Challenges Facing Groundwater Management in Sudan

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Abstract: Sudan has great potential of renewable and non-renewable groundwater resources which are important sources of water supply for domestic, industrial and agricultural uses. It is a key element for human settlement and sustained socioeconomic activities. Demand for groundwater in many areas of the Sudan has recently increased considerably in order to meet the needs for the implementation of agricultural and economic development plans but regrettably, these development are taking place in a rather unplanned manner leading to many problems such as overexploitation, reduction of reliable yield, and deterioration of quality .This emphasizes the need for sound polices and optimum plans for groundwater resources management in order to ensure its long term sustainability. However, Groundwater management in Sudan is faced with many challenges. The most obvious of these challenges is the absence of quantitative and qualitative monitoring and scarcity of information on aquifers geometry and their hydro geological characteristics. Another major difficulty is related to the understanding of flow dynamics and recharge sources and mechanisms for the different aquifers. This makes the estimation of recharge volumes an extremely difficult task. Correct estimation of groundwater recharge and aquifer storage are two of the most important requirements for long term management of any groundwater system. Fractured aquifers in Sudan cover very large areas and provide an important source of water particularly in rural areas. A major problem encountered in the management of fractured aquifers is the limited understanding of their hydrogeology and flow dynamics. The fractures characteristics could be extremely complex making it very difficult to locate areas of productive boreholes with sustainable groundwater yield. Vulnerability and risk of contamination of these aquifers are also very high. Other key challenges facing groundwater management in Sudan are the management of shared non-renewable aquifer resources, lack of comprehensive guiding plans and policies, poor governance and legislative framework, inadequate capacity, and lack of coordination among groundwater sub sectors. The purpose of this paper is to discuss these challenges in some details and suggest directions for overcoming them. The paper also includes a case study on the use of advanced methodologies for groundwater management and protection in Sudan.

Keywords: *Groundwater Management; Aquifer Recharge, Information base; Contamination; Shared aquifers; Fractured aquifers; Groundwater modelling; Governance; Policies; Legislations.*

1. INTRODUCTION

Groundwater is a vital source of water supply for domestic, industrial and agricultural uses in many parts of Sudan, especially areas away from the Nile valley. Surface water resources in these areas are often scarce and the options for their development are rather limited making groundwater the only viable source. Groundwater is potentially available in large areas of the country. Major aquifers cover more than 50% of the area of the country and fall under four main categories: The Nubian sandstone aquifer, the Um Ruwaba formation, the recent alluvial Wadi aquifer and the hard rock aquifers of the basement complex (Salih & Khadam,1984). Despite the large number of previous studies that have been conducted on groundwater resources in Sudan, there is no unified value of their estimated strategic potential. However, the various estimates given in the literature do indicate that it is huge.

One of the main difficulties in groundwater management is that, differently from surface water, groundwater is not directly visible to the decision makers, its response is usually very slow, and the consequences of any management policy are not immediate but could take a very long time before they are realized. Therefore an essential requirement for any groundwater management policy to be successful and effective is to have a thorough understanding of the groundwater system and the flow dynamics within it. However, this is rather difficult to achieve in view of the scarcity of data and the absence of reliable information base. Another problem that often hinders effective groundwater management in Sudan is the lack of integrated approach and the one-sided look of many hydrogeologists to groundwater as a separate body isolated from the overlying surface hydrological processes. Interaction between surface water and groundwater and quantification of groundwater recharge therefore remain major challenges for groundwater management and long term sustainability particularly in areas, where recharge rates are small – both as a proportion of the water balance, and in absolute terms (Wheater, 2007). Considering the huge potential of Wadi systems in Sudan and the shallow aquifers underlying them, better knowledge of surface and groundwater interaction is certainly a mandatory prerequisite for sound management of surface and groundwater resources in Wadi systems in many areas of Sudan. Key words that could be mentioned here are conjunctive use of surface and groundwater, water harvesting and management of groundwater recharge.

Extensive groundwater development for agricultural purposes is taking place in a rather unplanned manner in many areas of Sudan. A good example of this is the Northern state where very large scale agricultural projects are currently being implemented using nonrenewable groundwater resources (Mukhtar, 2008). In the absence of a comprehensive strategy for groundwater development and lack of coordination between the various concerned government authorities, in addition to lack of in-depth studies on the impacts of these projects, their long term sustainability is questionable. One could mention here the example of the Ogallala aquifer in the USA where extensive unplanned groundwater abstraction for agricultural projects over the years has lead to excessive drawdown, higher pumping costs and deterioration in water quality, affecting the sustainability of most of those projects (Loucks & Gladwell, 1999).

