Eastern Nile Subsidiary Action Program

Groundwater Availability and Conjunctive Use Assessment in the Eastern Nile

Country Report - Sudan

October, 2019
Addis Ababa, Ethiopia
Nile Basin Initiative (NBI)
Eastern Nile Subsidiary Action Program (ENSAP)
Eastern Nile Technical Regional Office (ENTRO)

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<th>Definition</th>
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<tbody>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DIU</td>
<td>Dams Implementation Unit</td>
</tr>
<tr>
<td>DTM</td>
<td>Digital Terrain Model</td>
</tr>
<tr>
<td>DWSU</td>
<td>Drinking Water and Sanitation Unit</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
</tr>
<tr>
<td>EIA</td>
<td>Environmental Impact Assessment</td>
</tr>
<tr>
<td>EN</td>
<td>Eastern Nile</td>
</tr>
<tr>
<td>ENTRO</td>
<td>Eastern Nile Technical Regional Office</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GWWD</td>
<td>Groundwater and Wadis Directorate</td>
</tr>
<tr>
<td>IWPS</td>
<td>Integrated Water Policy Strategy</td>
</tr>
<tr>
<td>IWRM</td>
<td>Integrated Water Resources Management</td>
</tr>
<tr>
<td>MCM</td>
<td>Million Cubic Meter</td>
</tr>
<tr>
<td>IWR</td>
<td>Ministry of Irrigation and Water Resources</td>
</tr>
<tr>
<td>MWRE</td>
<td>Ministry of Water Resources and Electricity</td>
</tr>
<tr>
<td>MWRI</td>
<td>Ministry of Water Resources and Irrigation</td>
</tr>
<tr>
<td>MWRIE</td>
<td>Ministry of Water Resources, Irrigation and Electricity</td>
</tr>
<tr>
<td>NCS</td>
<td>National Comprehensive Strategy</td>
</tr>
<tr>
<td>NCWR</td>
<td>National Council for Water Resources</td>
</tr>
<tr>
<td>NRWC</td>
<td>National rural Water Corporation</td>
</tr>
<tr>
<td>NWC</td>
<td>National Water Corporation</td>
</tr>
<tr>
<td>NWP</td>
<td>National Water Policy</td>
</tr>
<tr>
<td>PWC</td>
<td>Public Water Corporation</td>
</tr>
<tr>
<td>QCS</td>
<td>Quarter Century Strategy</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Terrain Mission</td>
</tr>
<tr>
<td>SWC</td>
<td>State Water Corporation</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Solids</td>
</tr>
<tr>
<td>TOR</td>
<td>Terms of Reference</td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations, Educational, Scientific and Cultural Organization</td>
</tr>
<tr>
<td>UNICEF</td>
<td>United Nations Children Fund</td>
</tr>
<tr>
<td>WAPS</td>
<td>Water Resources Assessment Program in Sudan</td>
</tr>
<tr>
<td>WASH</td>
<td>Water Sanitation and Hygiene</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

Sudan is endowed with considerable groundwater resources with more than 50% of the surface area of the country underlain by groundwater. This estimate also applies to the areas of Sudan within the Eastern Nile Basin which is the study area of this report. The aquifers of Sudan and those within the study area can be classified into four categories according the dominant aquifer formation. These are:

- The Nubian Sandstone Aquifers
- The Umm Ruwaba Formation Aquifers
- The Recent Alluvial Wadi-fill Aquifers
- The Basement Complex Aquifers

The Nubian Sandstone Aquifers are the most prevalent in the study area as they cover about 33% of its surface area, while the Umm Ruwaba formation cover about 13%. Alluvial aquifers occur within the deposits of the natural drainage systems. They comprise shallow aquifers of good quality water. These aquifers are significant in areas underlain by basement rocks as they provide a reliable source of water for the communities around them. This study focuses on the large sedimentary aquifers in the Eastern Nile basin within Sudan and will not address the numerous alluvial aquifers in the study area.

Six main groundwater basins were identified within the study area and while three of them are fully contained within the Eastern Nile Basin area within Sudan, the other three are transboundary aquifers that extend beyond the study area and into other countries. A summary of the main features/characteristics of these basins is given in Table 0-1.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Estimated Area (Km²) in Study Area</th>
<th>Dominant Water Bearing Formations</th>
<th>Estimated Annual Abstraction Mm³/year</th>
<th>Main Recharge Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>86,000</td>
<td>Nubian Sandstone</td>
<td>1</td>
<td>No appreciable Recharge</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>160,000</td>
<td>Nubian Sandstone</td>
<td>1,460</td>
<td>River Nile</td>
</tr>
<tr>
<td>Atbara</td>
<td>32,000</td>
<td>Nubian Sandstone</td>
<td>100</td>
<td>River Nile</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>76,000</td>
<td>Nubian Sandstone / Umm Ruwaba</td>
<td>490</td>
<td>Blue Nile</td>
</tr>
<tr>
<td>Gedaref</td>
<td>22,000</td>
<td>Umm Ruwaba / Basement</td>
<td>19</td>
<td>Inter-basin flow from the Ethiopian part of the Basin</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>68,000</td>
<td>Umm Ruwaba</td>
<td>100</td>
<td>Surface runoff generated from local precipitation</td>
</tr>
</tbody>
</table>

The total annual abstraction from the groundwater aquifer within the study area is about 2.2 billion m³ per year more than 65% of which is from the Nubian Nile Basin. Groundwater abstraction for irrigation purposes account for about 99% of the total abstraction.
Three of the six basins are fully contained within the boundaries of the Eastern Nile Basin namely (Nubian Nile, Atbara and Blue Nile groundwater basins), while the other three are transboundary aquifers extending to other countries and in the case of the Nubian Sahara beyond the Nile Basin as a whole. Maps and information showing the geology, groundwater flow patterns, depth to water, salinity and recharge sources were prepared for the six basins were prepared as part of this study.

During it recent history, Sudan has put a lot of emphasis on the development of its Nile waters, with little attention paid to groundwater resources. The use of groundwater was confined to the provision of domestic supply and the supplementary irrigation of small-scale agricultural projects. There was no strain on the groundwater resources and little attention was paid to the research, exploration, planning and management of these resources.

The available data pertaining to the six major identified basins within the study area were compiled during the course of this study. Data pertaining to groundwater abstraction quantities were generated in part from the analysis of remote sensing data. The available data was used to map and characterize the six basins. The compiled data included, Geological Data (maps, reports, etc.), Hydrogeological data (Water Level data, Water quality data, depth to basement data, lithology data, Isotope analysis, Hydraulic properties, etc.), Development and Management data. The available data differs from one aquifer to another in terms of detail, quality and extent of coverage.

While a significant number of exploratory studies and investigations were conducted within the six basins, the collected data and information is scattered among old reports without the existence of an adequate information database. Recently a large effort was conducted to enter point data pertaining to well observations into spatial databases, which facilitates the analysis of the existing point data to ascertain trends and determine the spatial variation of some parameter such as water level and quality. The case is different for old maps and observations particularly those related to geological observations. A rudimentary analysis of the quality of available data for the six basins considered in this study is presented in Tables 0-2,0-3,0-4 & 0-5 for the purpose of identifying the gaps in the data needed for the characterization of each aquifer.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>General Geological map of Sudan, semi detailed geological description of the different formations and the geological features in the basin using general location.</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>General Geological map of Sudan, Semi detailed geological description of the different formations and the geological features in the basin using general location.</td>
</tr>
<tr>
<td>Atbara</td>
<td>General Geological map of Sudan, Very general geological description of the different formations in the basin</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>General Geological map of Sudan, Semi-detailed geological description of some of the formations and geological features in limited parts of the basin.</td>
</tr>
<tr>
<td>Gedaref</td>
<td>General Geological map of Sudan, Very limited geological description of the geological features</td>
</tr>
</tbody>
</table>

Table 02: Geological Data
<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Kordofan</td>
<td>General Geological map of Sudan, general geological description of the different formations in the basin</td>
</tr>
</tbody>
</table>

### Table 03: Hydrogeological Data - Groundwater Inventory and Monitoring System

<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>- No Groundwater monitoring system,&lt;br&gt;- very limited groundwater level measurements in terms of extent and accuracy, groundwater levels are interpolated using regional groundwater measurements.&lt;br&gt;- Very Limited/Insufficient groundwater quality data to ascertain general salinity or water quality trends.</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>- Groundwater monitoring system covering about 30% of the Basin area, monitoring system only intermittingly operated due to budget constraints,&lt;br&gt;- Sufficient groundwater level measurements in terms of extent and accuracy generate general groundwater level maps.&lt;br&gt;- Sufficient water quality measurements to determine very general water salinity trends.</td>
</tr>
<tr>
<td>Atbara</td>
<td>- No Groundwater monitoring system,&lt;br&gt;- limited groundwater level measurements in terms of extent and accuracy, groundwater levels are interpolated using regional groundwater measurements.&lt;br&gt;- Limited groundwater quality data can be used nevertheless with other maps and soft data to approximately locate saline regions.</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>- No formal Groundwater monitoring system.&lt;br&gt;- Single Low accuracy groundwater level measurements from new wells cover about 70% of the Basin area, temporally inconsistent data can be used to establish groundwater flow trends.&lt;br&gt;- Sufficient yet temporally inconsistent water quality measurements can be used to determine general water salinity trends.</td>
</tr>
<tr>
<td>Gedaref</td>
<td>- No formal Groundwater monitoring system.&lt;br&gt;- Spatially limited single Low accuracy groundwater level measurements from new wells can be used with other soft data to establish average depth water within basin.&lt;br&gt;- Spatially limited and temporally inconsistent water quality measurements can be used to determine general water salinity trends.</td>
</tr>
<tr>
<td>Basin</td>
<td>Data Status</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>- Groundwater monitoring system covering about 50% of the Basin area, monitoring system disbanded due to budget constraints,</td>
</tr>
<tr>
<td></td>
<td>- Sufficient groundwater level measurements in terms of extent and accuracy to ascertain groundwater flow trend.</td>
</tr>
<tr>
<td></td>
<td>- Sufficient water quality measurements can be used to determine very general water salinity trends and water quality maps over about 50% of the aquifer extent.</td>
</tr>
</tbody>
</table>

