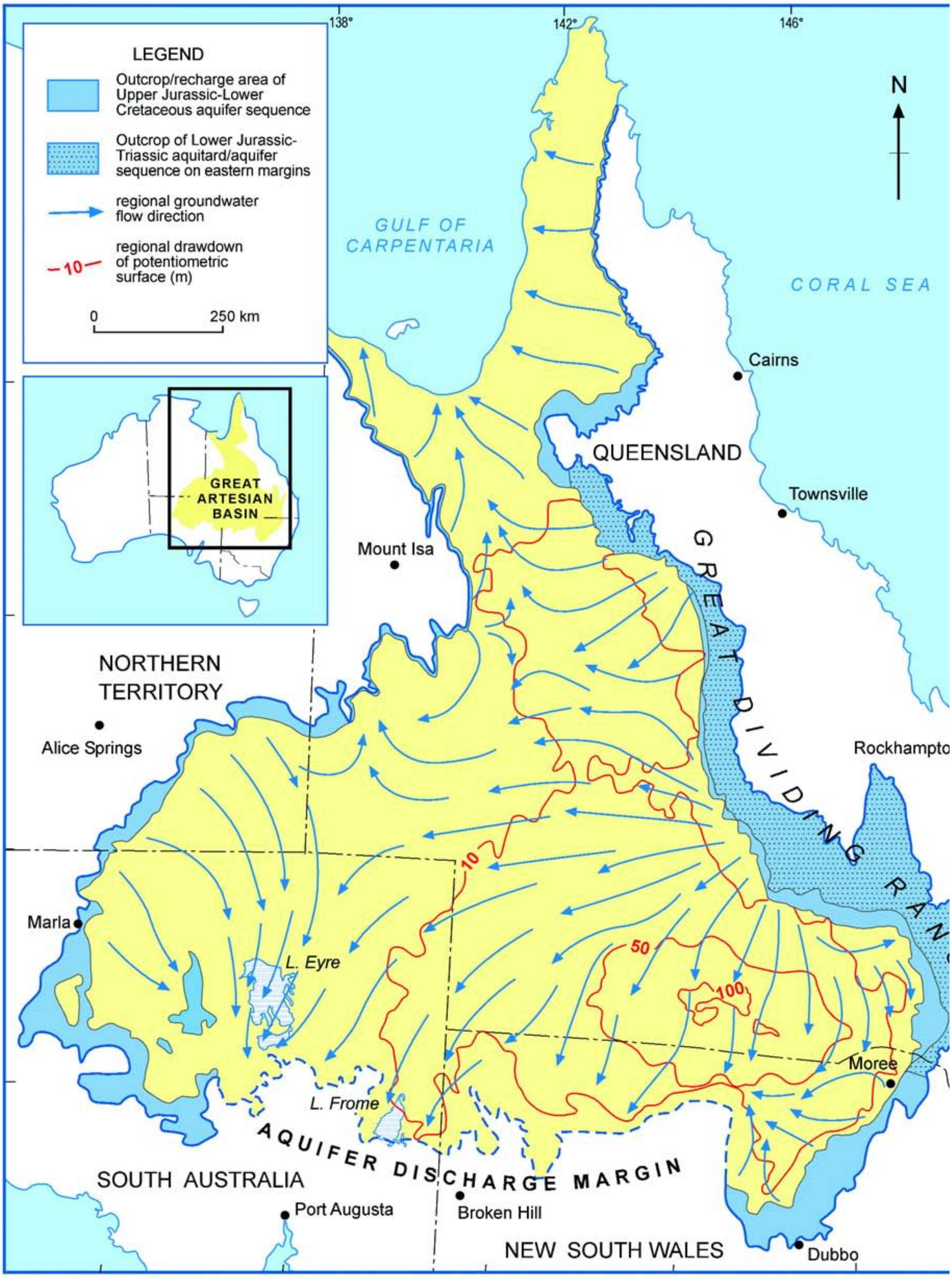
Development

Groundwater in the Great Artesian Basin has been exploited from flowing artesian waterbores since artesian water was discovered in 1878, allowing an important pastoral industry to be established. Waterbores are up to 2,000 m deep, but average about 500 m. Artesian flows from individual bores exceed 10 x 10^6 L/day (more than 100 L/s), but the majority have much smaller flows. About 3,100 of the 4,700 flowing artesian waterbores drilled in the Basin remain flowing. The accumulated discharge of these waterbores (including water supply bores in about 70 towns, as in most cases the artesian groundwater supply is the only source of water) is about 1,200 million L/day, compared to the maximum flow rate of about 2,000 million L/day from about 1,500 flowing artesian waterbores around 1918 (Figure 2).