A further most serious constraint impeding sound groundwater management is the absence of adequate quantitative and qualitative monitoring and scarcity of information on aquifers geometry and their hydrogeological characteristics .These are essential pre-requisites for any successful assessment, planning, design, operation and management of groundwater systems. Groundwater monitoring and water information system in Sudan had been very minimal and suffered huge deterioration over the years as a result of inadequate finance and capacity. This situation applies not only to sedimentary aquifers but also to fractured aquifers which cover very large areas and provide an important source of water particularly in rural areas. A major difficulty encountered in the management of fractured aquifers is the limited understanding of their hydrogeology and flow dynamics. The fractures characteristics could be extremely complex making it very difficult to locate areas of productive boreholes with sustainable groundwater yield. A further serious challenge is that related to the management of shared aquifer resources. Regional monitoring and agreements or formal frameworks for cooperation between the riparian countries, which are essential elements for managing shared aquifers, have not yet been well established. Groundwater contamination and deterioration of water quality has recently become a major problem particularly in urban areas where substantial loads of waste are inefficiently disposed into groundwater. Also agricultural and industrial chemicals pose serious threats that endanger the quality of groundwater. Decreasing rainfall trends in Sudan due to climate change and its negative impacts on aquifer recharge and sustainability of groundwater renounces is also a major challenge facing groundwater managers . Other key challenges facing groundwater management in Sudan are the lack of comprehensive guiding plans and policies, poor governance and legislative framework, inadequate capacity, and lack of coordination among groundwater sub sectors. All the above mentioned challenges are elaborated in the subsequent sections of this paper together with suggestions to overcome them.

2. Overview of Groundwater in Sudan

Major groundwater aquifers in Sudan cover about 65% of the surface area of the country (Figure 1). These aquifers fall under the following four categories (Salama, 1977, Salih & Khadam, 1994, and Khair & Salih, 1994): -

1. The Nubian Sandstone aquifers.
2. Um Rawaba formations.
3. The Recent alluvial wadi-fill aquifers, and
4. The Basement complex..

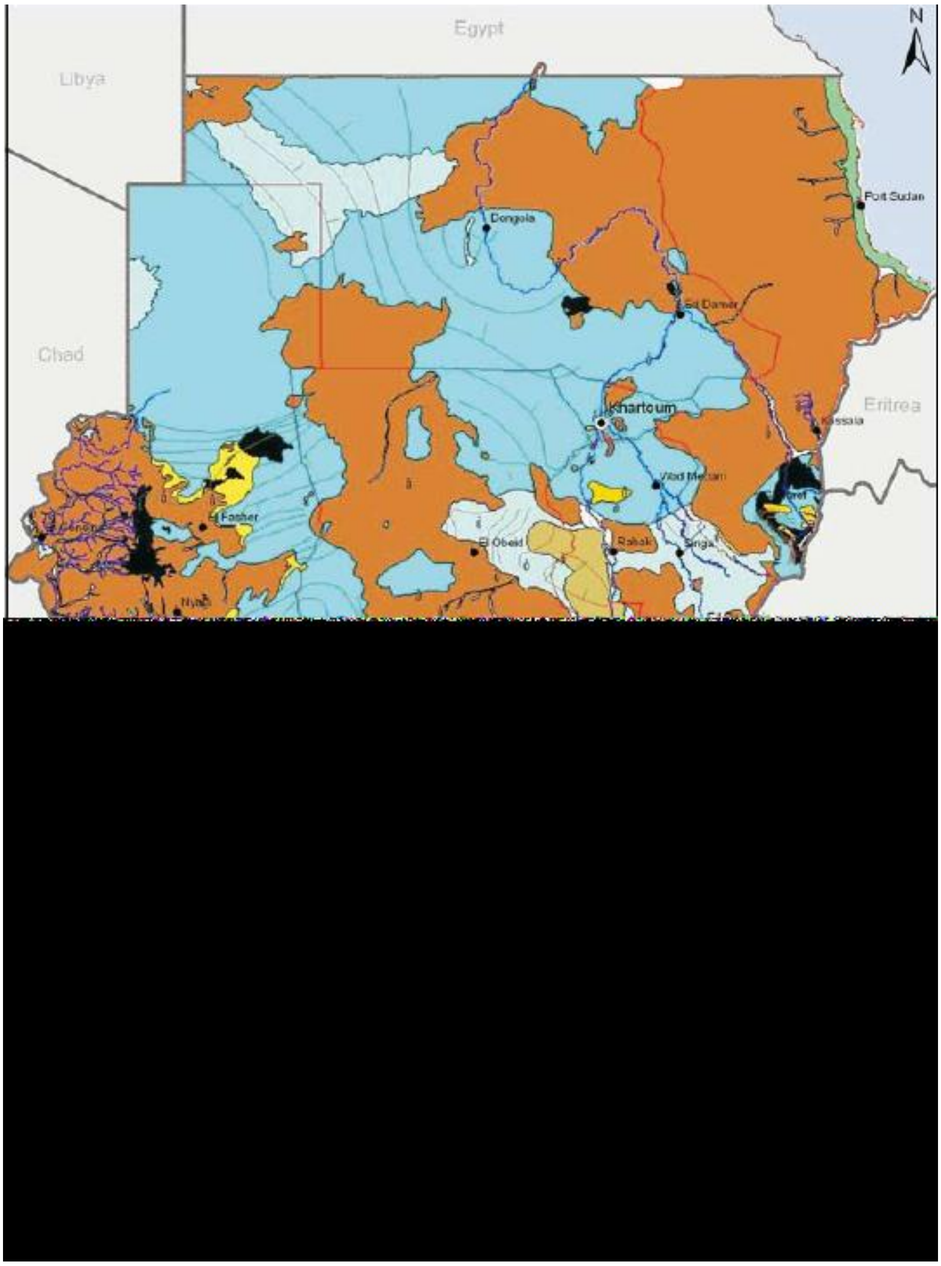


Figure (1). Hydrogeological Map of Sudan
(Please Note that this will be modified to exclude south Sudan)