**Table 04: Hydrogeological Data – Aquifer mapping and Hydraulic Properties**

<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>- Insufficient depth to basement data and/or maps</td>
</tr>
<tr>
<td></td>
<td>- Virtually no local pumping tests results to estimate and map hydraulic properties.</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>- Limited depth to basement data and/or maps</td>
</tr>
<tr>
<td></td>
<td>- Results of a number of pumping and recovery tests including limited proper pumping tests exist and can be used to prepare a general and spatially limited map of hydraulic properties.</td>
</tr>
<tr>
<td>Atbara</td>
<td>- Insufficient depth to basement data and/or maps</td>
</tr>
<tr>
<td></td>
<td>- Results of very limited number of pumping tests in terms of number and spatial extent, data insufficient to generate hydraulic property maps.</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>- Limited depth to basement data and/or maps</td>
</tr>
<tr>
<td></td>
<td>- Results of a number of pumping and recovery tests within the different formations of aquifer exist thus allowing for the estimation of the range of Transmissivity of the different aquifer layers.</td>
</tr>
<tr>
<td>Gedaref</td>
<td>- Insufficient depth to basement data and/or maps</td>
</tr>
<tr>
<td></td>
<td>- Results of very limited number of pumping tests in terms of number and spatial extent, data insufficient to generate hydraulic property maps.</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>- Limited depth to basement data and/or maps</td>
</tr>
<tr>
<td></td>
<td>- Results of a number of pumping and recovery test including a proper pumping tests exist and can be used to prepare a range of values of hydraulic properties.</td>
</tr>
</tbody>
</table>
It is evident that there are a number of factors that constrain the effective management of groundwater resources in Sudan in general including the groundwater basin within the Eastern Nile Basin. Some of factors that constrain the development and utilization of groundwater are related to the lack of the necessary data as well as the limited understanding of the aquifers dynamics these include:

- Poor groundwater information database in terms of data quality and the ability to readily consolidate data for the purpose of planning and management.
- Lack of the basic hydrogeologic data required to adequately map the aquifer and plan its development. This may include: Detailed geological data, lithology data, values of hydrogeologic parameters, recharge rates, Water level data, water quality data…
- Absence of the monitoring system necessary to fully ascertain water level and water quality as well as the behavior of the water table to pumping and recharge.
- Lack of information about end user current and projected needs.
- Poor connection and coordination with decision makers and planners to adequately plan or implement projects relying on groundwater (e.g. Agricultural Expansion).
- Poor public awareness about the susceptibility of groundwater resources to depletion and contamination.

The obstacles and challenges to the development and implementation of effective management plans for groundwater resources are not only technical, rather they include organizational, institutional and legal factors.
It can be argued that there is no shortage of policies, plans and regulations pertaining the management of groundwater within Sudan. The policies related to groundwater development are well developed and included in the all the recent water strategies of Sudan. Bylaws pertaining to the regulation and licensing of groundwater development were passed in 2108. What may be lacking is the establishment of the mechanisms and protocols needed to enforce the existing laws. Institutional reform is needed within the Groundwater Directorate, the agency responsible of managing the groundwater resources within the Ministry of Irrigation Water Resources and Electricity in Sudan. Some of the challenges that this agency faces and need to address include:

- Diminished capacity to conduct exploration and aquifer assessment research activities due to shortages in qualified and trained staff, equipment and tools as well the budget limitations.
- Lack of coordination and conflicting responsibilities of other MIWRE departments.
- Poor linkage and cooperation with other institutions working in the groundwater research and development sector (e.g. research centers, universities, drilling companies), as well as agencies in other sectors related to groundwater (e.g. Petroleum Industry)
- Lack of well-developed training and capacity building plans
- Absence of a well-developed and detailed working plans for conducting research and achieving set goals.

There are a number of factors that are currently negatively impacting the performance of the intuitions working in the groundwater development and management sector. The most prominent of these however appears to be the lack of coordination and comprehensive national management plan that determines a set realistic goals and objectives and consolidate all the available resources thereafter to formulate and achieve these objectives.
1. INTRODUCTION

1.1. Overview

This report was prepared for the Eastern Nile Technical Regional Office (ENTRO) headquartered in Addis Ababa, Ethiopia for the study entitled “Ground Water Availability and Conjunctive Use Assessment in the Eastern Nile”. The study which is implemented by ENTRO falls under the Nile Cooperation for Results Project (NCORE) funded by the World Bank NCORE Additional Financing 2 (NCORE AF2).

The Nile Basin countries has relied for a long time on the surface water resources to provide for their water demands. Indeed, the first human civilizations have been established within the Eastern Nile Basin and flourished for thousands of years on the abundance and reliability of surface water resources in the region. The development of groundwater resources through shallow wells was also practiced in the region with a limited scale. Groundwater was historically used for the provision of drinking water. However, in modern times groundwater has been increasingly tapped for the provision of domestic supplies as well as for small scale irrigation.

During the last fifty years the communities of the Eastern Nile have witnessed an increased shortage in surface waters. This is attributed to several factors including population increase, rapid urbanization and economic development as well as climate change. In its endeavour to satiate the increasing shortages of surface water, the Eastern Nile Countries are increasingly resorting to the exploitation of their groundwater resources.

Groundwater is the most abundant freshwater source on earth, it is a reliable source of perennial good quality water. Nevertheless, it is a hidden resource which must be explored and well mapped before it can be exploited in an effective and sustainable fashion. Water bearing geologic formations are known to cover most of the area of the Eastern Nile Countries. However, the groundwater resources within these formations are not well measured in terms of quantity or quality which hampers the efforts to plan for the effective development and utilization of this valuable resource. Information pertaining to the availability, quantity and quality of groundwater within the Eastern Nile countries is scarce and fragmented. Furthermore, the limited available data is scattered among different institutions in the four Eastern Nile Basin countries. These institutions lack the coordination effort necessary to assemble this valuable yet limited data into a useful groundwater database that can be used to further explore and manage the groundwater resources at the country or regional level.

The sustainable development and management of groundwater resources within the Eastern Nile requires the consolidation of all the existing data relevant to groundwater resources in one database repository. The data consolidation will facilitate the assessment of existing data and enable the identification of data gaps. Effective integrated plans for the further exploration and monitoring of groundwater resources can be subsequently prepared. The integrated data in the repository can also be used to conduct a comprehensive assessment of the potential of the groundwater basins within the Eastern Nile countries, and effectively plan their future development. The benefit of the data consolidation process will be extremely useful in the case of transboundary groundwater basins where the coordination, information
and knowledge sharing between the respective countries will be of paramount significance for the equitable and sustainable use of the shared resource.

### 1.2. Scope & Study Objective

This study seeks to develop a comprehensive understanding of the groundwater resources within the Eastern Nile Sub-basins and to generate a baseline data for these resources. The specific objectives of the study were cited in the terms of reference are as follows:

1. To make an assessment of the existing and readily available knowledge of groundwater resource potential in the Eastern Nile that includes characterization, mapping, recharge and safe yield.

2. Using already existing information to initiate the establishment of a comprehensive groundwater database in the Eastern Nile. This database can further be expanded as more data and information became available.

3. Harmonize groundwater monitoring practice between Eastern Nile countries.

4. Start a process to initiate and facilitate future inclusion of groundwater considerations into national and transboundary Eastern Nile water resources planning and management activities.

5. Establish a common understanding of groundwater policies, institutional issues and data and capacity gaps in the Eastern Nile riparian countries.

The scope of work covered in this report is limited to the groundwater resources within the parts of Sudan within the Eastern Nile. The geographic extent of the study area was explicitly stated in the terms of reference as limited to the four sub-basins of Eastern Nile i.e. the Abbay- Blue Nile, the Tekeze-Atbara, the Baro-Akobo-Sobat and the Main Nile in any of the four Eastern Nile countries of Egypt, Ethiopia, South Sudan and Sudan. In each of the four countries the study will be limited to the aquifers that fall partially or totally in the catchment of one of the four Eastern Nile sub-basins.

### 1.3. Geographic Extent

The total area of the Nile basin is about 3,176,500 Km² covering areas within 11 countries (Burundi, DR Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda). The Eastern Nile Basin comprises about 62% of the Nile Basin with an area of 1,958,993 Km² covering only four of the 11 Nile Basin countries namely (Egypt, Sudan, South Sudan and Ethiopia).

Sudan is the largest country of the four Eastern Nile countries in terms of total area (Area ≈ 1,864,049 Km²) as well as area within the basin with about 75% and 45% of its total area within the Nile Basin and Eastern Nile respectively (Figure 11).
Figure 1.1: Geographic Extent of the Study Area
2. GEOLOGY OF THE EASTERN NILE BASIN

2.1. Climate

The climate of Sudan can generally be characterized as arid climate in the northern part to a semi humid climate in the southern part. Rainfall occurs during the summer period commencing in May in the southern part and progresses northwards. Maximum rainfall occurs in August and thereafter decreases coming to an end in November. Analysis of rainfall data for the area of Sudan within the Eastern Nile reveal that the average annual rainfall progressively diminishes from more than 700mm in the south of the area to less than 10 mm in its northern tip (Figure 2.1). Maximum and Minimum daily temperatures vary according to the month of the year and location, the average maximum temperature is about 45 °C while the minimum is about 10 °C (Figure 2.2 and Figure 2.3).

