CHAPTER 20
Intensive use of groundwater in transboundary aquifers

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ABSTRACT: Transboundary aquifers are present in all parts of the world, ranging from hundreds to tens of thousands km^2. The largest have fresh water to provide the planets drinking water needs for 200 years, e.g. the Guarani. Intensive use of most of the larger transboundary aquifers has not yet taken place. Consequently, in broad terms they are not yet severely threatened, though with conspicuous exceptions e.g. the Middle East. Some smaller, and therefore more vulnerable transboundary aquifers are intensively used. Severe *overabstraction* is still contained within national boundaries, but continuing demands could impact across national boundaries especially in arid zones. For the sustainable use and sound management, plans need to be made in early stages of development, with the participation of all the riparians, to ensure equitable and fair share. This chapter outlines a multi disciplinary approach, involving the legal, institutional, economic and environmental inputs, that is needed, over and above the hydrogeological understanding. Suggestions are made about the staged process, commencing from the *status quo*, quasi-steady state analysis.

1 SCOPE

1.1 *Introduction*

The sound management of transboundary aquifers, let alone their intensive use, is as yet a very novel issue. In contrast to the management of transboundary river basins, for which several international treaties, conventions and agreements exist (Appelgren & Klohn 1997, Wolf 1999), there is very limited experience worldwide for similar aquifers. Some transboundary aquifers contain huge quantities of fresh water; e.g. the Nubian aquifer system of Northern Africa is thought to contain a volume of 542,180 km^3 (IFAD 1999), and when compared to the water resources of the Nile (168,000 Mm^3/yr, Shiklomanov 1998) it represents several tens of decades of extractable resources. Other transboundary aquifers might be small, but of critical significance; e.g. the Haute-Savoi Geneva aquifer is artificially recharged on one side of the international boundary for consumption on the other. In fact, this is probably the only example in the world where a formal transboundary aquifer agreement exists. The need for such treaties has been recognised for a long time; the most significant of these being the aquifers between USA and Mexico (Burman & Cornish 1975).

Therefore the use, sound management and sustainable development of transboundary resources are of considerable importance. These resources merit closer attention with regards to their current use, which may not be intensive, but increasing demands on these resources will result in their intensive use in the near future. As a result of this a cooperative initiative has been launched to gather more information about transboundary aquifers under the ISARM Programme (Puri *et al.* 2001).

1.2 *Multi disciplinary approach*

This chapter is about contiguous aquifers that extend across national boundaries. It does not deal with those aquifers that are crossed by national administrative divisions (e.g. see BGARC 1994, and the Borders Agreement in Australia[1]). Within a national context, most management issues can be addressed under the single national constitution. The complexities regarding the management of aquifers that extend across two or more national constitutions makes the question of intensive use of these groundwaters multifaceted.

It will be argued here, that the management of transboundary aquifers needs to be viewed from multi disciplinary and multi dimensional viewpoints. As a minimum it should include scientific and hydrogeological understanding, the frameworks of international law, socio economics, institutional constraints and address wide ranging environmental issues. This chapter will attempt to describe the full scope of the management of such aquifers and highlight the need for more work in the context of their probable future intensive use.

1.3 *Terminology issues*

The choice of terminology in the definition of such aquifers poses some semantic and technical dilemmas. In technical terms, the terminology should be selected so that the *dynamics* of the flow of groundwater is stressed, giving a clear understanding that there is an *upstream* and a *downstream* context, since there are very few aquifers in the world without any hydraulic dynamics. The semantics should provide the context of interdependence, thus revealing the need for cooperation and joint actions.

Transboundary aquifers can be portrayed through one, or a combination of the following terms, *shared aquifers*, *common aquifer systems*, *regional aquifers*, *multi-national aquifers*, etc. National preferences appear to dictate what terminology would be best applied. In the Middle East the translation into Arabic of the term *transboundary* implies an unacceptable external influence, consequently here the term *internationally shared* has been accepted. In contrast, in the Latin American region the Spanish semantic implication of *internationally shared* suggests diminished sovereignty and therefore in this region the term *transboundary* has been adopted. In the rest of this chapter, for convenience and consistency, the term *transboundary* will be used throughout without any intentional implications for national sovereignty.

1.4 *Definitions of terms*

The definition of *intensive use of groundwater* has been fully debated in the previous chapters. In this chapter therefore, the significance of terms that apply in the transboundary context are discussed.

Intensive use in terms of aquifer development must be related to one or a combination of the following references, time, space, socio-economic or legal constraints, with the latter two stemming from the first two. Therefore, intensive use of the resources of a transboundary aquifer has no meaning until it is related to a time frame, or to a spatial distribution and following on from this to a possible socio-economic or legal framework. It is possible to have several sequential time frames, but the spatial distribution is always fixed. Within any time frame, *quasi steady state* aquifer conditions can be established as the baseline for international agreements.

If intensive use is related to the dimensions of an aquifer, and implicitly to the size of the resource, then in a transboundary context, even small aquifers can have considerable local significance, e.g. several aquifers in Europe (Almássy & Buzás 1999), though small, are critical to community water supply and other environmental demands. In some of these, the land use on one side of the boundary may impact the other side. In this situation socio-economic priorities may define how the land is used, either as a natural reserve, or for waste disposal or industrial development.

Another term that will be considered later is the *sustainable use* of transboundary aquifers. As applied to any natural resource, its use can be considered sustainable when the rate of withdrawal and the rate of replenishment (or replacement) are in balance. There remains much debate on the time frame over which such a balance might be reached and it has a specific significance in the development of aquifers. Much of this is connected to uncertainty of the conceptual models, because significant data are unavailable.

[1] Border Groundwater Agreement, between the States of South Australia and Victoria, was simultaneously passed through both legislatures in 1985. Annual Reports are issued by the Review Committee and their tasks include, among other matters, the setting of sustainable abstraction limits, complementary monitoring, data exchange, etc.

Notoriously, data on regional aquifers is always sparse –conducting a thorough risk analysis can offset this uncertainty to some extent.

In contrast to the dynamic natural resources mentioned above, there are also static natural resources, such as minerals and hydrocarbons that can appear in transboundary contexts. Over a very long time span (tens of thousands of years), hydrocarbons might be replenished, while minerals may not be replenished except over millions of years.

One further term that needs to be explained is the *rate of replenishment* –exploitation of most dynamic natural resources will be accompanied by some rate of natural replenishment. Processes for this replenishment might be natural or human induced; the latter could be used to accelerate the natural replenishment rates. Examples of these can be found in the replanting of forests, establishment of fish hatcheries, etc. In a transboundary context, replenishment would benefit all parties and conversely, in the absence of property rights, all might feel harm if replenishment did not take place.

The question of cost benefit of replenishing transboundary natural resources needs to be addressed. While this is the domain of specialised environmental economics, in transboundary groundwater resource management it would be even more complicated, due to the longer time spans than the life cycle of infrastructure projects. Some experience can be gained from other efforts in natural resource management e.g. the Black Sea and the Caspian Sea. UNDP/GEF supported environmental programmes, aimed at conserving and replenishing depleted biodiversity reserves. Here the process of transition from planned to market economics among the riparians could provide guidance for projects such as artificial transboundary aquifer resource replenishment, should the need for this arise.

1.5 *Comparison with other transboundary resources*

Aquifers are not the only transboundary natural resources that need sound management. By comparing them to several other such resources, some similarities and dissimilarities can be noted. These could provide some comparative guidance for the sound management of aquifers for future intensive development.

Atmospheric air is a transboundary resource with some similarities in its dynamics to aquifers. Marine resources, such as fisheries and land based biodiversity of flora and fauna are also transboundary resources. The problems of transboundary biodiversity and its management has become a significant topic in many parts of the world such as the Black Sea and Caspian Sea, Tien Shan Mountain ranges, the Caucuses, and the Amazon forests (see Conventions on Biodiversity, and Conventions on Long Range Transboundary Air Pollution).

While transboundary river systems and transboundary aquifers could be treated in more or less the same way, there are differences to the approaches to their management, despite the fact that the utilisation of the resource, i.e. water, is for identical purposes, namely drinking, industrial use and irrigation. Navigation and water based transport are not included in this discussion.

The contrast between transboundary river resources and transboundary aquifer resources are shown in Table 1 and represented schematically in Figure 1.

Table 1. Contrasting features between transboundary surface and groundwater resources.

Transboundary rivers	Transboundary aquifers
- Long linear features.	- Bulk 3-dimensional systems.
- Use of resources generally limited to close to the river channels.	- Resources may be extracted from and used extensively over outcrop and subcrop.
- Replenishment always from upstream sources.	- Replenishment may take place from any, or all of 3-dimensions.
- Rapid and time constrained gain from replenishment.	- Replenishment could be slow, net gain can be drawn upon over longer periods.
- Little opportunity to manipulate storage within river body.	- Unlimited opportunity to manipulate storage in aquifer body.
- Abstraction has an immediate downstream impact.	- Abstraction impact can be much slower.
- Little impact on upstream riparian.	- Could have an equal impact on both upstream and downstream riparian.
- Intensive development has immediate impacts.	- Impact of intensive developments relatively slow.
- Pollution impacts transported downstream rapidly.	- Slow movement of pollution.
- Pollutant transport invariably downstream, upstream source may be unaffected.	- Pollutant transport controlled by local hydraulics. An operating well may induce upstream movement toward itself.

2 HYDROGEOLOGY OF TRANSBOUNDARY AQUIFERS

2.1 *Features of transboundary aquifers*

In the same way that there are many well-known transboundary river basins (the Rhine, the Chad, the Parana, the Mekong), there are also transboundary aquifers (the Nubian aquifer system in North Africa, the Guarani System in Latin America, the Karoo System in Southern Africa). The UN ECE (Almássy & Buzás 1999) inventory indicated that there are over 80 transboundary aquifers in Europe alone. The key features of transboundary aquifers include a natural subsurface path of groundwater flow, intersected by an international boundary, such that groundwater transfers from one side of the boundary to the other (Fig. 1). In many instances the aquifer system might receive the majority of its recharge on one side, and the majority of its discharge would be from another. Since such an international boundary itself can play no actual role in influencing hydrodynamics, as it normally is an anthropogenic feature, it is worth analysing the flows at this point. With reference to Figure 1, the subsurface flow system includes regional, as well as the local components. Production from a wellfield located close to the boundary, must therefore account for the local flows from within the territory and those from beyond the territory.