Figure 1 shows the distribution of these aquifers over the Sudan. A brief summary of the aquifers and their characteristics are given below. It should be mentioned that quantitative estimates given in this paper are rather approximate. Many other estimates are available in the literature but they are all based on preliminary studies and limited scanty data. Considerable effort is still needed in order to arrive at definite accurate figures.

The Nubian Sandstone aquifers (NSA) are the most extensive and largest aquifers in Sudan. They cover about 37% of the surface area of the country. The NSA's are preserved in nine major basins, which are the Sahara basin, the Nile basin, Atbara basin, central Darfur basin, the Blue Nile basin, Nuhud basin, Gedaref basin, Sag El Naam basin and Shaggara basin. The productive strata of these aquifers vary in thickness ranging from 100 to 2000 m. The Nubian Sandstone aquifers are characterized by low to moderate permeabilities. The storage coefficient range from 10-2 to 10-4 and the well yield ranges from 40 to to 400 m3/h. The depth to static water level varies between 5 and 100 m . The aquifers are of semi-confined type. The water quality is good and generally fit for most purposes.

Environmental isotope studies have shown that water in these aquifers is mainly fossil water. However, some recent recharge occurs by infiltration from the River Nile system as well as from bed transmission losses of floodwater of seasonal streams and wadis. Some studies estimate annual recharge in the NSA in the range of 1000 Million m3/y (SNCIHP, 2000). The aquifers sustain present annual abstraction of about 700 Million m3/y without any noticeable drawdown.

The Um Ruwaba aquifers cover about 7% of the surface area of the country. They occur in three main basins: Bara basin, Atshan basin and Baggara basin.The strata is formed mainly of unconsolidated, gravels sands and clays. Aquifer thickness is very large, amounting to some three thousand meters. Groundwater occurs under free water table conditions in the recharge areas and under confined conditions at the centre of the aquifers, as in the case of Bara and Baggara basin. The transmissivity values range between 35 m2/day to about 2000 m2/day. Well yield is much lower than in the Nubian Sandstone aquifers and it ranges from 5 to 20 m3/h. The aquifers receive significant recharge from direct rainfall where there is sandy cover as in Bara Basin, and/or by transmission losses from the major rivers and wadis as in the case of Baggara basin. Total annual recharge and abstraction are estimated at 600 and 150 Million m3/y respectively .The Depth to static water levels varies from 10 to 150 m below ground level. The water quality is generally fit for domestic uses but tend to be saline in some areas.

The alluvial aquifers are relatively small but numerous, rich and of high local importance e.g. Gash, Azum, Wadi Nyala, Wadi Kutum, Arbaat … etc. The alluvial aquifers possess high permeabilities, moderate to high transmissivity values (500-1500 m2/day). and storativity values of 10-1 to10-2. The alluvial aquifers are annually fully recharged through bed transmission losses of seasonal streams and wadis. The total annual recharge of these aquifers is estimated at 375 M m3. The depth to the water table is shallow and usually varies between 2 and 15m. The well yield is moderate to high and ranges from 50 to 100 m3/h. The total annual abstraction is presently estimated at 160 M m3. The water quality of the alluvial aquifers is very good. Total dissolved solids rarely exceed 400 mg/l. The water is usually fit for all uses.

A summary of the estimated storage potential, annual recharge and abstraction for the above basins are given in Table 1. The estimates in the table are based on data from Salih & Khadam (1984) and SNCIHP (2000). As can be seen, current abstraction represents a small percentage of storage, and therefore there are large opportunities for developing groundwater resources for various purposes. Since almost all storage is considered as fossil water, care must be taken in developing these resources in order to ensure sustainability.

Table (1). Estimates of groundwater storage, annual recharge and abstraction for aquifers in Sudan (SNCIHP ,2000)