2.2. Topography & Drainage

The relief of Sudan is generally dominated by the River Nile as it traversers the country from South to North. The country is predominately flat with widely separated mountain chains areas in the western and eastern parts of the country and many hilly areas in various parts within it. The topography of the Sudan within the eastern Nile Basin is bounded by the ridged and steep topography of the eastern, western and southern parts of the country, it engulfs the flat centre of the country along the path of the River Nile and its tributaries and the undulated north.

The topography of Sudan within the eastern Nile watershed is relatively flat decreasing from about 1500 m to about 180 meters above sea level with a gentle slope in the north-west direction as shown in Figure 2.4.
Figure 2.1: Annual Rainfall Distribution in the Eastern Nile Region in Sudan
Figure 2.2: Average Minimum Temperature Distribution in the Eastern Nile Region in Sudan
Figure 2.3: Average Maximum Temperature Distribution in the Eastern Nile Region in Sudan
Figure 2.4: Topography of the Eastern Nile Region in Sudan
2.3. Geology

The area of the Eastern Nile basin within Sudan is underlain mostly by the Nubian Sandstone Formation, the main geological units of this area of Sudan can be itemized from youngest to the oldest as follows:

- **Sand, Alluvium, Playa and superficial deposits**
- **Um Rwaba formation**
- **Volcanic Rocks**
- **Hudi-Chert Formation**
- **Abyad Formation**
- **Nubian Sandstone Group**
- **Basement Complex**

**Quaternary – Cainozoic**

- **Late Tertiary Pleistocene – Cainozoic**

- **Tertiary – Cainozoic to early Mesozoic**

- **(upper Cretaceous) to Cambrian - Mesozoic to Paleozoic**

- **Pre-Cambrian to Cambrian**

**Basement Complex (Pre-Cambrian to Cambrian)**

Basement rocks are composed of a Precambrian composition including gneisses, migmatites, granulites, quartz veins and pegmatites. Basement rocks cover about 50% of the area of the Eastern Nile Basin that lies within Sudan and are localized primarily in the Eastern and South western parts of the country. The basement rocks are composed of two main complexes; The lower complex which is located for the most part west of the Blue/ River Nile, it consists of quartz, feldspate and amphibole gneiss with quartzites, micaschists, marbles in elongated bands, amphibolites in lenses, invasions of gabbroid rocks and a general invasion of batholithic granite.

The higher (younger) complex known as “Greenschist complex” consists of oceanic basalt, andesite, rhyolite and ophiolites of greenschists metamorphic grade. The lower complex dips under the higher one along an irregular contact near the Nile, more or less along the 33° E meridian.

The hydrogeological significance of the Basement rocks is that they are considered as impervious bedrocks over which all other younger sediments had been deposited. Basement configuration largely affects depth to groundwater, and controls groundwater movement, and hence groundwater quality.

Although Basement rocks are virtually impermeable, water occurs locally in the weathered and fissured zones. The bedrock is dissected by numerous lineaments mostly faults and basaltic dykes some of which transport groundwater to the surface.

**Nubian Sandstone Group ((upper Cretaceous) to Cambrian - Mesozoic to Paleozoic)**

The Nubian Sandstone formation is the most important sedimentary deposit in Sudan due to its wide geographical distribution within the country and its water bearing characteristics. It is composed of sandstones, mudstones, shale, siltstone, inter-formational conglomerates and conglomerates. The term Nubian Sandstone Formation include several Formations that are known to exist within the Eastern Nile boundary inside Sudan, the most significant of these formations in the order of descending age include:
Lakia Formation; (Permo Triassic to Jurassic Period)

The formation consists mainly of medium to coarse-grained kaolinitic sandstone that forms a large east west striking basin in the north western part of the study area. The fluvial succession attains a thickness of up to 240 m and exhibits an increasing amount of mudstone and horizontal and cross laminated fine-grained sandstone in the upper parts.

Wadi El Milk Formation (Cretaceous)

Wadi El Milk Formation is the dominant rock type, in the areas extending from the northern part of Khartoum state up to the extreme north of Sudan. It consists of medium to coarse – grained sandstone, siltstones, interbedded sandstones and intercalated mudstones. Due to the continental depositional environment, the formation shows great vertical and lateral variability originated by cyclical deposition of fluvial lacustrine environments of limited extension and under increasing subsidence within the indicated graben structure (Klitzsch, 1990). The formation attains may attain thickness up to 350 m.

Lithological description indicated three units within El Melek Formation:

Unit (1) overlies unconformably the Basement and consist of pebbly sandstone, conglomerates, and sporadically intercalating siltstone. It crops out north of Dongola area along the River Nile where it unconformably overlies the granitic basement.

Unit (2) comprises up to 110 m of medium grained sandstone which represent in general the major sandstone sequence and is underlain by unit (1) or Basement.

Unit (3) represents the upper most layer and it consists of poorly sorted medium to coarse grained sandstone.

Wadi Howar Formation (Cretaceous)

The Wadi Howar Formation was first described by Klitzsch (1984). It mainly consists of medium to coarse-grained fluvial sandstones, attributed to low sinuosity braided rivers and intercalated paleosols. The base of the formation is characterized by a thin conglomeratic layer of quartz pebbles.

In some areas the Wadi Howar formation rests unconformably on basement of Middle to late Proterozoic age. In the Wadi El Milk area, the wadi Howar formation unconformably overlies the Wadi El Milk formation which can be seen at Gebel Nagashush in northern Kordofan.

At the southern rim of Gebel Abyad Plateau in the North West part of the project area (North of latitude 18°N and 160 Km west of ElBaja), the wadi Howar formation is overlain by the Kababish Formation as it extends eastward toward the Dongola area. The succession attains thicknesses of 50 -150 m

Kababish Formation (Cretaceous)

The locality of this type of formation is the Jebel Abyad plateau lying in the northwest region of the study area where it lies unconformally over the Howar Formation.

According to well log data, the Kababish sediments are predominantly composed of siltstones, mudstones, and fine grained sandstones. Gravelly, coarse ill-sorted layers can be found in the upper part of the formation. The thickness of the Kababish Formation varies from 30 to around 120 meters
The thickness of the Nubian sandstone formation ranges from few meters in the proximity of basement complex outcrops to thicknesses of about 500 meters. Grabens within the Nubian group may have thicknesses in excess of 2000 meters.

**Tertiary – Cainozoic to early Mesozoic**

- **Cenozoic Rocks (Tertiary)**

  Basaltic volcanos and related intrusions can be found in different areas Sudan. Tertiary volcanic rocks, predominantly basalts are exposed in Northern Sudan, Western Sudan, Eastern Sudan as well as in the eastern corner of Sudan, adjoining the Ethio-Sudan Corner. The most extensive volcanic fields in Sudan lies on the Darfur Dome in Western Sudan beyond the boundaries of the Eastern Nile Watershed and comprises the Meidob Hills area and the Jebel Mara Complex. Between these field remnants of lava flows, plugs, vents, and craters can be found. Estimates indicate that the Jebel Marra volcanic complex covers an area of 13,000 Km2 with a calculated erupted volume of the order of 8000 Km3. (Bermingham, et al., 1983).

  Within the Eastern Nile boundary in Northern Sudan tertiary volcanic rocks are exposed along the main Nile. Remnants of volcanic sills appear on the surface north of Khartoum, within Bayuda desert and North of Dongola towards the Sudanese Egyptian border. These fields are believed to be the result of small eruptions from hundreds of centres involving small volumes of magma from each centre. The overall erupted volume is estimated to be less than 5% that of Jebel Marra.

  Whereas small isolated basalt occurrences and minor volcanic fields are common in the Northern part of Sudan, the basalts of the Gedaref area in eastern Sudan are a result of significant tertiary magma flows into a tectonic depression filled with continental deposits. While exposed in the eastern corner of Sudan adjoining the Ethio-Sudan Border, the basalts of the Gedaref area are less well exposed and more deeply weathered than those of Northern Sudan. The Gedaref basalt underlie an area of about 2000 Km2 between Gedaref and Doka, its thickness varies from about 600 m at Doka to about 250 m at Gedaref indicating a more or less regular decrease in thickness in the northwest direction. The total volume of the Gedaref basalts is estimated as 800 Km3. (Almond, et al., 1984)

- **Abyad Formation (Tertiary)**

  Abyad Formation composed mostly of carbonates appear on top of Jebel Abyad at the north west part of the study area. The formation conformably overlies the Kababish formation and is restricted to the extension of the Abyad Plateau and its out layers.

  Abyad graben which have a thickness of more than 2000 meters extends east of the Jebel Abyad plateau and is most probably filled by Paleozoic sediments.

- **Hudi Chert Formation (Tertiary)**

  Hudi Chert formations are silicified fossiliferous limestones deposited from ancient lakes in which large amount of molluscan fauna lived. Isolated Hudi Chert outcrops occur in the Nile Valley between Wadi Milk – Wadi Muqaddam and in the Shendi /Atbara area. The type locality of the Hudi Chert formation is in a wadi Hudi station some 30 Km east of Atbara.
Um Ruwaba Formation (Late Tertiary)

The Umm Ruwaba series are lacustrine and fluvial deposits during the Pliocene to Pleistocene era. No surface outcrops of the Formations are known, its existence and lithology are known only from borehole logs. The formation consists of flat lying sequence of unsorted and unconsolidated gravels, sands, sandy clays and clays containing characteristic carbonate nodules or kankers. Umm Ruwaba formation was deposited unconformably over the Nubian Sandstone, but sometimes the Nubian may be absent and the Umm Ruwaba may directly lie on the basement complex, it may attain thicknesses of up to 350 meters. The formation is the second most significant in Sudan after The Nubian sandstone formation in terms of availing groundwater.