Non flowing artesian waterbores, which number about 20,000, are generally shallow i.e. several tens to hundreds of metres deep. It is estimated that these generally windmill operated pumped waterbores supply on average 0.01 million L/day per borehole, and produce a total of about 300 million L/day. High initial flow rates and pressures of artesian waterbores have diminished as a result of the release of water from elastic storage in the groundwater reservoir,

Figure 1

Hydrogeological sketch map of Great Artesian Basin of Australia



and approach a steady state condition in many areas. Exploitation of the aquifers has caused significant changes in the rate of various discharges in time (Habermehl and Seidel, 1979; Habermehl, 1980; Seidel, 1980; Welsh, 2000; Habermehl, 2001 and Figure 2). Spring discharges have declined as a result of waterbore development in many parts of the Basin during the last 120 years, and in some areas springs have ceased to flow.

RESOURCE MANAGEMENT IMPACTS

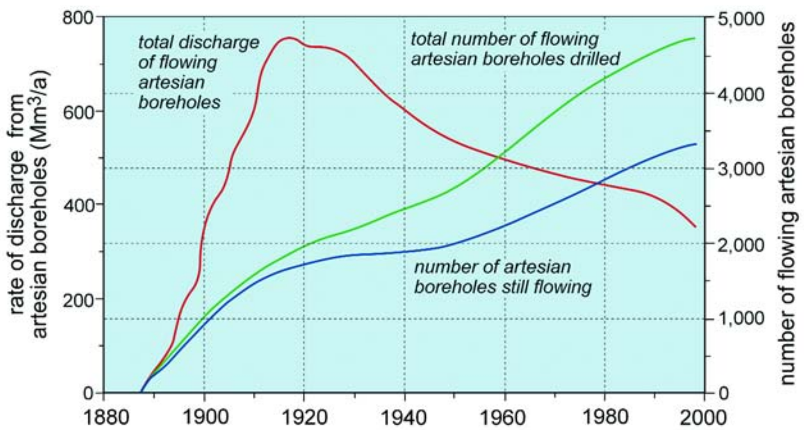
Natural resource management aspects of the Great Artesian Basin include issues caused by the development of the artesian groundwater resources of the Great Artesian Basin for the pastoral industry and the resultant large scale drawdowns of the potentiometric surface (Figure 1). The reductions in pressures and flowing artesian discharges of the water from boreholes following about 125 years of exploitation (Figure 2) has affected the pastoral industry, town water supplies and homesteads, and also has resulted in flow reductions at artesian springs. Reduced spring flows have decreased the biodiversity of the ecosystems at those springs (Noble et al., 1998). Many springs have ceased flowing.

The distribution and use of the artesian groundwater by the pastoral industry has also created an abundance of water on the surface of arid and semi-arid regions where previously water was sparse or only occurred following irregular high level (cyclonic) rainfall events. The availability of water in the arid and semi-arid landscapes has had a significant impact on the flora and fauna within the region, with major changes to the biodiversity (Landsberg et al., 1997). The inefficient bore drain distribution system wastes more than 95 percent of the groundwater produced, and has resulted in land degradation, erosion, salinisation and the spread of introduced weeds, shrubs and trees, pest animals and large increases of feral and native animals.

The development of the artesian groundwater for the petroleum and mining industries during the last 25 to 40 years has exacerbated these problems discussed above. As part of petroleum production, large amounts of artesian groundwater are brought to the surface in the oil and gas fields region of northeastern South Australia and in southwest and southeast Queensland within the Basin area (Habermehl and Lau, 1997). The water is disposed by surface

Figure 2

Trends in artesian overflow from boreholes in the Great Artesian Basin of Australia



discharge or more usually by evaporation in holding basins. The water associated with the production of petroleum provides a challenge for the petroleum industry, as the aim is to minimise waste and to increase the efficiency of the petroleum production. Alternatively, rather than surface disposal or evaporation, the water could be re-injected into the aquifers, avoiding any possible contamination and salinisation of the land surface, and depressurisation of the aquifers. As it is, reduced aquifer pressures caused by the introduction of more borehole fields have resulted in reduced yields at other borehole sites and the flows at some springs.

Other natural resource management issues in this region include the increased tourist visits and traffic to the (mound) springs near and northwest of Lake Eyre (Figure 1). This threatens the fragile ecology and the carbonate mounds, platforms and terrace structures of some of the springs. These fragile geological features, together with indigenous cultural and heritage values (including occurrences of stone artefacts near the springs), should be protected.