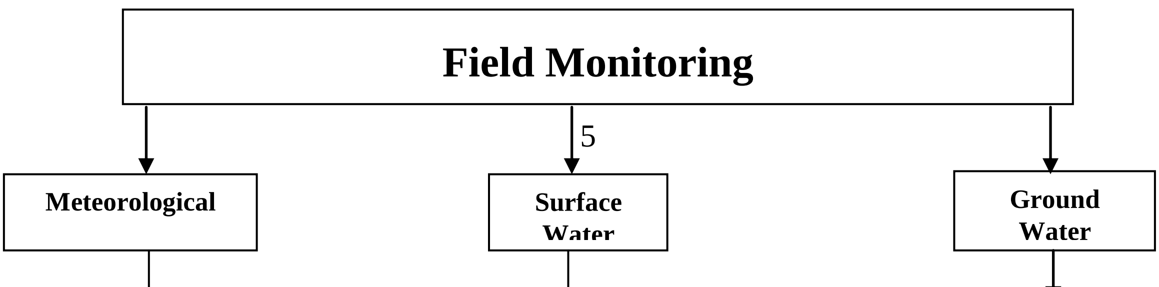
Major aquifer	Groundwater storage M m3	Annual recharge M m3	Annual abstraction M m3
Nubian sandstone basins	503,000	1000	700
Um Rawaba / Gezira basins	60,000	600	150
Alluvial	1,000	375	160
Total	564,000	1,975	1,010

Management Challenges and Recommended Actions

Lack of monitoring and adequate information base

The presence of adequate monitoring system is a pre-requisite for successful assessment, planning, design, operation and management of any water resources systems. Groundwater monitoring and water information system in Sudan had been very minimal and suffered huge deterioration in the past. This is mainly due lack of funds, inadequate capacity, and instability of the groundwater sector. There is no system of regular measurements and observations of groundwater levels, abstraction, groundwater quality as well as other relevant parameters, through well established monitoring positions designed and distributed aerially to provide adequate information for the various purposes mentioned above. This is a very serious constraint impeding research and in-depth studies required for groundwater development projects. In addition to the monitored parameters, the groundwater information base should contain other relevant and supporting data such as water use data, management base data, physiographic data, as well as previous and proposed groundwater projects. According to the author's knowledge such a comprehensive information base for groundwater is not available even for specific projects.

Ideally, a monitoring system should not be confined to groundwater measurements only. Surface hydrological variables should also be monitored in order to have a comprehensive hydrological information system (HIS). Figure (2) suggests the major components of such a system. This may look as the ideal and dream situation, but one would be realistic to suggest progress in phases linked to specific research projects recommended to be undertaken in future where monitoring could be included as an essential component. In designing the HIS, the system of monitoring wells to be proposed should be optimized using an appropriate optimization technique, in order to save time and financial resources. Methodologies to design an optimum groundwater monitoring system are discussed in Shakeel,et al (2008).



Limited understanding of major aquifers

In the past, research on water resources in Sudan has focused on the Nile water, whereas groundwater was not given the necessary attention. Scarcity of data and absence of monitoring and information base have been the main reasons contributing to this. Accordingly, hydogeologic boundaries of major aquifers, their flow dynamics, storage potential, recharge sources and recharge quantities are not yet accurately known. It is to be emphasized that effective planning, management and protection of groundwater resources can not be achieved without proper underatanding of the aquifer system, in addition to strengthening the capabilities of the groundwater authorities to implement monitoring activities, formulate information bases and conduct groundwater research and capacity building programmes. Figure (2) suggests an integrated modelling approach that could be used to understand the groundwater system and its linkage with surface hydrological processes (Wheater,2007)