The area between the White and Blue Nile known in Sudan as Gezira, features a sequence of unconsolidated sands, clays, and gravels which are lithologically similar to and are continuous with the Umm Ruwaba Formation beds west of the White Nile. The formation which is known locally as the Gezira formation overlies the Nubian Sandstone formation and its thickness reaches 80 meters near Khartoum. Given its sedimentological and age characteristics, the formation is inseparable from the Umm Ruwaba formation expect for being exposed between the White and Blue Niles.

The Gezira formation can be divided into upper and lower beds. The lower (older) Gezira formation (Oligocene – Miocene) is composed of moderately reworked interbedded sand and clay. The presence of high percentage of kaolinite and low percentage of smectite suggest a metamorphic source and points to the Ethiopian Highland.

The upper Gezira formation (Miocene – Quaternary) are composed of unconsolidated sands, silts and gravel. The changes between the two sub-layers is caused by the change of climatic conditions during the Pleistocene and Early Middle Holocene times from aridity to humidity, which reflected in the Blue Nile River discharges and the amount and type of sediments load.

Quaternary Deposits

Recent deposits overlay the older formations all over Sudan. They are usually the result of the erosion and deposition of the older formation through wind or water. Sand extends over the whole of the northern part of Sudan (North of Khartoum), and is usually windblown. The natural drainage system on the other hand carries and deposits alluvia in the more humid south parts of Sudan. Large rivers on the other hand such as Gash and Dinder develop deltas over older sediments. These recent deposits from the youngest to the oldest include:

- Recent alluvium and wadi deposits
- Colluvium, sand sheets and amalgamated dunes.
- Older alluviums and raised terraces
- Lacustrine deposits and alluvial fans, dunes and dune fields
- Palaeolevees, old gravel and stabilized dunes.
River deposits are composed of intercalated sands and clays 2 – 10 m thick confined to river banks and extend 1 – 5 km along the River Nile and its main tributaries (Blue Nile and Atbara River). Their hydrogeological significance is that they act as a membrane through which river water infiltrates to recharge the surrounding shallow aquiferous zones.

Wadi deposits, formed of sands and clays, are mostly confined to the old drainage system. Their thickness varies from few meters, to over 30 meters forming part of the shallow aquiferous zone.

Colluvium, sand sheets and amalgamated dunes are found primarily in the northern part of the study area (North of Khartoum) they are for the most part of limited hydrological significance due to their existence above the ground water table and the limited recharge potential from precipitation in the areas of their existence.

Older Alluviums and raised terraces are found along the banks of the River Nile and its tributaries and the major wadis draining into the river. The consist of unconsolidated clays, silts, sands and gravels.

Lacustrine deposits and alluvial fans are quaternary fluvial sediments deposited by the Nile drainage system. The Nile evolution has built extensive alluvial fans in southern and central Sudan at the outlets of major rivers issuing from the highlands of Ethiopia. The most significant of these deposits extends from the southern part along the Blue Nile up to Khartoum. Alluvial fans can also be found at the outlets of Gash and Atbara Rivers.
Figure 2.5: Geological Map for the Eastern Nile Region in Sudan
3. MAJOR GROUNDWATER AQUIFERS IN THE EASTERN NILE

3.1. Basement Aquifers

The basement complex outcrops in about half the area of Sudan. It is impervious unless subjected to extensive weathering, jointing and fracturing. In such cases and when recharge conditions are favourable, the basement rocks can supply enough water for small communities (Figure 3.1).

These aquifer zones are typically between 5 m and 20 m thick, but can be thicker. The saturated thickness depends on the degree of weathering. Water table depths range from 4 m to 60 m depth, and groundwater is typically unconfined. The basement complex areas in Sudan receive annual recharge depending on the rainfall intensity or connectivity to flowing rivers or wadis and Khors. Studies in basement aquifers of the Red Sea Hills of Sudan (Eastern Sudan), reveals a severe shortage of groundwater in basement areas. This shortage is partly due to the fact that the precipitation in this area is very small (<200 mm/yr.) and is exacerbated by the low hydraulic conductivity of the bedrocks. On the other hand, areas of Basement Rocks in western and Southern Sudan which experience comparatively higher precipitation and recharge features better yield. The water quality can be excellent or extremely bad depending on the degree of rock/water interaction and contamination hazards. Most of the wells in the basement complex are either large diameter hand-dug wells or narrow tube wells equipped with handpumps. Abstraction boreholes range from 10 m to 70 m, and borehole yields are generally low. The alluvial and basement complex aquifers normally recover fully after the first few rainfall/runoff events and are mostly exploited for domestic water supply. In basement rock covered areas of the Sudan, the principal aquifers may be the wadi bed aquifers within the pediment. The wadi aquifers may have good potential for shallow groundwater. However, the size of these plains as well as the properties of the water-bearing formations are limited by the following factors:

- Episodicity of rainfall events.
- Degree of weathering of underlying basement rocks.
- The direction of the lineament with respect to the orientation of the wadi beds.

3.2. The Nubian Sandstone Aquifer

The Nubian Sandstone Aquifer System (NSAS) extends over more than two million square kilometres in Northern Africa, covering the Northern Sudan, Southern Egypt, Eastern Libya and Northern Chad, thus forming the largest known body of contiguous liquid fresh water on the planet. The area of NSAS within Sudan is about 376,000 Km² which accounts for 17% of the transboundary aquifer area. The share of the other three countries are as follows: Egypt 828,000 Km² (38%), Libya 760,000 Km² (34%) and Chad 235,000 Km² (11%). The northernmost boundary of NSAS is with the Mediterranean Sea, with a north-western boundary set by a stable freshwater and saltwater interface. The western border is a groundwater divide extending from the Tibesti Mountains in the south northwards along the 19° Meridian. The southern boundary is believed to be another water divide that separates the NSA from Lake Chad and other regional water bodies. The aquifer is bounded in its southeast boundary by the River Nile and is separated from the Red Sea in the east by a mountain range that ends at the Suez Canal which forms the North eastern boundary of the NSA. The NSA is made primarily of fossil water, it lies in an arid part of the world that receives very little rain, as such recharge to most of the aquifer is mainly very minute. An exception to this may be found in the South eastern flank of the NSA which
receives regional recharge from the Nile and underflow from the adjacent Blue Nile basin. This part of the Nubian Sandstone Aquifer System is known as the Nubian Nile Basin and it constitutes the interface region between the NSA and River Nile and its associated groundwater basins.

The Nubian Sandstone Aquifer cover about 28% of the area of Sudan and 36% of its area within the Eastern Nile Basin. The aquifer thickness ranges from 50 meters to 2000 meters and groundwater storages is estimated as 6,000 BCM within the Eastern Nile area of Sudan. Groundwater occur under confined to semi-confined conditions and depth to static water varies between 5m to 140 m with the occurrence of flowing conditions in limited areas. The aquifer productivity is generally high and the water quality is good and generally fit for most purposes. The recorded hydraulic properties of the Nubian aquifer show large variations with transmissivity values ranging from 100 to 3900 m²/day, storage coefficient values ranging between $10^{-3}$ to $10^{-5}$ and an average specific yield value of 0.1.

### 3.3. The Umm Ruwaba Aquifer

Umm Ruwaba Formation forms a large unconsolidated aquifer in the central and southern parts of Sudan. The aquifer covers about 7% of the area of Sudan and 14% of its area within the Eastern Nile Basin and in many areas is underlain by the Nubian Sandstone Aquifer. The Umm Ruwaba aquifer thickness can reach 350 meters and its groundwater storage is estimated as 75 BCM within the Eastern Nile area of Sudan. Groundwater occur under unconfined to semi-confined conditions depending on the permeability of the overlying strata, indeed the occurrence of flowing conditions can be observed in some area such as Um Ballejeh in North Kordofan. The depth to static water generally varies between 10 m to 150 m and the water quality is good and generally fit for most purposes. The aquifer productivity is generally low to high depending on the hydraulic properties which are reduced by the rapid facies that characterize the formation and the aquifer type (confined/Unconfined). In the Areas of Umm Ruwaba formation along the Blue Nile the aquifer is typically unconfined, of thickness less than 80 meters, with low to high productivity and transmissivity values ranging between 100 to 1500 m²/day. In the areas west of the White Nile The Umm Ruwaba aquifer is typically semi-confined, can attain a thickness of 350 meters, is of low to moderate productivity and a maximum recorded transmissivity values of about 400 m²/day near Bara in North Kordofan. The reported median transmissivity of the aquifer west of the White Nile is 25 m²/day and the storage coefficient values typically range between $10^{-3}$ to $10^{-5}$.

### 3.4. Recent Deposits Aquifer

Holocene/young, thin unconsolidated sediments occur in various parts of Sudan. They have their origin from alluvial, lacustrine or wind deposits. These sediments form minor local aquifers for water use by communities. In addition, they may act as recharge mediums for the underlying aquifers in areas of high precipitation or surface runoff as well as in the areas adjacent to perennial water courses such as the River Nile. Various types of these young deposits have been recognized including:

- **Recent alluvium and wadi deposits**
- **Colluvium, sand sheets and amalgamated dunes.**
- **Older alluviums and raised terraces**
- **Lacustrine deposits and alluvial fans, dunes and dune fields**
- **Palaeolevees, old gravel and stabilized dunes.**
River deposits are composed of intercalated sands and clays 2 – 10 m thick confined to river banks and extend 1–5 km along the River Nile and its main tributaries (Blue Nile and Atbara River). Their hydrogeological significance is that they act as a membrane through which river water infiltrates to recharge the surrounding shallow aquifer zones.