Land use changes in the Basin area, such as land clearing through the removal of trees in the recharge areas, have affected the groundwater recharge to the Basin's aquifers. The disposal of domestic and industrial waste in municipal and other landfills within exposed aquifer sandstones in the eastern recharge areas of Queensland and New South Wales may pose a threat to groundwater quality. Expanding irrigation in and near the recharge areas in northern New South Wales and animal feedlots also threatens groundwater quantity and quality. Enhanced understanding is required of the location and extent of the recharge areas and the recharge processes.

Continued expansion is proposed for the spa-bath tourist facilities based on pumped warm artesian groundwater from boreholes in the Basin near Moree in the northeastern part of New South Wales. However, limits to the extraction might be imposed. A small number of cattle stations and towns use the higher temperature artesian groundwater in geothermal powerplants to produce electricity. Increases in the use of the geothermal resources of the Basin are expected (Habermehl et al., 2002*a*, *b*). A small number of sheep and cattle stations use the pressure of the artesian groundwater to drive Pelton wheel type electrical generators. The latter were used in shearing sheds at sheep stations during the first half of the 20th century. Both the geothermal and pressure-driven electrical generators use large quantities of water.

SUSTAINABLE USE AND MANAGEMENT

Australia is a federation of States, and each State is responsible for the management of its water under the Australian Constitution. The States of Queensland, New South Wales and South Australia and the Northern Territory have separate and different legislation and water management strategies. Nevertheless on issues relevant to the national interest the Federal Government coordinates and cooperates with, and provides financial and technical support to, the States in water resources research, planning, development and management. This includes extensive hydrogeological research and management policy advice related to the natural resources of the Great Artesian Basin. Interstate cooperation in the management and systematic investigation of the Great Artesian Basin has taken place since the early 1900s.

The Great Artesian Basin Bore Rehabilitation Program (1989–1999), funded by the Federal and State Governments and partly by the private bore-owners, sought to provide a basis for better management of the Basin and eliminate some of the wastage of water and increase artesian pressures. The Program aims to rehabilitate waterbores in poor condition and place control valves on free flowing artesian waterbores without control mechanisms (Reyenga et al., 1998). A large part of the 1,200 uncontrolled or corroded waterbores plus headworks have been rehabilitated at an average cost per bore of about $A50,000 (Reyenga et al., 1998). Important results of increased pressures and flows have been achieved in some areas (Reyenga et al., 1998, Cox and Barron, 1998).

A follow-up to the GAB Bore Rehabilitation Program, the Great Artesian Basin Sustainability Initiative, begun in 1999. This program accelerates borehole rehabilitation and borehole drain replacement programs to achieve partial recovery of artesian pressures in strategic areas of the Basin. Its goal of replacing the open bore drain distribution system with polyethylene piping combined with float valve controlled tanks and trough systems will substantially reduce water wastage. This in turn will reduce the demand for water produced by the bores, thereby leading to increased artesian pressures and artesian flows from water boreholes and possibly re-establishing flows from some water boreholes and springs that have ceased flowing.

National Groundwater Reforms were introduced in 1996 and provided a broad framework for sustainable groundwater management. For example, all boreholes in the Great Artesian Basin must now be licensed, though in most States this was already a requirement for many decades.

The Great Artesian Basin Consultative Council was established in 1997. It consists of representatives from federal, state and local governments, pastoral, petroleum and mining industries, traditional landholders, and community and conservation groups. In 2000 the Council developed a Strategic Management Plan for the whole of the Basin. The plan addresses basin-wide management issues aimed at achieving the sustainable use of artesian groundwater for optimum economic, environmental and social development.

SUMMARY

The pastoral industry's past and present distribution of artesian groundwater from the flowing artesian bores by open earth drains is extremely wasteful, owing to seepage, transpiration and evaporation of the water in drains having lengths up to many tens of kilometres. Wastage can exceed 95 percent of the groundwater produced. Introduction of (polyethylene) piping to replace the earth distribution system and combining piping with float valve controlled tanks and trough systems will significantly reduce the wastage and thus the demand on flowing artesian water boreholes. Piping of the water will also reduce the adverse environmental effects caused by the introduction of large amounts of water and watering points in the semi-arid and arid landscape. The availability of water in these areas has resulted in land degradation, the spread of introduced weeds, shrubs and trees, greatly increased numbers of feral and native animals attracted by the water. It has also decreased biodiversity around water boreholes, borehole drains, and near springs with reduced outflows (Noble et al., 1998).