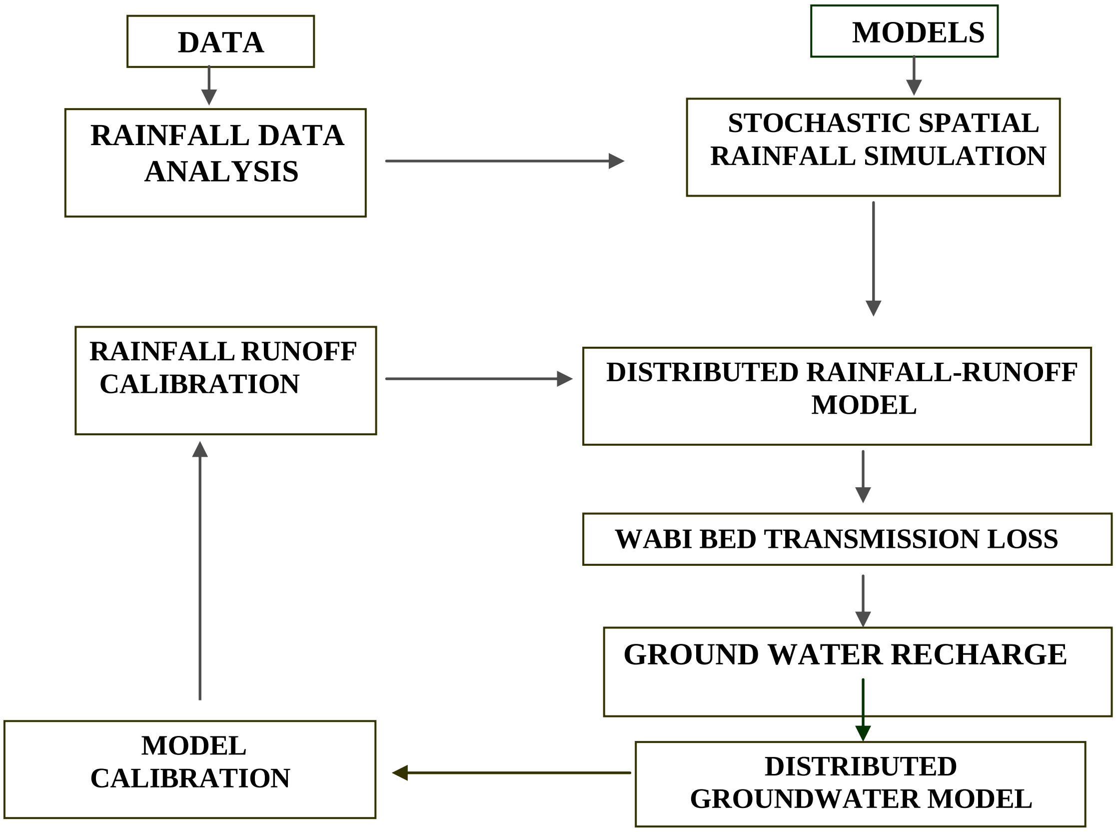


Figure (3). Integrated Modelling Approach for Surface and Groundwater Hydrological Processes (Wheater, 2007)

The Nubian sandstone aquifer extends over a huge area covering part of Sudan, Lybia, Egypt and Chad. Despite the large number of investigations that have been carried out in this aquifer, its lateral and vertical boundaries, its flow dynamics, the trans-boundary effects of groundwater development, as well as environmental impact assessment of development are not yet known and still require extensive investigations. The Um Rawaba formation has many problems facing its development. The most important of these is the complexity of its flow system due to the rapid facies change that causes local water stagnation and isolated small perched aquifers. This is why there are always large differences in the productivity of wells and water quality even though the wells are close to each others. With the current level of data availability, proper development and management are not possible. Concerning alluvial Wadi aquifers, technical issues such as high temporal and spatial variability of hydrological processes, surface and groundwater interaction, estimation of channel transmission losses and quantification of aquifer recharge are still not fully understood and they require in-depth studies and investigations. Better knowledge of these processes is a mandatory pre-requisite for sound management of Wadi alluvial aquifers. Management of fractured basement complex aquifers is also a particularly challenging issue. The analytical tools developed for homogeneous sedimentary aquifers are not directly applicable to heterogeneous and anisotropic fractured rock aquifer systems. It is recognized that flow through such a system is significantly influenced by the fracture characteristics. In such cases, it is difficult to apply the characteristics of hydraulic conductivity and storage coefficient as normally perceived for non fractured porosity aquifers. The rock itself has zero intrinsic permeability and the water occurs only in the fracture zones or in the weathered rock .The manner in which groundwater flow can occur is extremely complex. It is mainly controlled by the fractures or channels and essentially by the interconnections or connectivity of the channels which could be highly heterogeneous with different parameters in the different directions of flow. With such type of hydrogeological environment it is clearly essential to understand the flow mechanism and hence locate areas of more productive boreholes with sustainable groundwater yield. Significant advances have already been made in the management of fractured aquifers and various models have been proposed to simulate its behavior. For more details, the reader is referred to Shakeel,et al (2008).

Sustainable Management of Shared aquifer resources

Sustainable management of trans-boundary aquifers is an issue which is currently receiving considerable worldwide attention (UNESCO, 2001, UNESCO/ISARM, 2004). The most important shared aquifer in Sudan is the NSA which is shared between Sudan, Egypt, Libya and Chad, and the Um Ruwaba formation which has recently become a shared resource between Sudan and Southern Sudan. Such aquifers represent an invaluable resource of strategic importance for the socioeconomic and agricultural development, improved welfare, alleviation of poverty and improved food security. Trans-boundary sustainable management of shared aquifers is a major challenge, particularly for the NSA where groundwater is mostly non-renewable and often left to country based management and use; therefore there is a risk to impose high social and economic cost and incur loss of resources and benefits both at country and regional levels. To achieve sustainable management, efforts should be directed to promote regional cooperation and networking between riparian countries, develop regional agreements and implementation mechanisms, enhance institutional collaboration and joint decision-making regarding pumping policies, encourage joint studies and research programs for better understanding of the aquifer mechanism, strengthen monitoring networks and data information bases, and establish data exchange programs. Also there is a need to identify and agree on sustainability criteria especially with regards to non-renewable groundwater resources. Consideration should be given to important factors affecting sustainability such as hydrological, hydrogeological, social, economic and environmental factors. Mathematical models could be developed in which all these factors are integrated and mathematically represented into an overall model to achieve long term sustainability of non renewable groundwater resources (Loucks &Gladwell, 1999)

Vulnerability to pollution risk

In urban urban centers, inefficient liquid and solid waste disposal practices, pose serious environmental threat that endangers the quality of groundwater. Some recent studies and observations have indicated serious negative impacts. On-site disposal systems (septic tank + injection well, and pit latrines) are predominant. They are often poorly designed, located and constructed. Solid waste is either improperly dumped in the outskirts of cities, or left unattended. In such an environment, bacteriological contamination and other pollutants could readily find their way to groundwater. This is particularly true for many cities in Sudan since they mostly lie over shallow unconfined or semi-confined aquifers. Several studies to assess contamination have been conducted in western, eastern, northern and central Sudan. Results of chemical and bacteriological analysis of samples from a large number of boreholes within may towns show gross total and faecal colifirm bacteria, and/or Nitrate pollution (Abdel Gafar ,1999 and SNCIHP ,2000). Table 2 shows a summary of the results for some selected groundwater samples from supply wells in various regions. The results clearly show high levels of bacteriological and Nitrate contamination. This is to be expected since almost all disposal wells and pit latrines tap the groundwater table, and they are often located very close to production wells within a distance of 20 to 50 m.