In estimating the resources of transboundary aquifers and assigning resources between countries, these subtleties must be taken account of. In much of the prevalent water resource assessment methodology these factors are either ignored or just lumped into unknowns (see e.g. AQUASTAT[2] 2001). For sound management and allocation of the fair share of transboundary aquifer resources, estimates can only be made through good observations and measurements of carefully selected hydraulic parameters.

2.1.1 *Coincidence with boundaries*

While not many international territorial boundaries coincide with natural features, the mid

[2] AQUASTAT is FAO's database which provide land use and water resource data. It can be access from the following URL: http://www.fao.org/ag/AGL/aglw/Aquastat/aquastat.htm

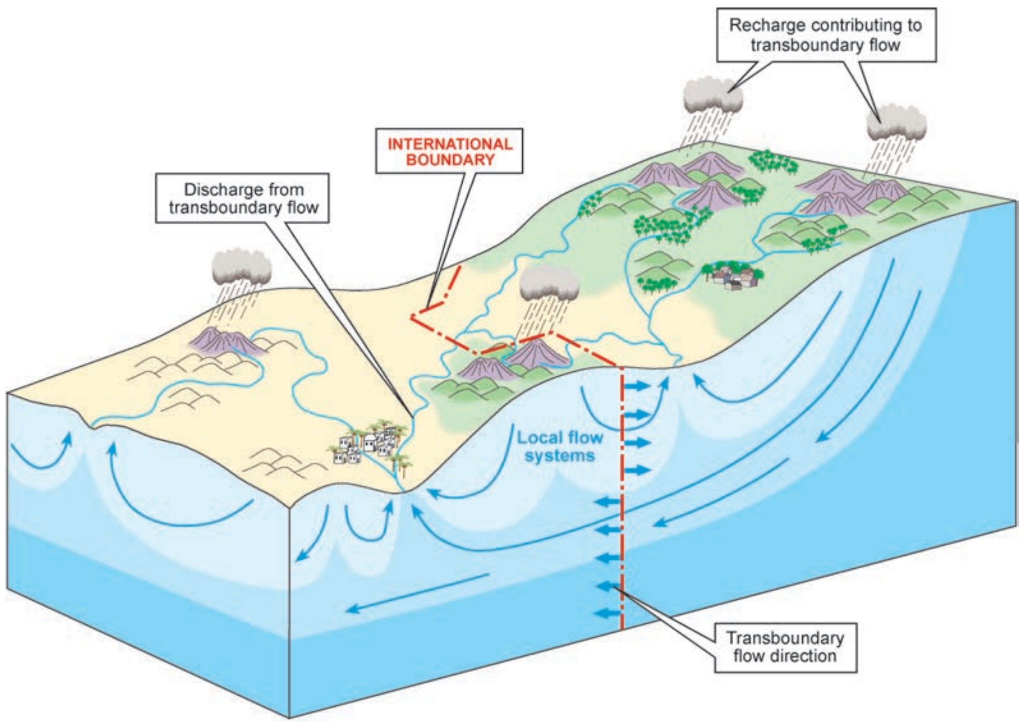

Figure 1. Schematic of a transboundary aquifer.

point of river channels often act as one, providing a good basis for allocating resources. It might be assumed that in this circumstance the resources of an underlying aquifer could also be similarly divided. However this may not be straightforward, as demonstrated in Figure 2. Majority of the major river systems of the world is underlain by relatively thick sequences of alluvial formations, consisting of complicated local as well as regional flow patterns. Example of such systems can be found in the transboundary aquifers in the Ganges-Brahmaputra alluviums, the Mekong alluviums and the SyrDarya-AmuDarya alluviums. It should be noted that the hydraulics of river channels will dominate local patterns of groundwater flow, and generally a considerable amount of interaction takes place here due to the stages of the river. However, regional components of flow, contained in the more dominant and regionally more extensive portions of the flow system can have distant impacts. The illustration in Figure 2 demonstrates that even if intensive use is planned close to the river channels, with the expectation that there will be limited transboundary impact, this may not be the case.

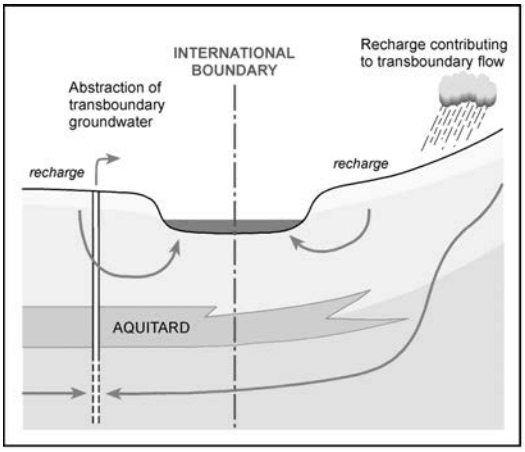

Figure 2. Transboundary flows in aquifers below river boundaries.

One of the more controversial situations regarding the interlinkage between surface and groundwater in alluvial systems is the Slovak-Hungarian Gabcikovo-Nagymaros dispute (Eckstein 1995). The area known as the Little Hungarian Plain is underlain by thick sequences of sand, gravel and silts brought down by the Danube river system. Due to the partial construction of dams and diversion schemes of surface water, there has been a substantial impact on the aquifers in the alluvial formations, resulting in decline of water levels, which might further increase. The issue was been the subject of consideration by the International Court of Justice in 1994, and the Courts decision, considered unsatisfactory by some (Eckstein & Eckstein 1998) was handed down in 1997. This is discussed further in a later Section (5.2).

2.1.2 *Spatial distribution of parameters*

Many factors affect the behaviour and the response to intensive development in transboundary aquifers, including:

- Hydraulic parameters.
- Rainfall - recharge zones.
- Confined and unconfined areas.
- Natural discharge zones.
- Present & planned groundwater development zones.
- Water quality, potential risks of its deterioration.
- Pollution vulnerability from industrial or agricultural activities.

In transboundary aquifers one or more of these factors may receive different weighting on either side of a boundary. Examples of transboundary aquifers, where recharge is received on one side while the natural discharge, and its intensive use, are across the border, include the Mountain Aquifer extending over Israel and Palestine (WRAP 1994). An estimated 83% of the recharge from rainfall takes place in Palestine, while the springs and the high yielding areas are located in Israel. The Iullemeden aquifer, extending over Niger, Nigeria, Mali, Benin and Algeria, consists of Mesozoic continental deposits outcropping along the northern and eastern periphery of the basin. Recharge almost entirely takes place in the southeastern outcrops in Nigeria where the rainfall exceeds 500 mm/yr. A significant part of the discharge, through evapotranspiration is in humid valley bottoms and in the river Niger itself. In the Guarani aquifer of South America over 1,000 mm/yr of rainfall occurs in the outcrop areas of Brazil, while discharge partly takes place in Uruguay (Fili *et al.* 2001).

2.2 *The significance of groundwater hydraulics*

The abstraction pattern transforms and re-organises the groundwater flow in response to the intensity of production. This has a number of practical consequences:

2.2.1 *Modification of the groundwater flow pattern*

Groundwater flow passing an international boundary cannot be measured directly. It is estimated from parameters and calculated through mathematical models. Abstraction on one side of the border may alter the flow through the border. An example from Northern Sahara Aquifer System, (UNDP/OPE 1983), illustrates this (Fig. 3):

- The underground outflow of the deep aquifer (Continental Intercalaire) is a source of recharge for the coastal aquifer (Jifarah aquifer).
- Additional development from the deep aquifer in Algeria only would reduce the outflow to the coastal aquifer by 5%.
- The development scenario was selected to minimise the impact of Algerian development on the Tunisian coastal aquifer.

Siting and pattern of production from wells in transboundary aquifers can be planned to ensure equitable share of the resources.

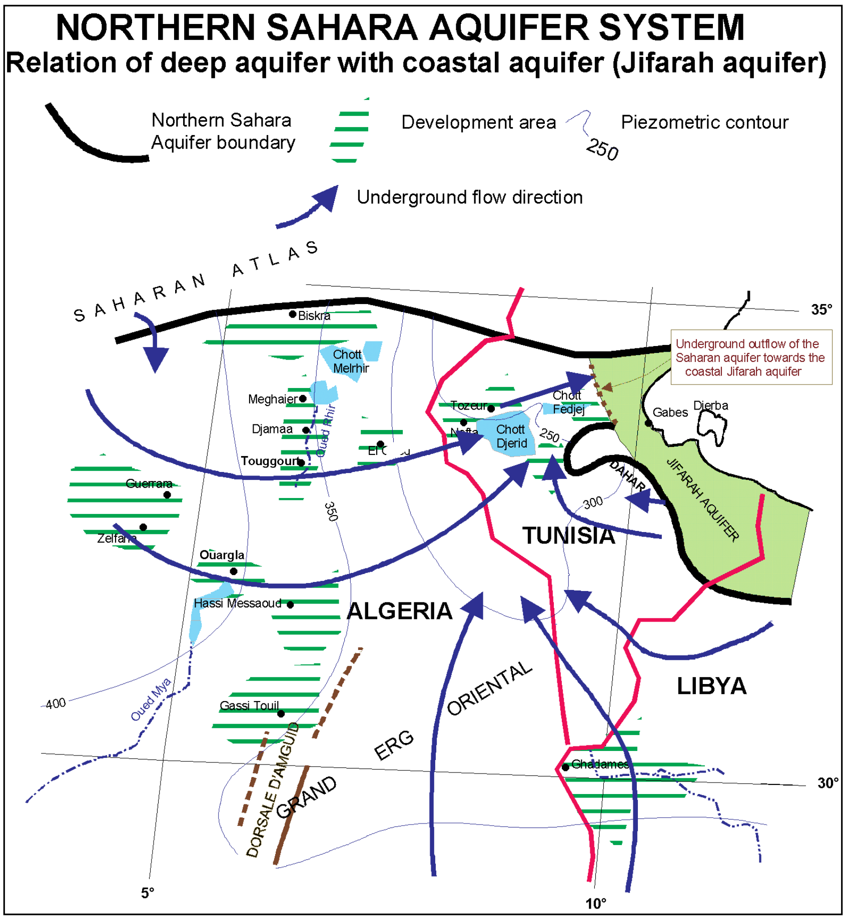

Figure 3. Northern Sahara Aquifer system.