The pastoral industry's impacts have been amplified in recent years by the mining, oil and gas production industries. These have become significant users and producers of artesian groundwater. Groundwater extractions by these industries have caused large drawdowns of the potentiometric surfaces, adversely impacting other water users and natural artesian springs. Other natural resource management issues include the changes to the recharge areas caused by land use changes.

The Great Artesian Basin Bore Rehabilitation Program and the Great Artesian Basin Sustainability Initiative are intended to maintain options for future uses of the Basin's artesian groundwater, to continue access to artesian supplies by existing users, and to achieve some recovery of artesian pressures. In addition they are designed to improve pastoral production through greater control of total grazing pressure and improved stock and vegetation management, and also to reduce the rate of land and water resource degradation associated with open bore drains and uncontrolled extraction of groundwater. Ultimately, the changes brought by the programs will provide for better management of the artesian groundwater resource. A reduction of the demand on these groundwater resources should alleviate fears of their unsustainable use. Tangible benefits should result from enhanced rangelands and pasture management, from reduced land degradation, from more control of the activities and numbers of animal pests, and from improved conditions of water-dependent ecosystems at the springs of the Basin.

Acknowledgements

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The Monturaqui – Negrillar – Tilopozo Aquifer of Chile

Jaime Muñoz Rodríguez

Introduction

Presently almost all of the surface water resources in Chile are allocated to current users of water and to the environment. In the Chilean Water Code the rights given to water users are in perpetuity regardless of their benefits. Managing water given these water rights without causing economic or environmental damages represents an important challenge for the Water Resources Administration Department, Dirección General De Aguas of Chile.

The demands for more water have focused on Chile's groundwater resources. Many aquifers located in the northern portion of the country (Figure 1) have reached their limit of exploitation. Authorizations of new extractions of groundwater require an analysis of aquifer recharge rates and of aquifer storage behavior in the long run under alternative extraction policies. For these analyses, hydrological simulation models have been developed.

The policy of Dirección General de Aguas related to the use of groundwater in Chile takes into consideration the interests of the public, the physical characteristics of specific aquifers and available groundwaters, sustainable use and environmental protection, potential harm or damage to third parties rights (surface or groundwater), and any legal requirements including the perpetual character of the granted rights to groundwater use.

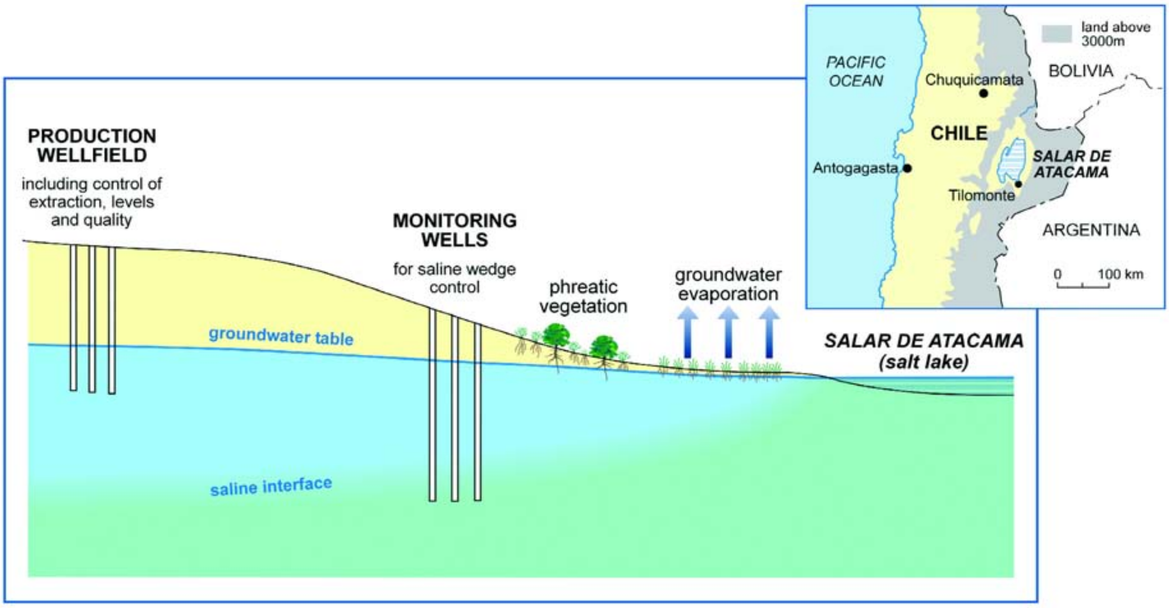
This paper outlines how the policy developed by the Dirección General de Aguas in Chile attempts to achieve a sustainable use of groundwater resources in the country specifically with respect to the intensive utilization of groundwater resources for mining operations. The extraction of groundwater is subject to an 'Early Alert Plan' to avoid irreversible environmental damages in sensible areas protected by the state.