Table (2). Results of bacteriological examination and NO3 for selected boreholes (Source: SNCIHP ,2000)

Well *	Region	Town	No3 mg/l	Bacteria Colonies /100 ml

No.				Total coliform	Faecal coliform
1	Western	Obaied	455	47	7
		Dilling	375	Uncountable	3
		Nyala	NA	14	10
2	Eastern	Kassala	19.8	40	5
		Gash	12.3	Uncountable	11
3	Northern	Dammar	NA	80	21
		Atbara	NA	36	23
4	Khartoum	Riyadh	NA	NA	37
		Burri	NA	NA	18
		Nasir	NA	NA	14

NA: Data not available *: Well number used by author

Industrial activities and increased industrial waste generation also impose a great risk on groundwter quality. Large industrial complexes exist such as fooad production, pharmaceutical, tobacco, plastic, fertilizers, asbestos, dry batteries and pesticides. The industrial waste can contain highly toxic compounds, heavy metals, radioactive materials as well as bacteria and viruses. The current procedure for industrial waste disposal in Sudan is endangering the groundwater resources. Recent studies have shown that the bulk of industrial wastewater is disposed of without treatment either in open fields as in Khartoum North Industrial area, or directly injected to groundwater (SNCIHP, 2000).

Likewise agricultural chemicals have their severe negative impacts on groundwater quality. The application of chemicals has recently intensified and introduced into many agricultural schemes and private vegetable and horticultural farms. A total of about 200 active ingredients are registered in Sudan in over 600 different formulations. Serious contamination has been detected in the Gezira scheme canals, as well as in some boreholes in Gezira and Kassala horticultural areas (SNCIHP, 2000) .

More recently, oil exploration and production, has imposed a major threat to the groundwater resources in Sudan due to the huge volume of produced water which is mixed with oil and which is often left to drain on the ground surface without treatment.

Capacity Development Challenges

Capacity development can be defined as the process by which individuals, organizations, institutions and societies develop abilities to perform functions, solve problems and set and achieve objectives (Lopes and Theisohn, 2003). It includes elements of developing competent human resources, providing sound institutional capacity and the creation of enabling environment. Figure (4) illustrates the levels, activities, outputs and goals of capacity development.