2.2.2 *Modification of the piezometric surface*

Depending on the intensity of abstraction, modifications of piezometric heads occurs in the form of a more or less concentric cone of depression. This is a contrast to surface water, where extensive withdrawal from a river channel impacts only the downstream conditions.

Cones of depression may spread beyond international borders. An example (Fig. 4) from the Nubian aquifer system illustrates the predicted long-term impact. Production is planned in East Awaynat –located in the southwestern part of Egypt, close to the Sudanese border. Mathematical modelling shows that by the year 2060 the cone of depression might spread in all directions and particularly upstream towards Sudan, into an area where no development is anticipated so far, though it incorporates the Selima oasis.

2.3 *Deterioration of the water quality*

Water quality deteriorations may take place as a result of intensive development. Poorer quality water from a coastal area or from saline aquifers may be mobilised. The impacts can be transmitted from unilateral actions in one of the countries sharing the transboundary resource.

Figure 5 illustrates the possibility of saline intrusion in confined aquifers at some distance from the sea, yet having an influence on a neighbour. Vulnerability of aquifer is higher when groundwater moves through formations where large interconnected fractures or cavities are present and encourage rapid flow as in the case of the karstic aquifers.

A mathematical model simulation, conducted under an IFAD funded project, illustrates the possibility of mobilisation of poorer quality water. Figure 5 shows the possible impact that might be generated by additional extraction in Siwa (Egypt) and the new development in Jaghbub (Libya). The saline water contained in the aquifer, currently some 20–25 km north of Siwa, would probably migrate towards the development areas, essentially towards Siwa.

Quality deteriorations from vertical leakage can also occur. In arid regions some topographic depressions favour evaporation of groundwa-

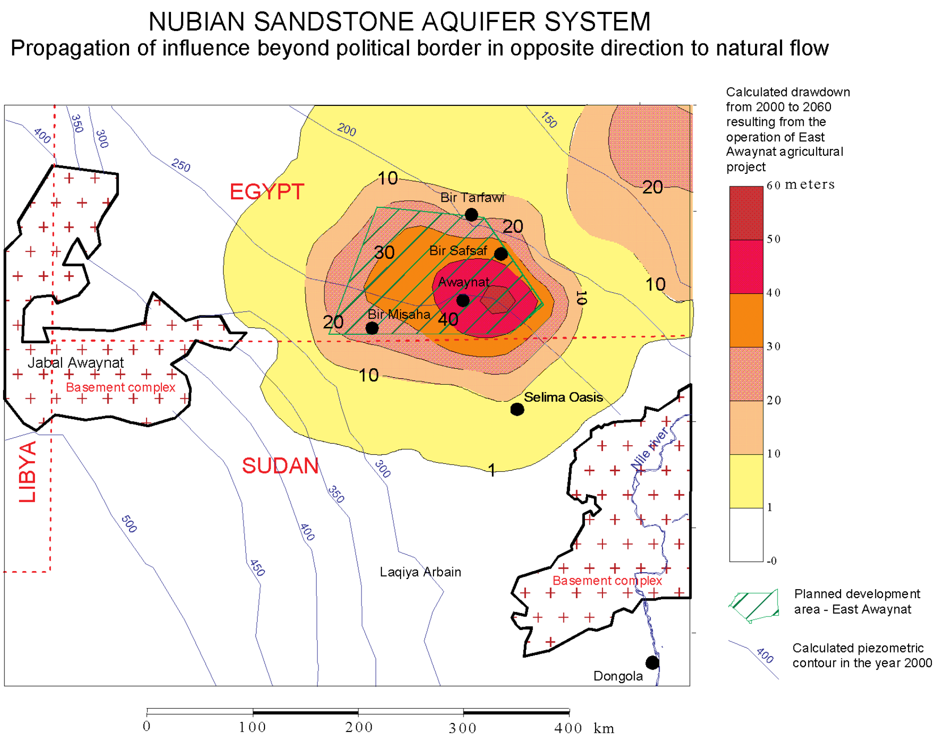

Figure 4. Possible spread of the cone of depression.

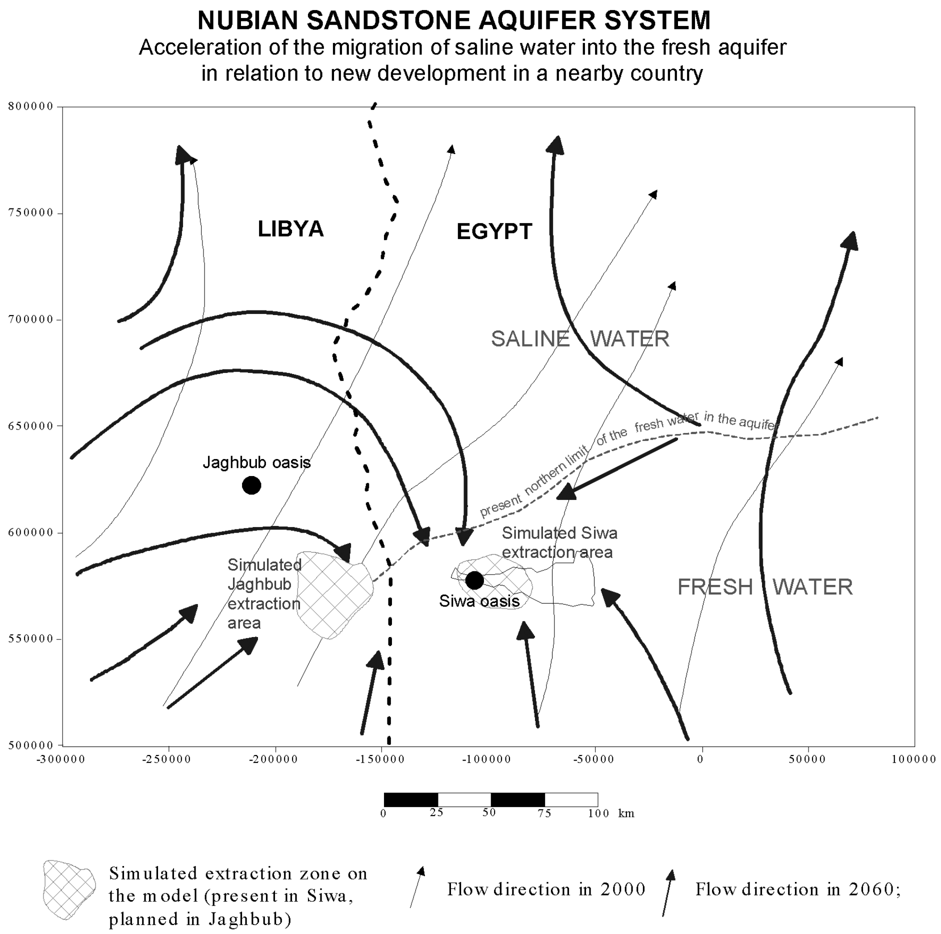

Figure 5. Possible impacts of saline intrusion from transboundary production.

ter due to high piezometric levels and create *sabkhas* containing poor quality water. Production from deeper better quality aquifers will result in reversal of leakage and invasion by poor quality water.

2.4 *Pollution*

Human activities at the ground surface, may severely impact some small underlying aquifers, e.g. improperly selected sites for landfill of waste, or industrial development, etc., resulting in aquifer pollution. With the flow of groundwater from one side of an international boundary, these impacts can be felt on the other side. Once polluted, aquifer cleanup is slow and expensive, the detection of its sub-surface distribution can also be expensive. In a transboundary context these issues can become almost impossible to resolve and to date there is little or no experience in conflict resolution and international law would have no guidelines on the dynamics aquifer contaminant transport[3].

2.5 *Issues in intensive development of transboundary aquifers*

Management of the resources in transboundary aquifers broadly follow the same principles as

[3] See e.g. *Draft articles on the law of non-navigational uses of international watercourses* in Natural Resources Forum 1997, vol. 21 no. 2 –there is no reference to aquifer systems, except those *connected* to water courses.

those for any national aquifer resource, driven by the national priorities. However, for a shared resource the national priorities may have to be adjusted, to ensure equitable distribution (Wolf 1999). In a thick aquifer, discharging to a river, the impact of abstraction of 50% of the annual recharge is depicted in Figure 6a. If initial groundwater level elevations at the edge of the aquifer are 100 m above some datum, then with abstraction of 50% of the recharge, they will stabilize at 50 m elevations. Simple calculations (Equation 1) can show that for an aquifer of L = 100 km width, a transmissivity of T = 500 m^2/d, and S = 0.1, the time t, to stabilization to the new levels will be about 110 years. Figure 6b, shows that the initial rate of decline is small, gradually increasing and finally stabilising at the new equilibrium. Since planning horizons of most river basin agencies are 5 years or so, and data longer than such periods are not collected systematically, then short term data shows a much more alarming situation, than the overall picture.

$$t = L^2 S / T \qquad (1)$$

If this aquifer is crossed by an international boundary midway through the flow path, the change of levels at this boundary will be proportionately smaller and levels will stabilise in about 27 years. The idealised calculations for even of abstraction over the whole of the aquifer are unrealistic. Usually wellfields are installed in a small area. In this situation a cone of depression develops and as shown in Figure 7, it would spread to a neighbouring territory and time for

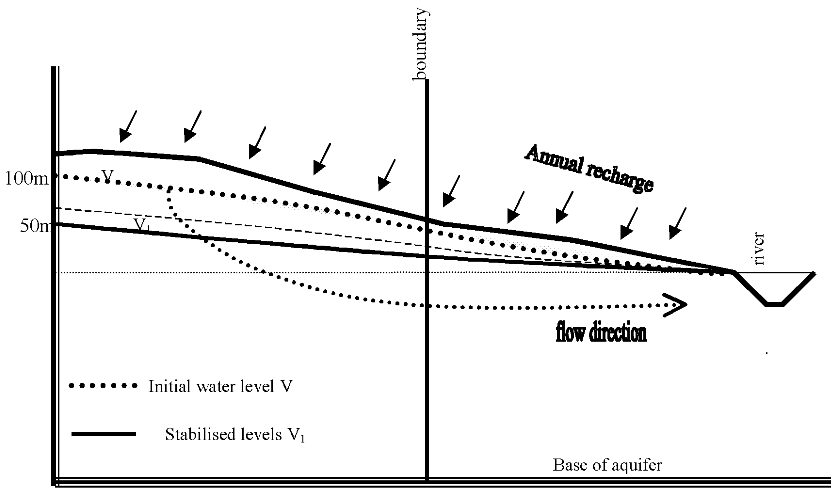

Figure 6a. Impact of abstraction of 50% of annual recharge.