Adaptive aquifer management under intensive exploitation

Knowledge of aquifer behaviour under alternative extraction rates and recharge scenarios is always uncertain. Thus it becomes necessary to continually improve one's knowledge about aquifer characteristics over time, and adapt to this new knowledge. The progressive knowledge of the aquifer's behaviour, the establishment of the acceptable impacts resulting from the exploitation of groundwater, and an 'Early Alert Plan' for the timely forecast of undesirable impacts, are necessary requirements when authorizing new extractions of groundwater from aquifers subject to intensive use and impacting environmentally sensible areas. Thus, granting groundwater use rights is necessarily subject to extraction policies that do not cause prejudice or deterioration of third parties rights, including the environment.

Figure 1

Hydrogeological sketch section showing distribution of fresh groundwater in the Tilomonte area of Salar de Atacama



The objective of an Early Alert Plan is to forecast, follow-up, evaluate and verify the expected effects or impacts at the moment of granting the groundwater use rights. It involves the use of indicators permitting the timely evaluation of effects or impacts and ways of managing groundwater exploitation so as not to exceed specified maximum damage indicator values. It involves assessing aquifer characteristics, determining acceptable impacts, developing and applying simulation models, establishing a monitoring plan, and evaluating and adapting the Plan as desired.

Determining the physical and hydrological properties of the aquifer or aquifers including current groundwater levels and their seasonal and annual variability, and the identification of all the areas considered sensitive or vulnerable to the groundwater extraction (such as wetlands, lakes, salt-marshes), is critical to the establishment of the Plan. For this characterization satellite images, showing seasonal characteristics over at least several years before starting the groundwater extraction, and mathematical groundwater simulation models, designed to predict of the behavior of the aquifer system and its impacted land surface areas under alternative extraction policies, can be very helpful.

The Early Alert Plan for the intensive exploitation of aquifers requires a complete monitoring program aimed at improving the knowledge about the aquifer's system and it's associated medium. This improved knowledge can lead to more control of the aquifer system under an adaptive policy of groundwater exploitation.

Adaptive aquifer management requires monitoring of all variables considered important for sustainable management. This includes information about the changes in hydrological and hydrogeological conditions, and about changes in environmentally sensible areas, that are taking place under a given plan, policy or practice of aquifer exploitation.

Finally, actions oriented to avoid undesirable impacts derived from the exploitation of groundwater are to be identified. If necessary the operation of the system may have to be changed in such a way so as to guarantee not exceeding the maximum tolerable impacts. Such actions, as permitted by law, may include:

- Proportional decreasing of the pumping rate in all the wells.
- Decreasing of the annual pumping volume.
- Reducing the maximum pumping rate in specific wells.
- Establishing of a monthly pumping curve for all the wells or only a group of them.
- Suspending the pumping in determined wells.

Early Alert Plan for the Monturaqui – Negrillar – Tilopozo Aquifers

The Aquifer of Monturaqui – Negrillar – Tilopozo (Figure 1) is located in the Northern Zone of the country. This extremely arid area is characterized by scarce precipitation and consequently a low availability of water, less than 500 m^3/inhabitant/year. This severely limits the development of that region.

The region is also characterized by the presence of environmentally sensitive areas, many under the official protection from the state. This is an important condition to be considered when studying the exploitation of water resources.

An evaluation of environmental impacts of groundwater extraction in the Monturaqui – Negrillar – Tilopozo aquifer has concluded that a lowering of up to 25 cm of the water levels of the wetlands would not adversely impact the flora and fauna. The analysis determined decreasing the water levels in the wetlands would reduce the natural flow from the aquifer towards Tipolozo, the sector where the environmental sensitive areas are protected by the State, by no more than 6%. The maximum exploitation of the aquifer system was estimated to be 1,800 l/s.

Based on these analyses, the Dirección General de Aguas approved groundwater use rights subject to not exceed certain undesirable thresholds and to comply with the 'Early Alert Plan for the aquifer of Monturaqui – Negrillar – Tilopozo' (PAT – MNT). The objective is to facilitate the intensive exploitation of groundwater in the sector while avoiding non-desirable impacts in the area.