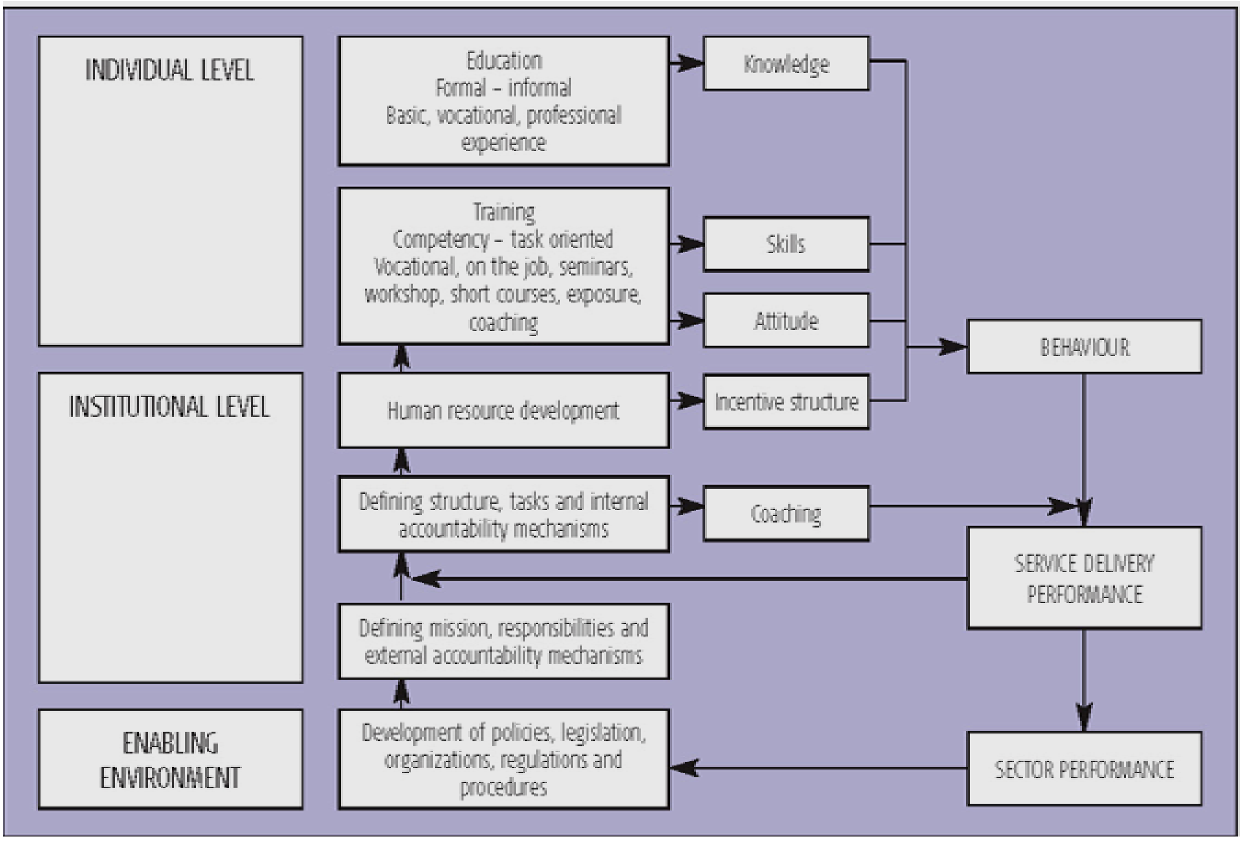


Figure (4). Capacity Development: Levels, Activities, Outputs and Goals
(The United Nations World Water Development Report, No.2)

In the developed world it was possible to couple large investments in infrastructures with capacity development and knowledge building. Unfortunately this is not the case in developing countries such as the Sudan, where meager financial resources represents a major constraint. As indicated previously there are great deficiencies in Sudan in both the knowledge Base (groundwater Information System) and the developed capacity to manage the groundwater resources of the country in a sustainable manner. This is clearly manifested in the inadequacy of data, human resources, institutional set-ups and enabling environment for good governance of the groundwater sector.
Recognizing the importance of capacity development, it is recommended to conduct a comprehensive capacity needs assessment exercise that should be undertaken as a perquisite to developing a project on capacity development in the groundwater sector in Sudan. Adequate financial resources should then be secured for the implementation of such initiative.

Institutional and legal challenges

Up to 1967 groundwater was treated as a mineral within the Geological Survey department. In 1967, a Groundwater Research Section was established within the Rural Water Corporation (RWC). In 1982, a Groundwater Research Directorate was established within the National Water Corporation (NWC). From 2000 onward, the Groundwater and Wadis Directorate was established in the Ministry of Irrigation and Water Resources and since then it became the main government institution entrusted with groundwater development and management in Sudan. As can be seen from the above historical development, the groundwater sector in Sudan has been highly unstable and suffered from many problems that make it rather inefficient and virtually paralyzed. Examples of these problems are limited budget allocation, institutional instability and diminishing capacity for groundwater monitoring, studies and research. Furthermore, there is no clear and comprehensive national groundwater policy and development plans. At present, groundwater development is taking place in a rather unplanned manner

i.e. only when and where need arises. Also there are many other institutions dealing with groundwater at national, state and local levels making authority mostly fragmented with no coordination and clear demarcation lines of responsibility. This often leads to conflicting actions and lower impacts of projects that could have given a much better return.
Regarding the legislative framework for groundwater development and protection in Sudan, there are many legislations and acts at national, state and local levels that could provide adequate coverage of all important groundwater management issues and protection aspects. Examples of these are the Environmental and Natural Resources Act (1991), the Water Resources Act (1995) and the Environmental Health Act (1995). However, in some cases there is duplication of responsibilities as the implementation is entrusted to different ministries resulting in inefficient enforcement of legislations for groundwater development and protection particularly with respect to alluvial aquifers. Furthermore, there is lack of basic logistics necessary for implementation of these legislations. Also there is a gap in legislations and laws related to groundwater development and management in shared aquifers. A big challenge therefore remains to develop mechanisms for allocating, managing and resolving disputes related to shared aquifer resources.

Advanced Tools for Groundwater Management

One of such important tools is groundwater modeling. Modelling has played and is playing a great role in groundwater resources assessment and management. Different types of models and their contribution to solving various groundwater management problems can be found in Abdo (2004). Groundwater modeling linked with GIS can provide an effective tool for spatial data preparation, manipulation, analysis and display of results. Such a system can also be used as a decision support tool for aquifer operation and management. Environmental isotopes have also been increasingly applied to solve many problems that are most critical to groundwater management. Results of isotope studies in Sudan have substantially contributed to estimation of groundwater recharge and identification of the sources of pollutants and their transport dynamics. Isotopes have also been used to improve understanding of the sources and origin of water, mapping of pales water and delineating and understanding the hydraulic interconnection between different aquifer units (Abdo & Khalafalla,2000). Application of climate change models to improve the limited understanding of the relationship between climate change and groundwater resources is an area which is receiving considerable attention worldwide. There has been almost no studies in this area in Sudan and therefore there is an urgent need to promote scientific interdisciplinary research among hydrogeologists, climate scientists as well as physical, social, and health scientists regarding the relationship between groundwater and climate change;