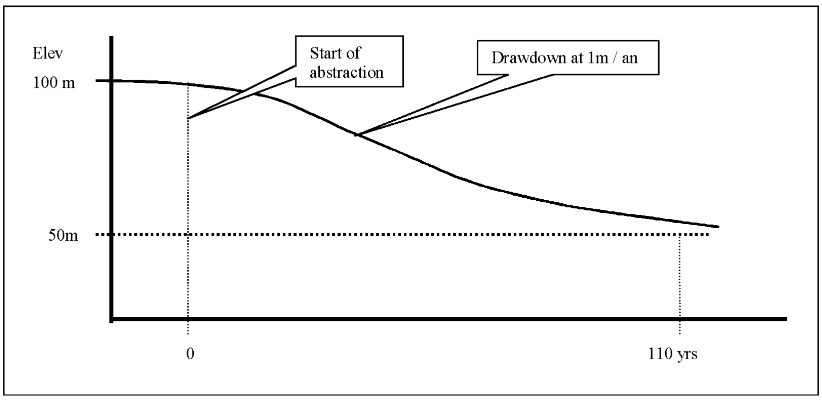

Figure 6b. Rate of decline of water levels responding to abstraction.

stabilisation of levels would depend on the aquifer properties.

These are simple illustrations of the dynamics of groundwater and serve to place into context *intensive use* and its transboundary impact. If the 50% abstraction were evenly distributed over the full width of the aquifer, the levels would respond as shown in Figures 6a, 6b. However, if the whole of this abstraction takes place within the downstream side of the boundary, the consequences of the production would be significant for the upstream riparian (Fig. 7). Conversely, a scheme located within the upstream territory would impact water levels more seriously within the territory than in the downstream side. Even though the impacts would develop over a period of time measured in tens of years, there would still be the need for some joint actions by the riparians for sound resource development.

Sound aquifer resource management clearly requires a thorough understanding of the hydrogeology of aquifers under consideration. The above simple example has simplified the reality to make the relevant points. In nature, aquifers, just like most other natural resources, are considerably more complicated. One crucial factor above all others is fundamental to the approach that may be adopted for aquifer resource management, that is whether or not the aquifer is recharged.

From one of the many hydrogeological resource management perspectives, the case of recharging and non-recharging aquifers can be contrasted. These are discussed next. The term contemporary recharge is used to qualify the classification below. It arises from the fact that due to natural climate change over the last 10,000 years, recharge patterns have modified. The arid regions of North Africa, at the time of the last pluvial benefited from substantial recharge, has declined now to practically insignificant levels.

2.5.1 *Transboundary aquifer with contemporary recharge*

In the case where the aquifer receives contemporary recharge, the overall strategy consists of preserving reduced natural outflows, and of abstracting a volume equivalent to some proportion of the average annual recharge. Such a strategy can only be achieved through joint management among the countries sharing the resource. Examples of this approach are given by the following ISARM Case Studies, situated in the temperate regions: the Vechte aquifer (shared by Germany and Holland), the Aggtelek aquifer (shared by Hungary and Slovak Republic), and the Praded aquifer (shared by Poland and Czech Republic) (Puri *et al.* 2001). A similar approach is applicable in the case of the Guarani Aquifer in South America (Fili *et al.* 2001).

Intensive use, in terms of volumes abstracted, could be related quite clearly to the annual recharge. Here the issue of sustainable resource development can be explicitly formulated, given that an agreement can be reached among those sharing the transboundary resources. Further discussion on this aspect is given in the sections dealing with environmental issues.

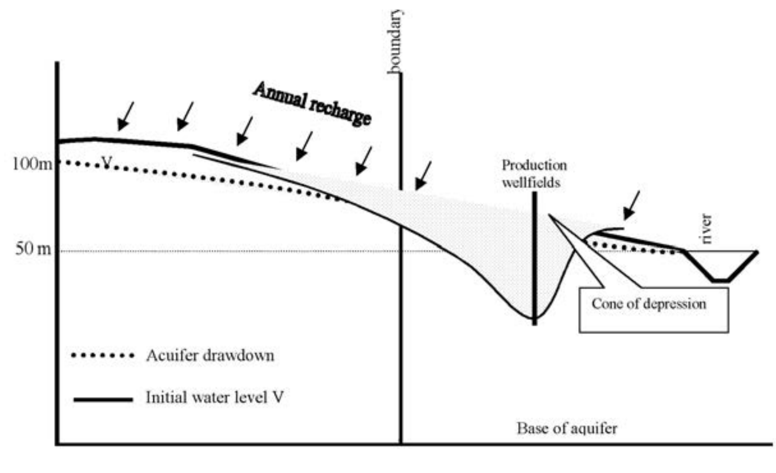

Figure 7. Impact of localised abstraction of 50% of annual recharge.

2.5.2 *Transboundary aquifer with minor contemporary recharge*

Transboundary aquifers in current day arid regions, with minor contemporary recharge, but large volume in storage, pose a more difficult problem. It is in this context that the use of the term *intensive use* requires great care. Lack of comprehensive experience in the management of these aquifers is a real challenge to the hydrogeological community. As yet there is little real consensus on how such resources should be developed, despite the fact that in many cases there is a desperate demand. In these circumstances the unused resource is a wasting resource, and unlike mineral resources, over long time spans, the resource would gradually discharge from the aquifer and be lost. The ISARM Programme, culminating in the year 2005 with the results of several case studies of such aquifers, will provide valuable authoritative guidance on the way ahead.

Nevertheless, such aquifers can be drawn on for limited time periods. Although comprehensive hydrogeological appreciation of these systems may be lacking, there is usually enough understanding for making some broad based development assumptions. These would dictate the amount and rate of extraction by each country and they should be subject to multilateral agreements. The purpose of these agreements would be to ensure that each sharing country accepts the mutual effect –even if projected to be somewhat detrimental– on its own resource, and of groundwater development in the partner countries.

Examples of transboundary aquifers with minor contemporary recharge but substantial volume in storage are:

- Algeria, Tunisia and Libya sharing the Northern Sahara Aquifer System mostly developed in Algeria and Tunisia.
- Libya, Egypt, Sudan and Chad sharing the Nubian Aquifer System developed only in Libya and Egypt.
- Egypt and Israel sharing the Nubian Sandstone aquifer in Sinai and Negev.
- Saudi Arabia and Jordan sharing the RumSaq aquifer (Macoun & El Naser 1999, Puri *et al.* 1999).
- The Karoo formation shared by Namibia, Botswana and South Africa.

In all these cases, no substantive formal agreement exist so far but studies are in progress, sometimes sponsored by international organizations such as IFAD (Northern Sahara) and SADC (The Karoo) to establish the basis of agreements regulating the groundwater extraction in each country. A draft groundwater treaty, drawing on the Mexican-USA situation, has been prepared (Hayton & Utton 1989) though never implemented. Following the experience gained by the UN ECE in compiling the European inventory, the role that the regional UN Economic and Social Commissions could play in promoting appropriate treaties would be invaluable.

2.6 *Conditions for sound management of transboundary aquifers*

The UN ECE survey of transboundary aquifers and other studies have confirmed the need for having a unified and a consistent knowledge base is a pre condition for the management of transboundary aquifers. Ideally this should be developed within a conceptual model of the whole transboundary aquifer, providing a firm foundation that supports sound development through risk analysis methodologies. Determination that a particular rate of groundwater withdrawal or general management plan is sound depends on in-depth understanding of the groundwater system, but avoiding the *analyse to paralyse* syndrome.

This understanding begins with knowledge of basic hydrological processes. Relating this to specific situations requires understanding of the extent and nature of the aquifer, how it relates to other aquifers and hydrogeologic features, how the recharge and discharge of water takes place within the aquifer, and where potential sources of contamination are located.

Without such understanding one cannot confidently plan the use of a transboundary aquifer. This conceptual model should be augmented by a consistent program on both sides of a boundary to monitor basic hydrologic parameters, such as precipitation, groundwater levels, stream flow, evaporation, and water use. The monitoring program will provide the data essential to generate a quantitative perspective on the status of the groundwater system and to validate the conceptual understanding, i.e. the data must be consistent with the conceptual model. If not, the conceptual model may need to be revised. The reality is that a comprehensive knowledge of the system is costly and time consuming. Therefore a risk assessment methodology should always be incorporated.

With such an approach, it should be possible to establish mutually accepted rules, adopted by all parties, based on a holistic definition of the aquifer system and principles of equivalence of impacts of abstraction.

3 THE NUBIAN AQUIFER SYSTEM: A CASE STUDY

The Nubian aquifer system, more formally called the Nubian Sandstone Aquifer System, has been mentioned several times above, and this section gives a summary of the knowledge of its transboundary features with reference to intensive development. The information presented is based on available reports (Pallas, pers. comm.).