The established PAT – MNT includes the following phases:

a) **Monitoring of the behavior of the aquifer and sensitive areas**
The analysis of the data obtained by long run monitoring, as illustrated in Figure 1, will permit more effective basin management and exploitation over time through improved estimates of the hydraulic parameters of the aquifer, improved understanding of both the behavior of environmentally sensitive areas and the sustainability of various extractions in the long-run.

b) **Forecast and evaluation of impacts**
Based on the model simulations, a precise but simple method has been developed for predicting the maximum aquifer yields from the well fields of Monturaqui and Negrillar.

c) **Periodical checking and implementing the PAT – MNT**
The method for forecasting reduced flow impacts is based on simulations of groundwater models. Using these models will result in an improved understanding of the Monturaqui – Negrillar – Tilopozo aquifer system, permitting more accurate predictions. One of the pillars of the PAT – MNT is its flexibility, as demonstrated by its actual use and the results obtained from periodic checking.

An exhaustive checking of the monitoring data will take place periodically. During the three first years, it will be done every year, and from then on, a frequency will be set according to the results obtained in the three first years.

Monitoring results up to December 2001

The exploitation of the Monturaqui – Negrillar – Tilopozo aquifer began in the mid-1990s. Before implementing the Early Alert Plan (PAT–MNT) the two mining companies of the country extracted over 47 million cubic meters (MCM) of groundwater from the Monturaqui and Negrillar sectors by 31 December 2000.

During 2001, the pumping rates from the Monturaqui well field increased so that by the end of 2001 the accumulated volume of extracted water from Monturaqui sector itself exceeded a total of 47 MCM. The pumping rates from the Negrillar sector continued at the same rate reaching a total extraction in excess of 30 MCM by the end of 2001.

These accumulated volumes were used to estimate the maximum future reduction of the aquifer's flow under the PAT–MNT. Under this policy the maximum reduction forecasted for the future of the aquifer's flow corresponds to approximately 0.8%. The permitted limit corresponds to 6%.

Summary

Chile has implemented a plan for adaptively managing its intensively used aquifers with the goal of long-term sustainability. This is challenging under its present legal system that gives water users rights to the water they use in perpetuity, but it is meeting this challenge with the aid of an Early Alert Plan. This Plan requires periodic monitoring of aquifer conditions, and the issuing of permits for withdrawals of groundwater that specify reduced extraction rates should conditions so warrant. Monitoring is an absolutely essential component of this adaptive management strategy.

The Jwaneng Northern Wellfield, Botswana

Pelotshweu Phofuetsile

Introduction

Botswana is an arid to semi-arid country with scarce surface and groundwater resources. Its rainfall ranges from 550 mm/year in the northern part of the country to 250 mm/year in the southwestern part of the country. Despite the increase in use of surface water schemes, most villages and a few towns continue to rely on groundwater resources for water supply because of the limited or no supply surface water resources. Indications are that groundwater mining is inevitably taking place over large areas in Botswana that receive little if any recharge because of low and unreliable rainfall.

This paper discusses the historical development and management of the Jwaneng Northern Wellfield (JNW) shown in Figure 1. The Jwaneng Northern Wellfield (JNW) is one of the country's major groundwater schemes. Its management typifies how many of the groundwater schemes in Botswana are being managed.

The Jwaneng Northern Wellfield

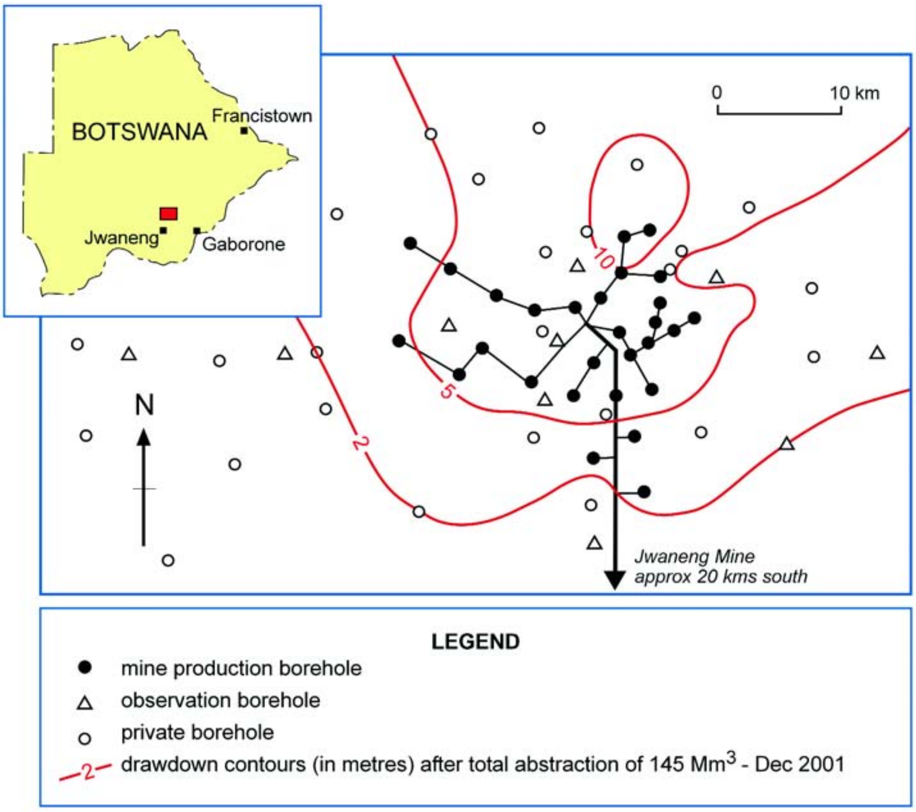
The JNW has been operated since 1979 when Jwaneng Diamond Mine started operation. Currently the wellfield is producing approximately 9 million cubic meters of water per year. The water is used for mining operations and for meeting the needs of the associated mining town. Monitored water levels in boreholes have shown a steady decline of slightly more than 5 meters since 1979. The quality of the water has remained good with total dissolved solids (TDS) ranging from 470 mg/l to 740 mg/l.