Case study: Contamination transport Modelling in Khartoum State aquifer

The present case study considers groundwater contamination in Khartoum State, Sudan resulting from on-site sanitation systems. The main sewage disposal system in residential areas is septic tank and disposal well draining directly in the upper aquifer zone. As the aquifer is unconfined or semi confined in nature, it is susceptible to Pollution. Recently signs of pollution have appeared in a number of supply wells in the State, with the result that some of these wells had to be excluded from the supply network. Examples of residential areas where bacteriological contamination have occurred are Riyadh, Burri and Imtidad Nasir. (Abdel Gafar, 1999). In a later study, chemical analysis also revealed high concentrations of Ammonia, total dissolved solids and heavy metals such as Zn and Fe (Amal et al, 1999). The objectives of this study is to develop a groundwater flow and contaminant transport model using Visual MODFLOW (WHS,1998) software in order to assess the future effect of pumping and directions of flow. Accordingly, the model is used to determine the future extent of pollution and contamination migration. Based on the findings from this study, recommendations for short and long term actions for groundwater protection are given.

The developed model includes major areas in Khartoum,Omdurman and Khartoum North . The main aquifer modeled is sandstone but the top layer contain pockets of claystone and mudstone of various horizontal and vertical extents. Groundwater recharge is assumed to take place from the Nile River only. Recharge from rainfall is considered to be insignificant. One pollutant is considered in this study, which is Ammonia (NH_4^+). It has been modelled as a point source pollutant. In simulation, Ammonia is assumed to be injected at a depth of 30 m below ground surface in first class residential areas, as well as in other areas such as the industrial areas of the three towns. Average Ammonia concentration has been determined as 60 mg/l, by analyzing samples taken from the second chamber of some selected septic tanks. This represents the last stage of treatment after which wastewater is introduced in to the aquifer. Due to limitations in the data, chemical reaction of Ammonia as it moves through the aquifer is not simulated. It is assumed that the flow of Ammonia with groundwater takes place under anaerobic conditions, and therefore chemical reactions are neglected. According to the results obtained, a maximum drawdown of 27 m above the present level will occur in Khartoum area after 30 years of simulation. The water balance results show that the recharge from the Nile is not as high as it is thought to be and represents only about 25% of the abstraction. The remaining percentage is taken from aquifer storage causing such a high drawdown. The results also show that Ammonia contaminant would migrate vertically up to a depth of 240 m in 30 years with concentration higher than the allowable. Figure (5) shows the

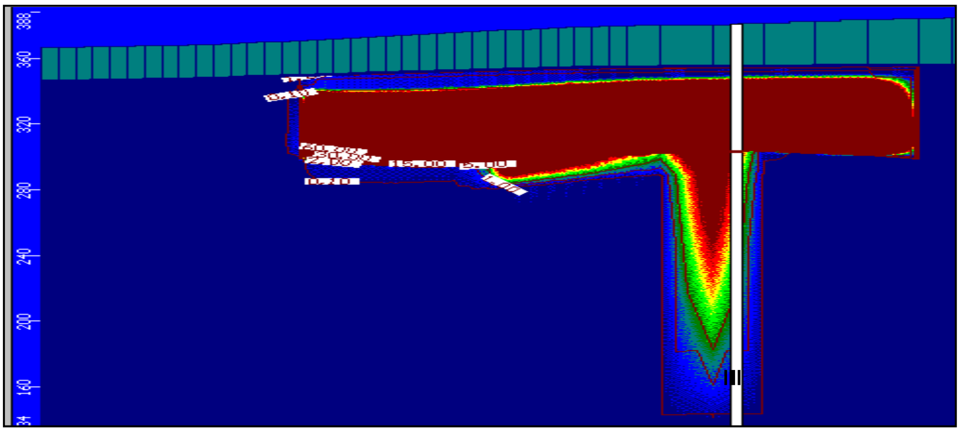


Figure (5). Expected Ammonia concentration after 30 years for a borehole in Khartoum

distribution of Ammonia concentration near an existing well in Khartoum. It can be seen that Ammonia will migrate up to the depth of well screen position in 30 years leading to well contamination.

Conclusion

Sudan enjoys considerable groundwater resources, which will be the governing factor in the development of many areas of the country. However, scarcity of data on groundwater, lack of monitoring and lack of reliable and coherent information base are major constraints impeding effective assessment, development and management of groundwater resources. Other constraints include lack of clear comprehensive groundwater policy and development plans, inadequate capacity and week institutional and legal frameworks for groundwater management and protection. This is a rather serious and alarming situation. Unfortunately, efforts to rectify the situation are minimum and are not keeping pace with the increasing demand on groundwater and the existing environmental hazard that endangers the sustainability of this resource. Government commitment to provide the required funds to the authority entrusted with groundwater management is of extreme importance so that it can conduct its mandated activities more efficiently. Collaboration with universities and research institutes in groundwater research and capacity building should be encouraged and will certainly contribute to the optimum and sustainable development and management of groundwater resources of the Sudan.

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