3.1 *Hydrogeological framework*

The regional distribution of the aquifer system is vast, extending 2,000,000 km^2, over the national territories of East Libya, Egypt, Northeast Chad and North Sudan (Fig. 8). It is called a system because it consists of a series of laterally and/or vertically interconnected formations, including:

- Palaeozoic continental deposits.
- Mesozoic continental deposits, pre-Upper-Cenomanian.
- Post-Eocene continental deposits in hydraulic continuity with the underlying low permeability formations.

Together these reservoirs of groundwater form a basin containing fresh quality water, although becoming very saline in the north. South of the 26th parallel the aquifer is unconfined. Here the yields are the best and drawdowns from wellfields are not extensive.

Major recharge took place in the last pluvial period and at present there is slow discharge from the aquifer system, while it responds to the current climatic conditions. The flow directions of groundwater are from the south to the north and natural groundwater discharges take place into several depressions in the coastal regions, of the Mediterranean Sea. The plan view shows some of the complexities in the aquifers system and this is better demonstrated in the block diagram of Figure 9.

These views help to appreciate the striking contrast between the water resources in a transboundary river compared to those of a major transboundary aquifer. The block diagram shows the bulk flow within the Nubian aquifer, the flows in the overlying post Nubian formations, the interactions between the two. That part of the Nubian system assumed to be in hydraulic connection with the marine waters of the Mediterranean, are saline.

3.2 *Development and management of resources*

The total volume of water held in storage within the Nubian system is very large. Resource estimates have been made under IFAD investigations (Table 2).

Table 2. Resources of the Nubian aquifer system [data taken from IFAD (Pallas, pers. comm.)].

Country	Nubian system (Palaeozoic and Mesozoic sandstone aquifers)		Post Nubian system (Miocene aquifers)		Total volume of freshwater in storage (km^3) [(a)]	Total recoverable groundwater volume (km^3) [(b)]	Total present extraction from the NSAS (km^3)
	Area (km^2)	Freshwater volume in storage (km^3)	Area (km^2)	Freshwater volume in storage (km^3)			
Egypt	815,670	154,720	426,480	97,490	252,210	5,180	0.506
Libya	754,088	136,550	494,040	71,730	208,280	5,920	0.831
Chad	232,980	47,810	Not applicable	Not applicable	47,810	1,630	0.000
Sudan	373,100	33,880	Not applicable	Not applicable	33,880	2,610	0.833[(c)]
Total	2,175,838	372,960	920,520	169,220	542,180	15,340	2.170

(a) Assuming a storativity of 10^{-4} for the confined part of the aquifers and 7% effective porosity for the unconfined part.
(b) Assuming a maximum allowed water level decline of 100 m in the unconfined aquifer areas and 200 m in the confined aquifer areas.
(c) Most of this water is extracted in the Nile Nubian Basin (833 Mm^3/yr) which is not considered to be part of the Nubian Basin.

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Water abstracted for agriculture, is used either for large development projects in Libya or for private farms located in old traditional oasis in Egypt (New Valley). A very large groundwater development scheme, probably the largest in the world, for transport of water from south of Libya to the coast, is already supplying some 70 Mm^3/yr of water to Benghazi and to the major coastal cities West of Ajdabyia. This volume represents about 0.01% of the estimated total recoverable freshwater volume stored in the aquifer system.

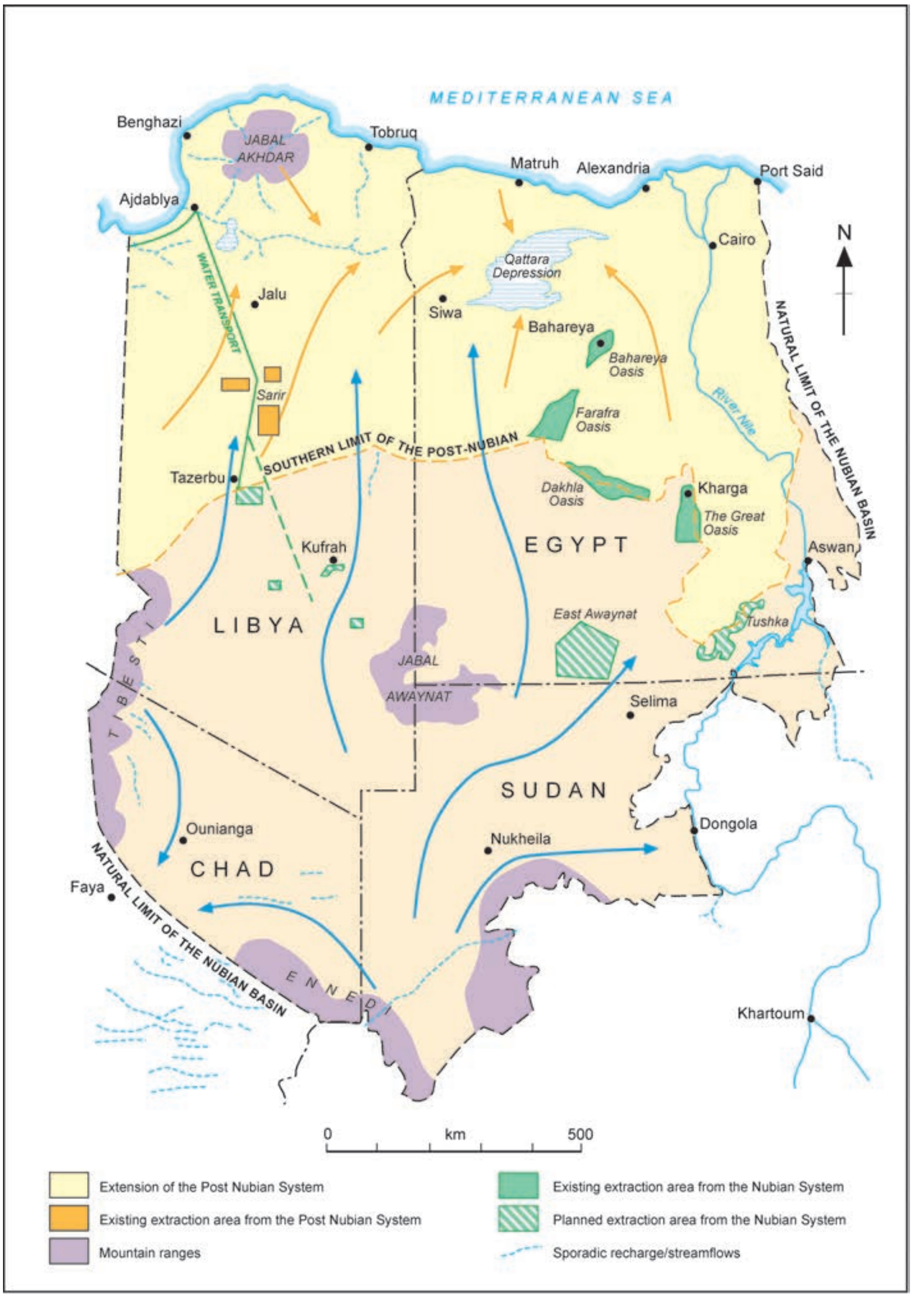

Figure 8. The Nubian aquifer system, plan view.

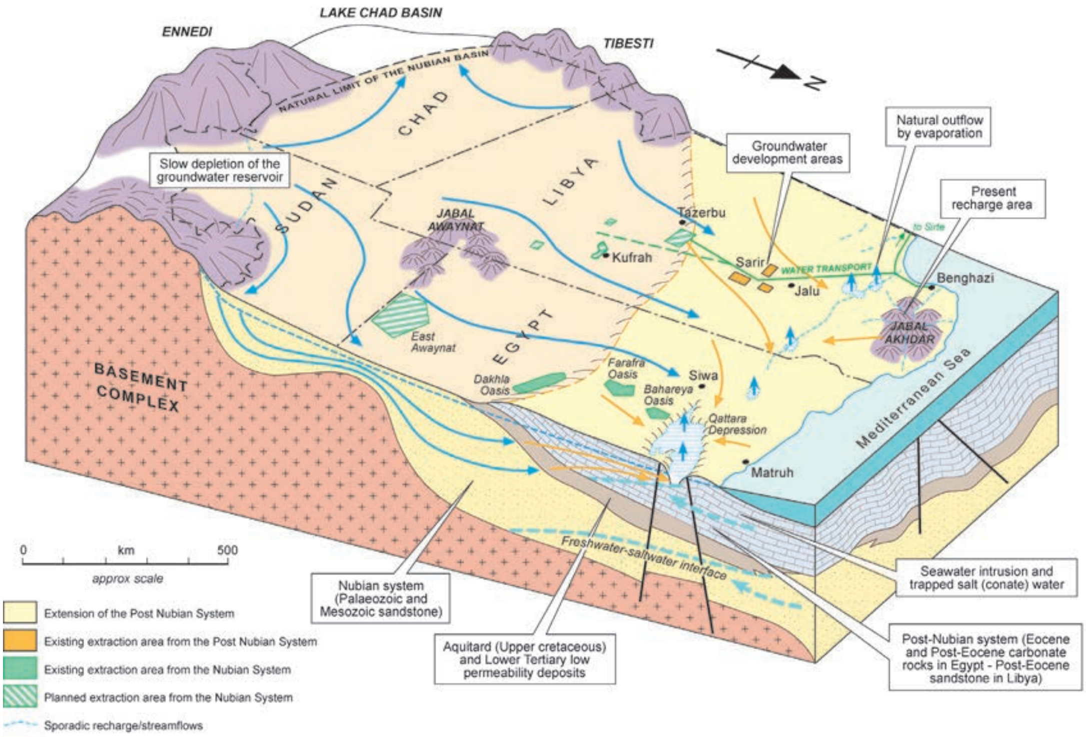

Figure 9. Block diagram of the Nubian aquifer system.

The development and the management of such a transboundary aquifer system requires a considerable investment in exploration and investigation of the system to gain a good appreciation of how it operates under natural and man induced conditions. All the tools for this investigation and subsequent evaluation for development purposes are easily available and were developed over the past 25 years. The tools, mentioned above, include the compilation of the data into mathematical models and prognosis of future conditions.