Wadi deposits, formed of sands and clays, are mostly confined to the old drainage system. Their thickness varies from few meters, to over 30 meters forming part of the shallow aquifer zone.

Colluvium, sand sheets and amalgamated dunes are found primarily in the northern part of the study area (North of Khartoum) they are for the most part of limited hydrological significance due to their existence above the ground water table and the limited recharge potential from precipitation in the areas of their existence.

Older Alluviums and raised terraces are found along the banks of the River Nile. Their hydrological significance is limited.

Lacustrine deposits and alluvial fans- These are quaternary fluvial sediments deposited by the Nile drainage system. The Nile evolution has built extensive alluvial fans in southern and central Sudan at the outlets of major rivers issuing from the highlands of Ethiopia. The most significant of these deposits extends from the southern part along the Blue Nile up to Khartoum. Alluvial fans can also be found at the outlets of Gash and Atbara Rivers. The formation is a water bearing formation and may cause semi confining conditions to the lower older formation.

Palaeolevess, old gravel and stabilized dunes may form shallow aquifers as well as enhance the recharge to the lower older aquifers in areas of significant precipitation / surface runoff.

The recent deposits aquifers are relatively small but numerous, rich and of high local importance. They are typically unconfined with a thickness that is usually less than 50 meters, a shallow water table which varies from 2 to 15m and good water quality. The productivity of these aquifers varies from low to high depending on the aquifer thickness, parent material and hydraulic properties. Transmissivity values ranging from 500 to 1500 m²/day and yields of up to 30 L/s had been reported.

One of the most significant Recent Deposits Aquifers within the study area is the Bara Shallow aquifer in North Kordofan which extends over an area of about 12,000 Km² and is the main source of water for the communities around Bara town. The stabilized sand dunes in the area form a significant unconfined aquifer, and act as medium for the recharge of the underlying older Umm Ruwaba formation.

3.5. Volcanic Aquifers

Volcanic Aquifers in Sudan within the Eastern Nile Boundary are limited to the south eastern corner of the country along the Sudan Ethiopian Border. The aquifer is of limited extent generally low yield but significant importance for the local communities. Most of the aquifer region is a clay plain, diversified by occasional flat-topped hills exposing Nubian Sediments or basalts. The Gedaref Basalts were a result of active volcanic activity in the region between the middle to late Eocene topping a succession of Nubian Sediments. The extent of the aquifer is bound within the borders of Sudan by crystalline rocks of basement complex which underlie its centre at depth of more than 1000 m. To the south-east, the Gedaref basalts join the main outcrops of the Ethiopian Traps. Groundwater occurs within the aquifer in unconfined conditions within the sandstone as well as the basalt formations.
Figure 3.1: Major Groundwater Aquifers
4. GROUNDWATER BASINS

4.1. Sudan Groundwater Basins

The formation of some of the major ground basins of Sudan is believed to be the result of a multistructural system of rifts which appear to have been activated several times since the Palaeozoic period. The central Sudanese rift basins and sub-basins began to develop in the late Jurassic -Early Cretaceous during the break up of Gondwanaland and the separation of South America from Africa. Intracontinental extensional forces that resulted from the opening of the Atlantic and acted upon and along the African continent facilitated the formation of several deep fault-bounded troughs. Figure 4.1 shows the location of the main groundwater basins of Sudan within the Eastern Nile Basin.

The identified basins as part of this study are the Nubian Sahara Basin, Nubian Nile Basin, Atbara Basin, Blue Nile Basin, Gedaref Basin and East Kordofan Basin. The Nubian Sahara Basin and the Nubian Nile Basin are two hydraulically connected basins that constitute the area of Nubian Sandstone Aquifer System within Sudan.

The sedimentary thickness in these basins reach up to 500 meters, with thicknesses of up to one kilometre reported in some areas. Deep grabens with thicknesses of up to 3500 meters believed to be filled with Palaeozoic sediments are known to exist within some of the aforementioned main groundwater basins. In addition to these main groundwater basins, groundwater occurs in the alluvial channels underlying the wadi courses within the basement complex areas. These shallow aquifers are the only perennial source of water for the small communities living near these wadis. In spite of their significance in terms of their social impact and geographic spread within the Eastern Nile Basin in Sudan, these groundwater resources are not part of the scope of this study, which is restricted to the six aforementioned basins.

Groundwater is found in the identified basins mainly in unconfined and/or semi-confined conditions. The direction of groundwater flow is primarily in a north/north-west direction for the basins within the Main Nile, Tekeze-Atbara and Blue Nile sub-basins of the Eastern Nile (within the Blue Nile and Atbara Rift Systems) and in a South east -direction in the basins within the White Nile Sub-basin (within White Nile Rift System) namely East Kordofan Basin.
Figure 4.1: Location of the Main Groundwater Basins in Sudan
4.2. Nubian Sahara Basin

4.2.1. Location and Extent

Most of the area of NSA within Sudan can be divided into two hydraulically connected basins, namely the Nubian Sahara and Nubian Nile basins and they will be divided as such in this report. The area of the Nubian Sahara within Sudan is about 376,000 Km$^2$ of which about 86,000 Km$^2$ lies within the area of the Eastern Nile within Sudan (Figure 4.2). The area referred to as the Nubian Sahara aquifer hereinafter refers to the area of the Nubian Sahara Basin within the Eastern Nile Boundary.

4.2.2. Climate and Topography

The climate in the Nubian Sahara Basin is characterized as a desert climate with virtually no precipitation in the north of the basin and total annual precipitation of about 20 mm year at the south end of the basin. Temperature varies between (23 °C – 42 °C) for maximum and (9 °C– 25 °C) for minimum. (Figure 2.2 and Figure 2.3).

The basin is divided by the Nile valley and the elevation increase from a low of 173 m.a.s.l at the River Nile towards the east and west directions to high values of 785 m.a.s.l. The topography is in general undulated with higher ridges in the areas to the east of the River (Figure 4.3).
Figure 4.2: Location Map of the Nubian Sand Stone Aquifer System
4.2.3. Geology and Hydrogeology

The Nubian Sandstone Formation which underlies most the Eastern Nile Basin area within Sudan dominates the entire Nubian Sahara Basin. The geology of the basin can be summarized from younger to older into:

- Sand, Alluvial and Playa Deposits
- Volcanic Rocks
- Abyad Formation
- Kababish Formation
- Wadi Howar Formation
- Wadi El Melik Formation
- Undifferentiated Basement

Quaternary-Recent deposits comprise sand sheets, sedimentary thickness increases from few meters within close proximity to the basement complex moving westwards to more than 500 meters westwards within the area of Jebel Abyad plateau. The graben of Abyad Sub-Basin to the south of Jebel Abyad has a depth of more than 2000 meters, where the lower sediments are believed to be Palaeozoic. The maximum sedimentary thickness in the areas of the Nubian Sahara basin to the east of the River Nile are believed to be within 100 – 150 meters.

Groundwater within the basin occurs under unconfined conditions and depth of groundwater is largely affected by topography. The depth to the water table is expected to range between 40 to 100 m. The Sahara Nubian lies in an arid area and the basin do not receive any appreciable recharge. The groundwater within the basin is Palaeo water that dates to 10,000 years ago. The aquifer is hydraulically connected to the Nubain Nile Aquifer to the east.

There are no existing studies to determine the hydraulic properties of the Nubian Sahara basin within the Sudan. On the other hand the Nubian Sandstone Aquifer System had been well studied in Kufran basin (Libya) as well as Dakhala and Kharga Oasis in Egypt. These studies report transmissivity values ranging between 250 m²/d to 3020 m²/d for Kufran and 520 m²/d to 3600 m²/d for Kharga and Dakhala. The hydraulic conductivity was subsequently found to range between 2.8 m/d to 5.9 m/d at Kharga and Dakhla (Klitzch 1990).
Figure 4.3: Topography of the Nubian Sahara Basin
The studies also reveal that the storage coefficient of the aquifer is about $5 \times 10^{-4}$ at Kufra and that it varies between $10^{-4}$ to $10^{-3}$ at Kharga and Dakhla, the specific porosity on the other hand was calculated as 11% at Kufra and 10% at Kharga and Dakhla. These values are usually considered as representative of the hydraulic properties of the aquifer within the Nubian Sahara. (Figure 4.4)

**4.2.4. Groundwater Flow and Development**

The regional groundwater flow in the Nubian Sahara within the Eastern Nile Boundary is in a North east or west east direction. The flow is counteracted in the interface area with the Nubian Nile by flow from the River Nile in the opposite direction. This indicates the presence of a transitional zone where the fresh Nubian Nile water emanating from the River Nile water is exchanged with the Palaeo Nubian Sahara water. (Figure 4.5).

Stagnant zones due to basement contact or other flow conditions are likely to cause an increase in groundwater Salinity. The groundwater flow pattern in the NSA suggests the presence of such saline zones. Notwithstanding these zones the water quality of the NSA in general is excellent as reported in the literature with TDS values of about 500 mg/l.

There are no significant groundwater developments in the Nubian Sahara basin, settlements and development are confined mainly to the areas in close proximity to the River Nile. The total annual abstraction from the Nubian Sahar within the Eastern Nile boundary area limited to one million cubic meter per year.
Figure 4.4: Geology of Nubian Sahara and Nubian Nile Basins
Figure 45: Average Groundwater levels and Depth to Groundwater for the Nubian Sahara Basin
4.3. Nubian Nile Basin

4.3.1. Location and Extent

The Nubian Nile Basin extends from the area North of Khartoum in a north westerly direction up to the basement outcrop North of Dongola (Figure 4.1). The basin has length of about 500 Km and covers an area of about 160,000 Km². The basin is considered as the northern extension of the Blue Nile - Khartoum rift basin and it contains three main hydraulically connected sub-basins, namely Dongola subbasin, Ed Debba sub-basin and Wadi ElMuqaddam sub-basin. The aquifer is hydraulically connected to the Blue Nile Basin in the South, the Atbara basin in the East, East Kordofan Basin in the South West as well as the Nubain Sahara Basin in the North West. The hydrogeology of the aquifer is dominated by the River Nile which forms its eastern boundary in the basin’s southern (lower) half and runs through its northern half. In spite of its geological similarity and hydraulic connection to the Nubian Sandstone Aquifer (NSA), the aquifer is considered in Sudan as a separate from the Nubian Sahara Basin which is the part of the NSA within Sudan.