Once the Jwaneng Northern Wellfield (JNW) scheme started a network was established for monitoring groundwater quantity, quality and water levels. The purpose of monitoring was to ensure the sustainable operation of the scheme, to safeguard the water rights of local farmers in the area and to mitigate possible environment impacts as a result of groundwater exploitation. The mining company has used groundwater modelling as a management tool for predicting groundwater levels under alternative management scenarios. The Water Apportionment Board Control is responsible for ensuring compliance with water rights.

Currently there are 28 production boreholes in operation that are supplying water to Jwaneng mine and associated township. Groundwater abstraction in 1984 was 5,262,205 m^3 while in 2000 it was 8,929,220 m^3. The cumulative abstraction from 1979 through 2000 was 130,790,082 m^3. The bulk of the water goes to the mine. In 2000 the mine used 83.7% while Township water supply was 16.3%. Process water is recycled at the mine and this has the effect of

Figure 1

Groundwater level drawdown in the Jwaneng Northern Wellfield of Southern Botswana after 20 years production for mine and town water-supply



reducing abstraction. Borehole yields range from 31 m^3/hr to 119 m^3/hr and have averaged 73 m^3/hr.

In 1994, remodelling was done to verify the capability of JNWF to supply approximately 12 million cubic meters (MCM)/yr for a period of at least 15 years (i.e. 1994 to 2008) in line with demand. The 1994 model revision concluded that the JNW is capable of supplying Jwaneng mine and township over a period of 1994 to 2008 an annual discharge of 13.29 MCM. The water right for JWF is 12 MCM per year.

Modeled regional drawdowns during the period 1981–84 were about 2–3 meters greater than those actually observed despite the increase in pumping rates. This discrepancy between modeled and actual water levels resulted in a re-examination and recalibration of the model.

The model run was begun in 1980. Annual abstractions for the period from 1984 to 1990 were assumed a constant 5,262,205 cubic meters. For the subsequent period (1990–95) abstractions were increased by 10% to simulate increased water demand. After modifying aquifer parameters and running a series of sensitivity analyses, a revised model was used to compare 1984 and the original drawdown predictions. The drawdown was revised to be 13 m after 15 years, that is, up to 1995 of pumping at 22,262 m^3/day.

The 1984 recalibrated model ceased to be used as a management tool shortly after its release since it was apparent from an increasing discrepancy between observed and predicted drawdowns. Fortunately, the discrepancy was favourable.

In addition to normal wellfield groundwater level monitoring, there are several privately owned boreholes within the 8 km radius of the wellfield. These have been monitored so that compensation of private farmers can be effected when it is deemed that the drawdown induced by the mine equals or exceeds 5 m.

Conclusions and recommendations

Public education is needed to create and maintain awareness among all water users of the need to conserve and reuse water and protect it from pollution. Guidelines are needed for the construction of boreholes/wells and for identifying the appropriate water quality parameters to monitor.

Government efforts on conjunctive use of water should be pursued to ease pressure on exploitation of groundwater resources. Modelling is, and should continue to be, carried out for major water schemes such as JNW to estimate optimum drawdowns and the safe yield, in an effort to try to manage the wellfield sustainably. Based on model predictions the Jwaneng Northern Wellfield seems capable of supplying the demands of the mine and township up to the year 2008 at an acceptable quality. However, predictive models should be audited regularly by an independent agency.