3.3 *Significant issues*

Most of the significant issues, as the spread of cones of depressions into neighbouring territory (East Awaynat), the inducement of poor quality water in neighbouring territory due to pumping (Siwa) and abstraction with reference to the volume of the stored resource, have been mentioned above.

Developments of some universal abstraction rules, such that the principles of good stewardship and sustainable management of transboundary aquifers apply, have not been attempted. In this context too, the notions of intensive use need to be well formulated.

The IFAD supported project is making a contribution to this lack of experience through coordinating the activities of experts within each of the stakeholder territories. The process will include joint assessment of priorities, the allocation of resources and the definitions of schemes that will subscribe to sound development. In this context then, intensive use still remains to be better defined.

4 RISK BASED RESOURCE MANAGEMENT

In view of the uncertainties that are often found in large regional transboundary aquifers due to the incomplete knowledge base and other legal and institutional obstacles, one way forward in assessing the impact of intensive development is to undertake a risk analysis. Although specific methodologies for transboundary aquifers have not been developed, experience from other risk based natural resource management approaches can be applied. The following sections outline the approach applied to a transboundary aquifer between Jordan and Saudi Arabia.

The Rum-Saq aquifer forms part of the Nafud basin located in the northwestern of Saudi Arabia and covers most of the territory of Jordan. The outcrop of the formation is in a rim of elevated highlands between Petra in Jordan to Tayma, Hail and Qasim in Saudi Arabia. An investigation was conducted to assess the availability of the resource for use in Jordan, incorporating the current production in that part of Saudi Arabia where mutual impacts might be felt. A portion of the Nafud basin, the part that drains towards the Dead Sea was included into a 3-D mathematical model. Results of exploration and testing from the past twenty years provided a reasonably good understanding of the aquifer system where production has been underway since the late 1970s (Puri *et al.* 1999). Figure 10 shows the 3-D depiction of the system and the interrelationships with overlying aquifers. For the purposes of the risk analysis, a considerable amount of mathematical model analyses have been completed.

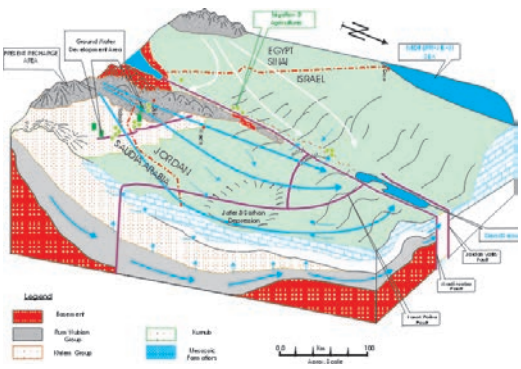

Figure 10. 3-D block diagram of the Rum-Saq aquifer system.

4.1 *Risk assessment methodology*

The procedure that can be adopted comprises of a number steps that form a structured framework, providing an objective basis for establishing the risks that a set of hazards will impact the proposed development. The methodology is summarised in Table 3.

Table 3. Risk assessment methodology.

Procedure	*Step*
Identification and definition of hazards and their consequences.	Hazard analysis
Ranking the hazards identified in order of importance, to highlight the most serious and least significant hazards.	Hazard assessment
Determining the factors that influence whether hazards are likely to occur.	Risk analysis
Determining the severity of the risk that a hazard will occur and cause detrimental consequences.	Risk evaluation[4]

The procedures and activities are carried out in steps as shown in Table 3, starting with the identification of the hazards and their consequences that apply in the aquifer under consideration. In the case of the Jordanian-Saudi aquifers risk was determined by the following equation

$$R = N_i \, D_t \, p / t \qquad (2)$$

where, R = dimensionless risk factor; N = rank given to the hazard; D = duration of the hazard; p = probability; and t = timing.

The rationale is that high rank, long duration and high probability produce a high risk hazard, but if the occurrence of the hazard is delayed, the risk is lowered. The values assigned to the timing, duration and probability are based on engineering experience, available hydrogeological data and supporting information such as future trends in regional groundwater abstractions. Some of the hazards with the highest risk included:

- New cross border wellfields: *water quantity hazard.*
- Cross border abstractions increase: *water quantity hazard.*
- Aquifer properties more heterogeneous: *water quantity hazard.*
- Leakage from overlying poorer quality: *water quality hazard.*

The results of this analysis permitted the formulation of a matrix, setting out the above parameters and also the remedial measures that

[4] The term *risk evaluation* is used to avoid confusion with the term *risk assessment* used for the overall process.

can be taken to minimise the risk. The risk analysis should be accompanied by a full analysis of the uncertainties. In the case of the above planned development, the uncertainties that were significant included the long term water quality evolution related to the changes in the piezometric distribution. A well constructed programme of testing can reduce the uncertainties and the recommendations included further long term test pumping, possibly within the early stage of the implementation of the scheme. Other uncertainties, including notification of proposals to riparians, have been addressed through application of the evolving international water law, even though no such law on transboundary groundwater as yet exists (Macoun & El Naser 1999).

5 INTERNATIONAL GROUNDWATER LAW

5.1 *Current status*

In the consideration of international groundwater law a preliminary question that arises is: to what depth below ground does the territory of the State descend? While international law has addressed these issues in the context of airspace and the marine sea bed, the implicit rule is that the borderline extends vertically into the sub soil, unless otherwise provided. By extension therefore groundwater contained in storage beneath a country may be regarded as the property of that country. This leaves the crucial issue of the flowing component of transboundary aquifers still unresolved[5]. To date international water law as applied to aquifers remains unsatisfactory (Eckstein & Eckstein 1998). By extension of this, there is no legal framework in which intensive groundwater development might be addressed, except to base this on UN Conventions and International Law Associations recommendations.

Experience shows however, that there are sensitivities about sovereignty, diversities of legal and socio-political systems and differing national agendas in neighbouring States that are linked by transboundary aquifers, such as the Nubian or the Rum-Saq. Further it would appear that the national groundwater laws and institutions of the neighbouring States do not have widely acceptable rules of governance. As a result universal rules must be found elsewhere, i.e. in other existing treaties and agreements.

5.1.1 *Rules of governance*

In the absence of law, some rules of governance can be considered. There are exceptional cases that might provide guidance; one such case that might be explicitly concerned with intensive groundwater use is described below.

5.1.2 *The Geneva-Haute-Savoi Agreement*

In 1977 the Canton of Geneva in Switzerland and the Department of Upper Savoy in France concluded a convention on the protection, utilization and recharging of the Geneva aquifer. The convention provides for a joint commission composed of six members (three from each country), including four water experts. The work of the commission includes preparation of an annual plan for the use of the groundwater resource, proposing measures to protect it against pollution. Furthermore, it gives advice and approval on the construction and modification of new and existing abstraction equipment.

Since the Geneva aquifer is artificially recharged, the commission also verifies the costs of constructing and operating the artificial recharge station. A complete inventory of all pumping installations is maintained and the amounts of water to be withdrawn are limited and recorded with metering devices. Finally, the quality of the water withdrawn from and recharged into the Geneva aquifer is regularly analysed. Due to this extensive system of control, the commission is always informed on the quantity and quality of the groundwater supply and hence it appears that it can plan the withdrawals from and recharges into the aquifer with a considerable accuracy.

This single agreement, based on its success, could be developed into a form of a model agreement for localized intensive transboundary aquifer resource management. However, conditions such these are very rare.

[5] In the Australian Border Agreement, the extractable groundwater volume equals, *volume derived from vertical recharge + proportion of groundwater throughflow + proportion of groundwater storage* (equivalent to a drawdown of storage of 0.05 m/yr).

5.1.3 *Evolution of water law*

The level of exceptional cooperation in the Geneva/Upper Savoy convention, and the far-reaching obligations and arrangements also reflected in it are the exception. On a less ambitious scale, Mexico and the USA reached agreement in 1973 on specific volumetric limitations annually on groundwater pumping in the territory of both, within 8 km of the Arizona-Sonora international boundary. The agreement further requires the two countries to consult each other prior to undertaking any new development or substantial modification of either surface or groundwater resources in its own territory in the border area that might adversely affect the other country.

The agreement was facilitated by, and was reached within the framework of, the Mexico-USA International Boundary and Waters Commission (IBWC). The Commission, consisting of two separate sections located in the twin border cities of Ciudad Juarez, Mexico and El Paso, Texas and each headed by a Commissioner, has been in existence since 1944. The groundwater resources in the border area of the two member countries have been progressively brought within the scope of the Commission's remit. As a result, short of a comprehensive treaty or agreement dealing with the groundwater resources Mexico and the USA share along their frontier, a well-tested bilateral institution is available to address authoritatively groundwater problems as they arise on either or both sides of the border.

5.2 *Observations from the International Court of Justice ruling on the Nagymaros-Gabcikovo case*

This case is about an anticipated significant impact upon a transboundary aquifer that was subjected to *intensive use*. Eckstein & Eckstein (1998) and McCaffrey (1999) have described it in some detail. Hungary's hydrogeological case claimed that as a result of construction work, groundwater levels would have declined in most of the Szigetkoz area of Hungary, having a wide ranging environmental impact.

The decision reached by the court was not based on the application of water law to aquifers. The hydrogeological evidence presented was deemed to be secondary to other considerations such as financial and developmental matters. The court was not convinced that the *peril* was sufficiently *imminent*, noting, "the future environmental damage would be the result of some slow natural process, the effect of which could not be easily assessed".

This process by which the case was dealt with demonstrates the lack of scientific appreciation among government officials, legislators, policy-makers, jurists, and legal scholars. It is the opinion of the scientific technical community that the inclusion and understanding of technical information in the decision making process can only serve to achieve more balanced, scientifically based, and thoughtful decisions.

Mainly as a direct response to similar situations, and the anticipation that more cases of this type, with increasing complexity, are likely to arise with increasing demand for water resources, the ISARM Programme has been initiated. Its aims are to incorporate science into legal, socio-economic and institutional issues so that decisions can be based on an integrated approach.