4.3.2. Climate and Topography

The climate within the Nubain Nile basin varies from semi-arid in the south at Khartoum to arid in the North (north of Dongola). The rainy season lasts from May to October with maximum rain falling in August. Total annual precipitation varies from about 200 mm in the south to 10 mm per year in the north of the basin (Figure 4.6). Maximum and Minimum daily temperatures vary according to the month of the year and location. (Figure 2.2 and Figure 2.3).

The topography of the basin area was compiled and ascertained from remote sensing data; specifically, the Shuttle Radar Terrain Modeling Mission data (SRTM) was processed to generate the Digital Elevation Model (DEM) for the project area and to delineate its drainage patterns. The obtained data reveals the presence of relatively high outcrops along the eastern and western flanks of the project area that extends across the southern half of the basin. The northern part of the basin is flat along the Nile valley which varies in width between 7 – 20 kilometres with undulations and high ridges away from it. Elevations of the basin vary from about 1130 m.a.s.l to about 200 m.a.s.l with a general slope towards the north and north west. There are three main old wadi systems connected to the Nile, namely Wadi Howar, Wadi El AlMalik and Wadi Almuqadam (Figure 4.7).

4.3.3. Geology and Hydrogeology

The Nubian Sandstone Formation which underlies most the Eastern Nile Basin area within Sudan dominates the entire Nubian Nile Basin. The geology of the basin can be summarized from younger to older into:
Quaternary-Recent deposits comprise sand sheets, Nile- and wadi deposits, and lacustrine deposits. Lacustrine playa deposits dominate the Qaab Depression which extend 20-40 km west of Dongola town forming a low altitude palaeo-channel of Wadi Hower. Lacustrine deposits consist of marls with calcite, and less abundant argillites, siltite, and gypsum laminae. Their hydro-geological significance is that they can affect the quality of the shallow groundwater by dissolving carbonates.

Nile deposits are represented by silt with sand, sometimes intercalated with lenses of coarse sand and gravel. Their total thickness ranges from 2 to 20 meter. Forming the membrane through which Nile Water infiltrates to recharge the underlying and adjacent auriferous zones.

Sand dunes in form of sand sheets and stabilized dunes cover most of the land east of the River Nile.

The Nubian Nile Basin can be divided into three hydraulically connected sub-basins, namely Dongola subbasin, Ed Debba sub-basin and Wadi ElMuqaddam sub-basin. The aquifer is hydraulically connected to the Blue Nile Basin in the South, the Atbara basin (South East), East Kordofan Basin in the South West and the Nubain Sahara Basin in the North West (Figure 48). The hydrogeology of the aquifer is dominated by the River Nile which constitute it southern boundary and runs through it northern half. In spite of its geological similarity and hydraulic connection to the Nubian Sandstone Aquifer (NSA), the aquifer is considered in Sudan as a separate from the Nubian Sahara Basin which constitute most of the NSA within Sudan.
Figure 4.6: Annual Rainfall Distribution in the Nubian Nile Basin Region
Figure 4.7: Topography for the Nubian Nile Basin
Figure 4.8: Major Sub-basins of the Nubian Nile Basin
Sedimentary thickness within the Nubian Nile Basin increases from 50 meters within close proximity to the basement complex at the Northern border at Abu Fatma to 250 m at Dongola and to more than 300 meters towards the south. The sedimentary thickness is believed to even exceed 500 meters in some areas. The sedimentary thickness in the grabens of Humar and Salamat basins are more than two kilometres deep (Figure 4-4). The aquifer structure towards the basement complex forming its eastern side is not well studied, it is believed that the sedimentary thickness remains at 300 meters until it decreases due to the presence of the ascending basement.

Groundwater, within the whole system in the study area, occurs largely under water table conditions which may vary locally to semi confined or confined conditions depending on the thickness and continuity of the horizons of reduced permeability. Depth to groundwater is largely affected by topography and proximity to the recharging source. The shallowest water table is found in the deepest parts of the Gaab depression (1.5 – 3.0 m). In the areas close to the Nile and up to 10 km, away from its banks depth to water varies between 5 and 15 m and reaches depths up to 40 meters in areas 30 – 40 km away from the Nile and along the plateaus. Along the lower reaches of Wadi El Muqaddam depth to water varies from 20 to 40 m and reaches up to 140 m along Qoz Abu Dulu north of Khartoum. Confined conditions had been observed about 70 Km west of Dongola where the piezometric head is seven meters above the ground level.

Isotope analysis carried out in the project are during the Nubian Sandstone project investigation (1985-1986) indicates that wells closely located to the Nile (8-10 km) carry a considerable percentage of Nile water and that their water level fluctuations follow those of the River Nile. The degree of mixing between groundwater and Nile water is controlled to a great extent by the anisotropy of the aquifer. The results of isotope analysis for the project area conducted within the activities of the IAEA and Groundwater Research Directorate has concluded that groundwater close to the Nile (up to 40 km) is affected by river bank infiltration and that some areas along Wadi El Muqaddam may be affected by relatively young recharge from Khartoum-Blue Nile Basin to the South. The study clearly shows however that most sediments distant from the Nile (more than 40 km) host regional palaeo groundwater of the Nubian Aquifer System (NAS).

Proper pumping tests were conducted in the Dongola sub-basin by the National Water Corporation (NWC) in 1986 as well as by Bonifica (1987) with the latter using 2-3 piezometers around each testing well. Established data was used to classify the transmissivity around and south of the Dongola area into three classes

**Class I:** High transmissivity (2000 m²/d – 3900 m²/d)

**Class II:** Moderate transmissivity (700 m²/d – 1700 m²/d)

**Class III:** Low transmissivity (120 m²/d – 400 m²/d)

It was found that low transmissivity values occur in areas of thicker sedimentary formations, dominated by mudstone.

The hydraulic conductivity value varies within a range of 1x10⁻⁴ m/s and 6x10⁻⁴ m/s (8.64 – 51.84 m/day) with an average hydraulic conductivity of 2.8x10⁻⁴ m/s (24.2 m/day). Compilation of results from various tests and hydraulic conductivity values obtained through data consolidation and model calibration (Pre-
feasibility Study – Merowe Dam, 2004) estimated that the overall hydraulic conductivities are given in a range between $6 \times 10^{-5}$ and $9 \times 10^{-5}$ m/s ($5.18 – 7.78$ m/day), with higher values ($>1 \times 10^{-4}$ m/s) north of Dongola. This estimate seems to provide a more realistic range of hydraulic conductivities.

The wide range of hydraulic conductivity values underlines the heterogeneous nature of the underlying strata and formations. Storativity varied between $1.3 \times 10^{-4}$ and $4 \times 10^{-4}$.

4.3.4. Groundwater Flow

The groundwater flow patterns were ascertained through the measurement of groundwater levels in more than 200 observations wells and two major groundwater flow components were subsequently identified; a regional groundwater flow pattern and flow attributed to the River Nile. The regional pattern shows a flow towards the River Nile in a north east or west /east direction basically opposing the flow emanating from the River. Regional interbasin flow from the Blue Nile aquifer in a north-west direction could also be identified. Stagnant zones are created in the areas where the regional flow is counteracted by the opposing flow from the River Nile (Figure 4.9). The groundwater flow direction is generally impacted by the discharges of the River Nile as it functions as a source of recharge during the flood season (June – October) and a sink during the low season. Flow from the River Nile as well as inter basin flow from the Blue Nile basin are the only source of appreciable renewable recharge to the basin.

4.3.5. Groundwater Quality

Total dissolved solids in the Nubian Nile Basin were found to range from 112 to 5590 mg/l. The average value of TDS for the study region was found to be 685 mg/l. Further statistical analysis of the results did indicate that 84% of the results have a TDS value less than 1000 mg/l. In addition, the mapping of the results has indicated that the areas in the north of Basin exhibited low TDS values (< 500 mg/l) indicating a strong recharge influence of the River Nile. A front of fresh water also appears to be advancing through the south west corner of the basin toward the Nile in a NE direction indicating the existence of subsurface flow of fresh water in this direction underneath the main wadis in the area (Wadi AlMuqadam). In general, the salinity increases away from the Nile. An exception can be found in area of stagnant zones due to the existence of two water fronts moving in opposite directions or contact with the Basement. The former appears near EdDebbga town and in the upper west side of the basin in the interaction area between the Nubian Nile and the Nubian Sahara Basins, while the latter appears near Merowe town.