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Appendix 1: Resolution XII-8

RESOLUTION XII-8
(adopted by the Intergovernmental Council of the International Hydrological Programme of UNESCO at its 12th session, Paris 23-28 September 1996)

'Study of Fossil Groundwater in Sub-Saharan and Saharan Africa'

The Intergovernmental Council of the International Hydrological Programme

Recalling

the high priority that the Director-General of UNESCO accords to the development of Africa;

Noting

with great interest the particular importance that IHP-V ascribes to integrated water resources management in arid and semi-arid zones and to the study of the pollution and protection of groundwater;

Welcoming

the fruitful cooperation that exists between UNESCO and the Sahara and Sahel Observatory (OSS) in promoting consultation and coordination among countries sharing immense natural sedimentary basins containing aquifers that are renewable to a greater or lesser degree;

Aware

of the degree of tension between water resources and anarchical forms of utilization in sub-Saharan and Saharan African countries which share the same fossil groundwater owing to their susceptibility to drought;

Invites

the Director-General of UNESCO to allocate funds to undertake and update hydrogeological studies during IHP-V with a view to improving knowledge about fossil aquifers of sub-Saharan and Saharan Africa;

Urges

Member States to provide financial and technical support to this programme.

Appendix 2: Tripoli Statement

More than 600 hundred participants from more than 20 countries and regional and international organizations and associations attended the International Conference on

'Regional Aquifer Systems in Arid Zones – Managing Non-Renewable Resources'

Tripoli, 20–24 of November 1999

We the Participants of the Conference recognize that:

1. In most arid countries the scarcity of renewable water supplies implies a serious threat to sustainable coupled and balanced socio-economic growth and environmental protection. This threat is clearly more pronounced in the less wealthy countries.
2. In many arid countries, however, the mining of non-renewable groundwater resources could provide an opportunity and a challenge, and allow water supply sustainability within foreseeable time-frames that can be progressively modified as water related technology advances.
3. The Conference marks a milestone in the discussion of the emerging concept of planned groundwater mining.

We the Participants consider that:

1. Adoption of this concept at national level could have international repercussions;
2. A national integrated water policy is essential with, where feasible, priority given to renewable resources, and the use of treated water, including desalinated water.

We recommend that:

- **a.** Groundwater mining time-frames should account for both quantity and quality with criteria set for use priorities, and maximum use efficiency, particularly in agriculture;
- **b.** Care should be exercised to minimize the detrimental impact to existing communities;
- **c.** Consideration should be given to the creation of economical low water consuming activities.

We the participants further consider that in situ development, or development based upon transferred mined groundwater, depend upon many non-hydrogeological factors outside the scope of this Conference. Nevertheless, hydrogeological constraints need to be defined for both planners and the end users.

We recommend the participation of the end users in the decision making process and the enhancement of their responsibility through water use education and public awareness. We believe that for efficient water-use, cost recovery could eventually be necessary.

In recognition of the fact that:

- **a.** some countries share aquifer systems;
- **b.** international law does not provide comprehensive rules for the management of such systems as yet, and
- **c.** clearly groundwater mining could have implications for shared water bodies;

We the participants draw the attention of Governments and International Organizations to the need for:

- **a.** rules on equitable utilization of shared groundwater resources,
- **b.** prevention of harm to such resources and the environment,
- **c.** exchange of information and data.

We also encourage concerned countries to enter into negotiations with a view of reaching agreements on the development, management, and protection of shared groundwater resources.

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PhD in hydrogeology, and expert on aquifers modeling. He has a large experience in the hydrogeology of arid zones. He has worked at the Directorate of Water Resources in Tunisia, and at the Ecole des Mines de Paris. He is currently professor at the National School of Engineers of Tunis.

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Groundwater resources whose replenishment takes very long in relation to the time-frame of human activity are conveniently termed '**non-renewable groundwater resources**' – and the volume of such groundwater stored in some aquifers can be huge. In these cases one is usually dealing with '**fossil (or palaeo) groundwater**', recharged in past, more humid, climatic regimes.

Development of non-renewable groundwater resources implies the **'mining of aquifer storage reserves',** and as such takes on particular social, economic and political sensitivities. But especially in many of the world's more arid regions, the use of non-renewable groundwater offers an opportunity to alleviate growing water scarcity, improve social welfare and facilitate economic development. Such development can be considered **socially-sustainable** if certain criteria can be met and specific risks can be managed.

This publication intends to provide decision makers with a contribution addressing the environmentally and socially sustainable policies that should be set up in order to give due consideration to the assessment and management modalities for non-renewable resources.

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