6 INSTITUTIONAL ISSUES

6.1 *River basin commissions and joint bodies*

The foregoing sections provide a clear indication that there is limited institutional experience that can be drawn upon as far as the management of transboundary aquifers is concerned. Some guidance may be inferred from a series of conventions relating to the use of shared natural resources. Among these is the highly innovative and prescient 1968 African Convention on the Conservation of Nature and Natural Resources. In Article V(2) the convention provides that:

> "Where surface or undergroundwater resources are shared by two or more of the Contracting States, the latter shall act in consultation, and if the need arises, set up inter-State Commissions to study and resolve problems arising from the joint use of these resources, and for the joint development and conservation thereof".

This is also stated in the ILA's Seoul Rules on International Groundwaters (1986), under Article III, Clause 3, which states that "Basin states shall cooperate, at the request of any one of them, for the purpose of collecting and analysing additional needed information and data pertinent to the international groundwaters or their aquifers". However, for such cooperation to be fruitful and yield results, there is a need for adequate capacity and institutional strength. Traditionally groundwater management remains dispersed and fragmented in most countries of the world.

6.2 *Constraints in existing commissions*

In the absence of institutional arrangements for transboundary aquifers, it may be relevant to review the existing arrangements for shared surface waters, noting some of the difficulties that have constrained their activities, shown in Table 4.

Table 4. Existing river basin commissions.

Basin Commission	Comment
Danube and Rhine Commissions	Set up for the purpose of regulating navigation. Recent extension of responsibility to pollution issues.
Indus and Nile Commission	Established to settle water apportionment. The latter only includes two members.
International Joint Commission USA-Canada and International Boundary and Water Commission USA-Mexico	Both have operated well with discussion and settlements of most disputes
Mekong Commission	It has recently started to become fully active

6.2.1 *Scope of activities for aquifer commissions*

Several general observations, which might be of value in establishing aquifer commissions, can be made:

- Commissions issue recommendations and may be advisory.
- Commissions may be of indefinite or long durations, and thus have time to adapt to changes.
- They have the authority to undertake studies, conduct investigations; consequently they have an important influence during early stages of planning, when coordination is crucial.
- A technical bias in a commission precludes the domination of political influence. It may be retained at the Commissioner level, therefore participation of all members is needed.
- They should possess judicial powers to settle disputes, decide on allocation of water, costs and benefits.

Assuming that riparians in a transboundary aquifer decide to establish institutions for the joint management of resources, the Table 5 shows an outline of the scope of responsibilities that should be considered.

Table 5. Scope of responsibility for aquifer commissions.

Scope	Responsibilities
Technical	• Establishing a sound conceptual model of the whole aquifer. • Formulation of a sustainable basin development plan and coordination, including prioritisation. • Water quality and pollution prevention plans. • Control of beneficial uses; allocations for municipal demands, agricultural demands, industrial demands. • Establishing other aquifers uses, e.g. thermal energy, balneological needs, natural discharges to wetlands, etc.
Economic and financial	• Internal financing, including cost sharing and sharing criteria. • Financing specific projects, management of international funds, compensation criteria, sharing benefits, payment of interest and repayment of debts. • Assessment of collection of revenues, setting of tariffs. • External financing.
Legal and administrative	• Administration of the right to use water at the national level and coordination with national agencies and institutions, establishing water users associations. • Prevention and settlement of disputes between water users. • Drafting and implementing required legislation: international agreements, ministerial resolutions, harmonization of legislation. • Other legal advice.
Public participation	• Ensuring full involvement of the stakeholders. • Empowering water user associations and defining property rights. • Implementing the full scope of sustainability in resource use.

The above scope of tasks to be entrusted to a Commission should not preclude other options that could be adopted. Since the existing agencies may well have river basin management responsibilities, then consideration should be given to development of the existing basin management agencies. In their absence a new authority, or a specialized management institution, e.g. irrigation agency could be developed. Other aspects such as duration, constitution of the commission, procedures for decision making and their legal status would have to be taken into account.

7 SOCIO ECONOMIC ISSUES

7.1 *National* vs. *transboundary priorities*

All the national socio-economic issues that relate to aquifer resources management apply to some degree in the management of transboundary aquifers. The following discussion relates to national issues and is based on Burke & Moench (2000). The social, economic and environmental values associated with groundwater are often unrecognised and undervalued. Groundwater is the most reliable source of supply for potable water and supports a wide array of economic and environmental services. Of these, agriculture, the largest abstractor of groundwater to date, is less sensitive to water quality but is generally the highest volume user.

The role of groundwater in agriculture is important to recognize. Groundwater is the primary buffer against drought, and areas with access to groundwater irrigation are generally able to achieve higher agricultural yields even in the humid tropics (e.g. Punjab, India and Pakistan, Mekong basin).

If climatic variability increases, as many analysts predict will be the case with global climatic change, the buffering value of groundwater, will be a particularly important factor determining society's ability to meet basic food security, drinking-water supply and environmental needs that depend on reliable water sources. Even without climatic change, supporting global populations will require reliable water supplies.

7.2 *Increasing demands*

At the start of the 21st century, over 50% of the world's population will reside in urban areas –a dramatic increase from the 30% in urban population in 1950. Some of this urban population growth will occur in areas that will draw on transboundary aquifers (e.g. Campo Grande, Uberaba, Porto Alegre in Brazil may draw on the transboundary Guarani aquifer). In rural areas, transboundary aquifers may be the sole source of waters, e.g. the Karoo transboundary aquifer supplies local communities in Botswana and South Africa, stock watering five smaller towns in Namibia. Increasing demand for irrigation will stress the resources.

7.3 *Poverty reduction and access to water*

Equally important to its role as a critical source of water supply for agricultural and municipal uses, groundwater plays a more subtle role related to poverty alleviation, health and social vulnerability. Access to groundwater is perhaps the most critical factor enabling many rural populations to maintain sustainable livelihoods. Intensively used transboundary aquifers would have to satisfy competing demands and ensure that a reliable quantity is available, at low cost to the poor.

Assured water supplies greatly reduce the risks poor farmers face when investing in such agricultural inputs as seed and fertilizer. Secure water supplies enable them to increase yields, income levels, savings and capital formation substantially. Similar effects occur where health is concerned. Groundwater is generally less vulnerable to pollution than surface water sources. It is also often available in close proximity to points of use. In combination, these factors reduce the risks from water-borne disease and reduce time spent in collecting water from distant locations.

Fewer sick days and reductions in time *wasted* collecting water translate into more time available for more productive purposes. Overall, by enabling individuals to accumulate reserves, access to groundwater enables rural populations to reduce their vulnerability, not just to drought, but also to the full range of natural, economic and social hazards that generate much rural poverty.

7.4 *Staged confidence building measures*

In order to translate some of these issues into more practical reality in the transboundary context, a large measure of will power and confidence building is needed. There are many examples of the start of this process. The resources of the Guarani Aquifer are being reviewed through High Management Council, established through the support of the GEF Programme. The resources of the Karoo Aquifer are under study through the coordination provided by SADC. In Europe, the EU and Water Framework Directive has been instrumental in improved communications and joint setting of priorities over shared aquifers. The UN ECE has published comprehensive guidelines for the monitoring of transboundary aquifers.

The steps that might be needed in establishing good procedures for the sound management and beneficial uses of transboundary aquifers will evolve in the ISARM Programme. In it, several case studies are to be conducted in Latin America, Africa and Europe in order to gain the background required for developing a *toolkit*. In advance of the results, the following suggestions can be made with reference to likely intensive use of a transboundary aquifer.

Two main stages are suggested; in the first, a comprehensive and a logical multi disciplinary analysis would be conducted, as outline schematically in Figure 11. Much of these suggestions have been discussed in the foregoing chapters. The main feature of this stage is to establish the *status quo* in the aquifer system, in its steady state. This is based on the basic principles of hydrogeology, easily understandable and appreciated by the partners in this process, i.e. the decision makers, legal experts, socio-economists and the stakeholders.

A second stage of the process would move from the baseline information and develop the ideas of joint commissions or similar bodies. In this stage the prime focus would be seek equivalence in the legal and economic frameworks of the riparians –while each can operate with its own national system, it would be important to establish the *approximation* of the rules and regulations. A considerable degree of experience is being gained through this process being applied in the Central European countries that will be acceding to the EU. The lessons learnt could be applied in riparians wishing to jointly share their resources.

8 ENVIRONMENTAL ASPECTS

The environmental issues that affect the intensive use of transboundary aquifers are wide

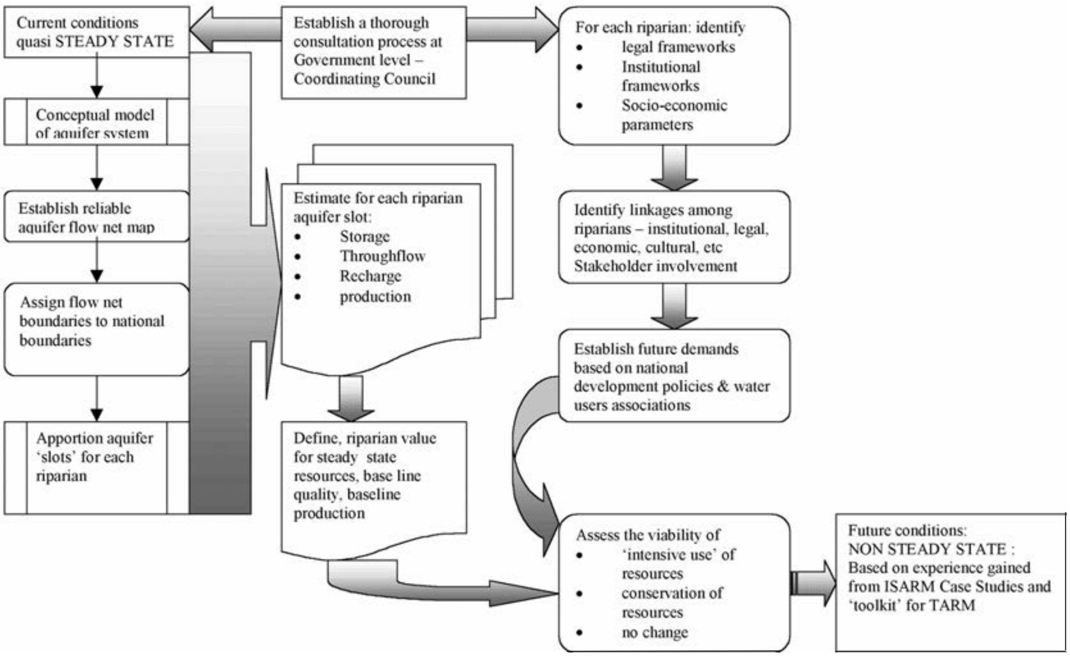

Figure 11. Stages in the sound development of transboundary aquifers.

ranging and can be viewed both from a local and a global perspective. The issues addressed here will be developed further in the context of the ISARM case studies.