4.3.6. Groundwater Development

Groundwater, within the Nubain Nile Basin, is developed by open shaft wells, driven wells or matara, and boreholes. The basin is considered one of the most important basins in Sudan in terms of groundwater availability, water quality and degree of utilization. It is in an arid area of Sudan where reliance on groundwater is the only option for any development away from the River Nile. Groundwater development has expanded significantly within the basin since the year 2005. This expansion was brought about by the relative economic boom that Sudan witnessed at the time as well as the significant improvement of infrastructure in the region namely electricity and road networks. Investment in medium and large-scale agricultural projects using groundwater and sprinkler irrigation started to spring within the previously deserted upper terraces (5 – 20 Km from the Nile). It is currently estimated that daily abstraction for domestic water supply from the Basin is about 60 Mm³/year and that agricultural areas irrigated by using groundwater amount to 77,500 Ha requiring about 1,400 Mm³ per year.
Figure 4.9: Average Groundwater levels and Depth to Groundwater for the Nubian Nile Basin
4.4. Atbara Basin

4.4.1. Location and Extent

The Atbara basin is bound by the River Nile reach between Khartoum and Atbara town at the confluence of the Nile on the west side while the Atbara River and the basement complex along the Atbara River forms it’s the eastern boundary. The basin is part of the Atbara River rift which extends from Atbara town and extends southward to the Ethiopian Border. The Atbara Basin covers an area of about 32,000 Km² and is hydraulically connected to the Blue Nile Basin at the South West across the Nile River and the Nubian Nile Basin to the North West. (Figure 4.1).

4.4.2. Climate and Topography

The climate within the Atbara basin is arid with total annual precipitation of about 300 mm and extreme high temperatures during the Summer (Figure 4.10). The terrain of the basin area feature ridges on the south-western to western side where the elevation reaches about 600 m.a.s.l.. The rest of the basin slope gently in a North/North-west direction almost parallel to the Atbara River towards the Main River Nile (elevation 340 m.a.s.l.). The basin features two major wadis (Wadi Elhawad and Wadi ElMukabrab) (Figure 4.11).

4.4.3. Geology and Hydrogeology

The geology of the Atbara basin can be summarized from younger to older into:

- Recent Superficial Deposits
  - Alluvial Deposits
- Quaternary

- Volcanic Rocks
- Cenozoic

- Hudi Chert Formation
- Mesozoic

- Nubian Sandstone Formation
- Pre Cambrian - Cambrian

- Basement Complex

The Nubian Sandstone formation underlies all of the basin, the thickness of the water bearing formation increases from less than 100 meters east of Sabologa to more than 300 meters in the middle of the basin. The thickness of the layer decreases towards the basement complex to the east and the south. The depth of the formation decreases to about 50 to 70 meters at the southern border of the basin.
Figure 4.10: Annual Rainfall Distribution in the Atbara Basin Region
Figure 4.11: Topography of the Atbara Basin
The Hudi Chert formation unconformably overlies the Nubian Sandstone in some areas. Thick chert conglomerate up to 11 meters thick was found between Shendi and Atbara.

The Quaternary Alluvial Deposits were deposited by the Atbara River and are mainly composed of gravels, sands and clays. The thickness of the Alluvium layer varies from 50 to 200 meters.

Superficial deposits include Butana clays as well as sand dunes and thin sand sheets which overlie the soft non-cracking clays.

Groundwater occurs within the basin in semiconfined condition within the alluvium deposits as well as the Nubian Sandstone Formation. The saturated thickness varies from 50 meters at the southern border to about 200 meters in most of the basin and more than 500 meters in the area of Wadi ElMukabrab. The depth of the saturated zone in the narrow flood plain strips of the River Nile and Atbara River (one to three kilometers wide) exceeds 150 meters and comprises mainly alluvial deposits. Depth to water increases from about 10 meters within the flood plains of the Nile and Atbara Rivers to about 100 meters towards the centre of the Basin.

The fluctuation of the groundwater levels close to the River Nile is in tandem with that of the River which indicate that unlike the Atbara River the Nile is hydraulically connected to the aquifer and is a potential source of recharge. Recharge to the basin also takes place through its southern border at the point of contact of the sedimentary Nubian Sandstone with the basement where it contacts the surface runoff generated in the major wadis (Wadi El Hawad and ElMukabrab) during the rainy season. The hydraulic properties of the aquifer reported in the literature cite values of transmissivity ranging between 100 and 10000 m²/day and storativity between 0.01 and 0.0001

The groundwater flow pattern in Atbara Basin ascertained from the regional groundwater data show north and north west flow components in the basin in general, with indications of recharge from the River Nile. (Figure 4.12)

4.4.4. Groundwater Quality

Studies of the Atbara Basin area report the total dissolved solids (< 400 mg/l) in the area along the River Nile which is a sign of hydraulic interaction with the river. Areas close to Sabolaga outcrop report TDS values of 2000 mg/l. Areas towards the center of the Basin are also reported to exhibit salinity as the TDS values reaches 1500 mg/l. Values of TDS at the southern boundary of the aquifer close to the identified recharge zones are reported to be fresh (TDS < 800 mg/l ). The reduced salinity towards the southern border are attributed to the potential impact of recharge from surface runoff.

4.4.5. Groundwater Development

Groundwater Development in Atbara Basin is mostly practiced to meet domestic supply as well as livestock watering demand. Irrigation using groundwater is primarily localized within the floodplains of Atbara and the Nile Rivers. Limited large-scale agricultural development takes place within 20 Km of the River Nile. It is estimated that abstraction for domestic supply and livestock watering is about 10,000 m³/day. Areas developed for agriculture using groundwater from the Atbara Basin are estimated to be about 5000 Ha abstracting about 95 Million m³/year. The total estimated annual abstraction from Atbara aquifer is thus estimated to reach about 100 Million m³/year.
Figure 4.12: Average Groundwater levels and Depth to Groundwater for the Atbara Basin
4.5. Blue Nile Basin

4.5.1. Location and Extent

The Blue Nile groundwater basin extends from the Sudan Ethiopia border in a north westerly direction up to the Sabaloga outcrop North of Khartoum beyond the confluence of the Blue and While Niles (Figure 4.1). The basin has length of about 500 Km a width that ranges between 80 Km – 260 Km and an area of about 76,000 Km$^2$. The hydrogeology of the study area is dominated by the Blue Nile and it two main tributaries namely the Rahad and Dinder ephemeral rivers. Two of the main features of the study area are the Roseries and Sennar Dams which regulate to a great extent the flow regime in this segment of the Blue Nile.

4.5.2. Climate and Topography

The climate in the study area is characterized by a semi-arid climate in the northern part to a semi humid climate in the southern part. Rainfall occurs during the summer period commencing in May in the southern part and progresses northwards. Maximum rainfall occurs in August and thereafter decreases coming to an end in November. Analysis of rainfall data at a number of stations in the study area reveal that the annual rainfall increases progressively from 200 mm in the northern tip of the study region to more than 700 mm in the southern part of the study area. Annual potential evaporation ranges from 3000mm in the northern part of the study region to more than 1800 mm in the Southern part. Maximum and Minimum daily temperatures vary according to the month of the year and location. In the central part of the study region they range between (32° C – 42° C) for maximum and (13°C–24° C) for minimum (Figure 2.2 and Figure 2.3). Similarly, relative humidity, sunshine hours and wind speed vary from month to month but the average of these in the central part of the study region are 47%, 9 hours and 1.8 m/s respectively. Figure 4.13 show the variation of the annual rainfall in the Blue Nile Basin.

The topography of the basin area was compiled and ascertained from remote sensing data; specifically, the Shuttle Radar Terrain Modelling Mission data (SRTM) was processed to generate the Digital Elevation Model (DEM) for the project area and to delineate its drainage patterns. The obtained data reveals that apart from the relatively high outcrops in the southern and eastern flanks of the project area the topography of the Blue Nile Basin is relatively flat decreasing from about 500 to 340 meters above sea level with a gentle slope in the north-west direction as shown in Figure 4.14.
Figure 4.13: Annual Rainfall Distribution in the Blue Nile Region
Figure 4.14: Topography of Blue Nile Basin
4.5.3. Geology and Hydrogeology

The Blue Nile Basin is one of the major African Rift related basins in Sudan. It can be divided into two major sub basins named herein as Dinder and Gezira sub basins (Figure 4.15). The two sub basins have slightly different hydro-geologic characteristics but they are hydraulically connected to each other’s.

The Dinder sub-basin is bound from three sides by no flow boundaries that are comprised for the most part of igneous basement rocks. The sub-basin extends in a North West direction up to the confluence of the Blue Nile and Dinder Rivers and is hydraulically connected in the North West side to the Gezira sub-basin.

The main geological units in the sub-basin from the youngest to the oldest are:

- Blue Nile Terraces and recent superficial deposits (Recent – Quaternary)
- Al-Atshan Formation (Quaternary – Tertiary)
- Nubian Sandstone Formation (Cretaceous – Jurassic)
- Basement Complex (Cambrian – Pre-Cambrian)

The Nubian Sandstone formation is the most important sedimentary deposit in Sudan. It is composed of sandstones, mudstones, shale, siltstone, inter-formational conglomerates and conglomerates. The formation thickness varies from zero at the Sudan Ethiopia border and reaches more than 300 meters within the sub-basin.

Al-Atshan Formation is found locally in the Blue Nile Basin. It consists mainly of fluviatile clays, sand and gravel. Its thickness ranges from 10 to 150 meters. The formation was most likely deposited by the early tributaries of the Blue Nile. The deposition was from braided rivers at the base of the formation with meandering environment at the top. The deposits are Tertiary to Quaternary predating the alluvial fans and recent clay deposits that overlay the formation in some areas. Al-Atshan formation may overlay the Nubian Sandstone formation or the Basement Complex. The name Al-Atshan formation is widely used among geologists in the area, and in spite of the fact that it is referred to in this report using this name, it can be argued that the formation is for all practical purposes is an Umm Ruwaba formation series.

The recent deposits are mainly clays and restricted sand edifices which range in thickness from 2 to 10 meters.

Available information reveals that there are two water bearing formations in the sub-basin. An upper unconfined layer comprised of the Al-Atshan formation and a lower semi-confined to confined layer comprised of the Nubian Sandstone formation.