8.1 *Sustainable development of transboundary aquifer resources*

If the conventional definition of sustainable development, i.e. "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987), can be applied to aquifers within a nation, then there is no reason why the same cannot be applied to transboundary aquifers.

However the broader socio-economic notions of sustainability and *sustainable development* remain relative across nations, despite the wealth of thought and publications on the subject. The Commission for Sustainable Development uses a framework for defining acceptable withdrawal of groundwater. The framework, which is based on *driving force-state-response* indicators (UN DPCSD 1996), suggests that withdrawal quantity should be relative to either *available water*, or *to groundwater reserves*. In some situations this steady state mass balance approach is too restrictive. Recently work on the *vulnerability* of aquifer systems to pollution and other impacts (Robins 1998) points to the appropriateness of source vulnerability indicators rather than state-response indicators.

In sustainable management of transboundary aquifers, problems such as groundwater overdraft will often emerge gradually. If they are identified and actions initiated to address them early, joint action may cause little social disruption. If, on the other hand, joint responses are delayed until major problems arise, massive social disruption may be unavoidable. In a scenario where to return groundwater use to sustainable levels, extraction needs to be drastically reduced, the resulting social disruption will be politically difficult and socially unacceptable.

Sustainable development of transboundary aquifers requires making predictive analyses involving the use of computer modelling techniques, to define the life of the resources. A holistic conceptual understanding of the groundwater system is the basis for the proper construction of a computer model. Real and relevant hydrologic features of the groundwater system must be correctly incorporated into the model. Furthermore, all models need to be calibrated using real and consistent data. The results of the monitoring program provide this validation check. The more sophisticated tools and methods of analysis that can indicate sustainability are built on a foundation of conceptual understanding and monitoring.

Determining the sustainability of a transboundary aquifer with any degree of confidence can only be conducted in a resource planning context having detailed information and understanding. Ultimately, though, resource development policy involves trade-offs. Most aquifer systems have ecosystems, landscape elements, or pre-existing water users that are dependent on current discharge or recharge patterns. Further development may require trading off these dependencies in favour of new plans or policy. If dependencies are not well understood or considered, management changes may have major unanticipated impacts. The best approach to minimize negative outcomes is to follow the progression of investigation outlined above.

8.2 *Biodiversity*

Examples of ecosystems that depend partly or totally on groundwater are numerous. There is often no inherent conflict between preservation of these ecosystems and withdrawals from transboundary aquifers for socio-economic development.

Since an aquifer system is essentially below ground, biodiversity issues generally relate to the regions where aquifers discharge through rivers, lakes or swamps. Such water bodies frequently have specific characteristics, related to the physical and hydro chemical features of the aquifer that create special ecosystems.

In many regions, but especially arid regions discharging groundwater fed water bodies can be absolutely critical to the maintenance of biodiversity. Even in temperate climates, the discharge region of a transboundary aquifer can provide specific conditions of quality, temperature and nutrients that rare species will be reliant upon.

In Tunisia, in the Ichkeul National Park, the Ichkeul Lake and related swamps rely partly on groundwater discharge to provide seasonal fluctuations in salinity (which ranges from low levels in winter up to 30–40 g/L in summer). The conditions are essential for maintaining *Potamogeton*-bird, swamp-bullrush-geese, fish and fishing ecological compartments and their relationships. The Azraq lakes in Jordan are another example of a surface water body supported by the transboundary flow in aquifers. These lakes are an important stopover and watering point for annually migrating birds. In recent years with the strong abstraction of groundwater, the lakes size has reduced drastically thus having a serious impact on the transmigratory routes for birds.

Discharge of transboundary groundwater into inland seas, e.g. the Caspian and the Aral, supports important marine ecosystems. In Azerbaijan, discharge from the alluvial aquifers of the river Kura, which rises in Georgia and flows to Armenia, maintains an important sturgeon fishery. Aquifer over abstraction and excessive fertiliser application in the irrigation areas of these countries have had negative impacts on the quality of groundwater flowing to the coastal areas, where natural feeding areas for sturgeon have been impacted.

8.3 *Climate change*

The impact of climate change on transboundary aquifers of the world is yet to be fully evaluated in the same way as it has been for agriculture and land use. In some regions climate change will result in increasing recharge and in others reducing. The consequences of either of these impacts on abstraction, maintenance of wetlands, discharge to water bodies could be very serious, especially where well developed infrastructure has been established. Global sea level changes, may impact marine saline intrusion –the hydraulic reference point change could mean that many aquifers may extend inland intrusions, thus affecting groundwater quality.

As stated earlier, aquifer response to stimuli such as climate change will be even more gradual than those resulting from human intervention. The detection of these impacts will require a very careful analysis of data. For transboundary aquifers, the need for consistent data and a comprehensive conceptual understanding is essential.

The earlier discussion about aquifers with and without contemporary recharge is relevant to climate change. The approaches that have been developed for managing non-recharging aquifers may need to be revised in the context of climate change. Conversely, aquifers currently being recharged may suffer *surcharges* due to increased recharge. This could have an impact on existing infrastructure such a building with deep foundations. Swamps, wetlands and lakes that are supported by aquifer recharge may extend in area, possibly flooding surrounding infrastructure, such as roads and highways, etc. These impacts could be gradual and problems may not be noticeable until damage has occurred.

8.4 *Poverty alleviation, water and health*

The role of transboundary aquifers in poverty alleviation and health is linked to socio-economic development. In under developed economies, low levels of awareness of this linkage seems to hinder the provision of aquifer resources to alleviate water shortages to the under privileged, especially the rural populations. Since water, sanitation and health go hand in hand, provision of drinking water to rural populations could relieve them of the worst incidences of drought and the related deprivation. The current development of national *Poverty Reduction Strategy Papers* being developed under World Bank and other Development Agencies, need to stress this issue, where large shared resources are available but unused. Transboundary aquifers that are subject to pollution through excess application of agro-chemicals (e.g. in many regions of the Former Soviet Union), and other impacts such as industrial waste, lock the poor into a cycle of poverty and ill health, related to their use of poor quality water for drinking or irrigation.

8.5 *Conflict prevention*

The UN has initiated a major programme devoted to prevention of water related conflicts. This has been embodied in the WWAP, which responds to the challenges formulated at the Hague Ministerial Conference of March 2000. The UNESCO IHP VI also incorporates two themes related to conflict resolution and prevention especially in shared water resources. By their very nature transboundary aquifers have to be at the centre of conflict prevention and resolution. Some estimates have suggested that nearly 300 water bodies cross international borders and 47% of the worlds land area overlaps with an international freshwater basin (Samson & Charrier 1997). While at present there are few known conflicts concerning transboundary aquifers, there are many signs of discord regarding them, particularly in areas where resources are limited. The UNESCO programme *From Potential Conflict to Cooperation Potential,* which has recently been initiated, will have a significant linkage with the ISARM Programme.

Conflicts, relative to transboundary aquifers may be couched in terms of competition, confrontation or disputes. A scale of interrelationships in competition for natural resources may be presented as shown in the Table 6.

Table 6. Definition of intensity of conflict.

Increasing tensions

Harmony	An ideal state, achieved in sparsely populated regions with ample resources per capita.
Institutional mechanism	Very few of these can be found for transboundary aquifers, the exception being the Geneva-Haute Savoi Agreement.
Informal mechanism	Various forms of cooperation such as personal contacts among governmental officials, academia, etc.
Tension	Movement towards formal conflict, low level government profile.
Diplomatic action	Formal act, or protest concerning specific issues.
Open dispute	Diplomatic acts supported by open heated debate. Linkage to other issues.
Armed conflict	Violent though isolated conflict.
War	Highest level of potential conflict strongly correlated to water.

Conflict resolution and prevention can take several routes, among them:

- Awareness building.
- Multi sectoral partnerships.
- Integrated assessment and management.
- Implementation of sustainable strategies.

The most serious conflict related transboundary aquifers is the Mountain Aquifer system shared by Palestine and Israel. Other aquifers over which some conflicts have arisen include the Guarani in South America. The ISARM Programme aims to provide scientific inputs to assist in the process of resolution and prevention mentioned above.

9 CONCLUDING REMARKS

This chapter has dealt with the very wide ranging issues that relate to the development of transboundary aquifers. Intensive development of majority of the large regional aquifers in arid zones has not reached a level of concern, but there are strong expectations that with rising demand these resources will be exploited. Smaller transboundary aquifers have been subjected to intensive use, defined not simply as a source for water, but also in terms of landuse and the related impacts. A landmark case of an alluvial aquifer in the Danube flood plains has been considered at the International Court of Justice. The lessons learnt from the judgement are that hydrogeologists have not been able to present their case sufficiently well –the *uncertainty* in hydrogeological forecasting did not provide the Court sufficient basis to make the judgement. In the event the judgement was based on financial and developmental grounds and not on environmental management criteria. There will more situations of this type, where the hydrogeological prognosis will have to be constrained by uncertainty envelopes –a scientifically accepted concept, but of little value in the world of politics and adjudication.

In the forthcoming decades aquifer resource management will have to take on a more multi dimensional and multi disciplinary approach. The more initiatives that involve the relevant professions, the better the chances that sound and sustainable resource management will take place.

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SECTION 5

Common issues and the way forward