The Gezeria Sub-basin is an area of vast flat clay plain made up of unconsolidated sediments essentially silts and clay deposits. The sub-basin is dominated by the Blue Nile which is the most prominent hydrogeological feature as it cut the contour lines from the south-eastern end of the sub-basin to the north western end. The main geological units in the Gezira sub-basin from the youngest to the oldest are:
Superficial and Alluvium deposits (Recent)
Gezira Formation (Quaternary)
Nubian Sandstone formation (Cretaceous)
Basement Complex (Cambrian – Pre-Cambrian)

The geology of the sub-basin area east of the Blue Nile is made of Quaternary deposits overlain over Nubian sandstone formation which overlies the basement complex. The superficial deposits in this area of the sub-basin are made up of loose sands and dark cracking clay.

The Gezira formation which are Quaternary deposits represents relatively thin polygenic sedimentary deposits that were laid down by the River Nile drainage system. They occur in the west area of the Blue Nile in the area between the Blue and White Nile and North of ElManagil Ridge. They are younger than Al-Atshan formation and older than the recent alluvium deposits. The thickness of the layer varies from zero to close to more than 80 meters near Khartoum.

The geology of the sub-basin area west of the Blue Nile is made of superficial deposits overlain over Gezira formation which overlies the Nubian sandstone formation which in turn rests on the basement complex. Superficial deposits on this part of the sub-basin are mainly made up of dark cracking clay or vertosls. The Sedimentary thickness increase from close to zero at the eastern end of the sub-basin to depth of 200-250 meters away from the outcropping basin boundaries. The sedimentary thickness is believed to exceed 500 meters at some areas within Medani and Khartoum. (Figure 4.16).

In general, the Groundwater is found in the Gezira sub-basin in the Gezira formation as well as the Nubian sandstone layer. Groundwater in found mainly in unconfined conditions in the Gezira formation and confined to semi confined conditions in the Nubian sandstone aquifer due to the presence of thick mudstones. The Gezira sub-basin is connected hydraulically from the south east side to the Dinder sub-basin and is bounded along its eastern side with basement complex. The sub-basin is hydraulically connected in its north eastern side to the Atbara basin, it also connected to the Nubian Nile Basin to the north and is potentially impacted by inflows from the White Nile in its north western side.

Groundwater is found in the Blue Nile Basin in two main water bearing layers, a lower confined to unconfined aquifer in the predominantly Nubian Sandstone formation and an unconfined upper aquifer in the Al-Atshan or Gezira formation. The depths to water vary from seven meters below the ground surface near the rivers to 30 meters within 20 Km away from them. In general groundwater is found at depth of less than 60 meters within most of the basin.

Isotope analysis of the Blue Nile Basin groundwater was conducted in the year 2000 as part of a Ph.D. research conducted at the University of Khartoum – Sudan. The study focused on the areas of the basin south of the confluence of the Dindir and Blue Nile Rivers. It has concluded that the Blue Nile is the main source of recharge to the Basin. The impact of the river was particularly noticeable in areas within a 10 kilometres distance. The analysis has also shown that the Diner River contributes to aquifer recharge. In addition, the study detected signs of possible recharge to the aquifer from local precipitation which most probably reached the aquifer via palaeo channels at the southern end of the basin. It can be argued that the impact of the Rahad River was not conclusively detected due to the limitations of the study and that
the river also contributes to the recharge of the Blue Nile Basin. Observations of groundwater levels in the basin have revealed that there are annual water level rises ranging between 0.5 and 8.0 meters at the areas close to the rivers in the center of the Groundwater Basin in response to increased river stages.

Data and reports of the hydraulic properties of the Blue Nile Basin rely primarily on the results of single wells pumping and/or recovery tests as well as laboratory analysis of soil samples as opposed to proper pumping tests. The results of some of these tests were obtained for four aquiferous zones within the Blue Nile Basin, as described herein after;

- Nubian Sandstone Formation west of the Blue Nile within Gezira Sub-basin: the value of the hydraulic conductivity varied between 3.25 m/day and 29.69 m/day with an average of 9.35 m/day
- Nubian Sandstone Formation East of the Blue Nile (Butana Area) within Gezira sub-basin: where the value of the hydraulic conductivity varied between 1.43 m/day and 30.44 m/day with an average of 13.77 m/day
- Gezira Formation within the Gezira sub-basin: where the value of the hydraulic conductivity varied between 5.26 m/day to 31.49 m/day with an average of 13.12 m/day. It should be noted that there were concerns that some of the wells used in the analysis may have penetrated the upper Gezira Formation to the lower Nubian Sandstone aquifer.
- Al-Atshan Formation within the Dindir Subbaisn: The value of the hydraulic conductivity ranged between 0.27 m/day and 52.3 m/day with an average of 13.9 m/day

Values of storage coefficients for areas within the Blue Nile Basin (Mussalmi 2003) were reported to vary between \((2.2 \times 10^{-2} – 6.4 \times 10^{-5})\) for the Nubian Sandstone formation and \((10^{-2} – 10^{-4})\) for Al-Atshan formation. The variation appears to reflect in part differences in the aquifer conditions (i.e. confined Vs unconfined).

Data from over 900 wells were compiled and used to ascertain the groundwater levels and flow directions in the basin. Groundwater flow direction was found to be following the meandering of the Blue Nile for the most part. It starts in a northerly direction at the southern border of the basin and then changes to a North West direction (Figure 417). The groundwater table elevation was found to vary between 460 and 360 m.a.s.l.

### 4.5.4. Groundwater Development

Groundwater development in the Blue Nile Basin is very common in the villages and towns that are scattered primarily along the Blue Nile. It includes driven wells as well as open shaft wells. Development of the lower Blue Nile Basin Aquifer is practiced through deep boreholes and is limited for the most part to water distribution systems for domestic consumption. In addition, development of the upper unconfined aquifers of the Blue Nile Basin is very prevalent along the Blue Nile River banks for irrigation purposes by using driven wells (Matara), which tap the top aquifer using 2 to 4 inch pipes driven up to depths of twenty or thirty meters.

Official estimates indicate that there are about 3700 well within the Blue Nile used for domestic supply and livestock demand. The daily estimated abstraction rate for these wells is about 245,000 m³/day.
Areas close to the Blue Nile (within five kilometres of the river banks) witness a significant use of groundwater for agricultural development. The agricultural areas that depend on groundwater were ascertained through the analysis of satellite imagery of the region. It is estimated that these areas amount to about 40,000 Ha consuming about 400 Million m$^3$/year for irrigation. The total annual abstraction from the Blue Nile Basin is estimated to be about 500 Million m$^3$/year.

### 4.5.5. Groundwater Quality

The amount of total dissolved solids (TDS) in groundwater is a result of soluble minerals in the geologic strata, specific surface area of aquifer material and contact time. A rapid determination of total dissolved solids can be made by measuring the electrical conductance of a groundwater sample. For most groundwater, the specific conductance (µS/cm) multiplied by a factor of 0.55 to 0.75 depending on the dissolved minerals give a reasonable estimate of the dissolved solids. This factor is obtained by statistically correlating the total dissolved solids (mg/l) measured in the laboratory to the specific conductance.

Data of the Total dissolved solids (TDS) readings in the Blue Nile Basin was compiled for 811 samples distributed within the basin the results were found to range from 98 to 4200 mg/l. The average value of TDS for the Basin was found to be 520 mg/l. Further statistical analysis of the results did indicate that about 90% of the results have a TDS value less than 1000 mg/l. The mapping of the results has indicated that the areas of the basin along the Blue Nile has a TDS value of less than 300 mg/l, that the TDS in most of the basin is less than 500 mg/l. Saline zones within the basin were identified at areas of out-cropping basement (e.g. near Sabaloga in the north and at the south west of the basin), as well as in the area close to the White Nile in the west and North west parts of the basin. The saline zones are attributed to either to the existence of stagnant zones due to basement contact or due to the interaction with White Nile. The groundwater flow adjacent to the White Nile may be impeded by the existence of thick low transmissivity clays or the existence of an opposite flow gradient from the River. This is bound to create the stagnant zones that in turn can cause the witnessed increased salinities.
Figure 4.15: Hydrogeological Map for the Blue Nile Basin
Figure 4.16: Sub-basins of the Blue Nile Basin
Figure 4.17: Average Groundwater levels and Depth to Groundwater for the Blue Nile Basin
4.6. Gedaref Basin

4.6.1. Location and Extent

Gedaref Basin lies in eastern Sudan at the border with Ethiopia extending over an area of about 22,000 Km². The basin is one of the rift basins in Sudan that has been formed due to reactivation of the Central African Shear Zone (CASZ). The aquifer is a transboundary basin that is shared with Ethiopia. (Figure 4.1)

4.6.2. Climate and Topography

The climate within the Gedaref Basin is semi-arid at the north of the basin and semi-humid at the south. The rainy season lasts from May to October with the total annual precipitation varying from 800 mm at the south to 300 mm at the extreme north of the basin (Figure 4.18).

The topography of the Gedaref basin features high ridges in the southern and southwestern parts of the basin, low ridges on the eastern side of the basin with the interior of the basin sloping mildly in a northwest to north direction in the same the path of Atbara River. The elevation of the basin changes from a high of about 1000 meters at the south tip of the basin to about 460 meter at the north (Figure 4.19).

4.6.3. Geology and Hydrogeology

The geology of the Gedaref basin can be summarized from younger to older into:

- **Recent Deposits**
  - Quaternary
- **Volcanic Rocks**
- **Umm Ruwaba Formation**
- **Cenozoic**
- **Nubian Sandstone Formation**
  - Mesozoic
- **Basement Complex**
  - Pre Cambrian - Cambrian

The Basement Complex is of Pre-Cambrian age and comprises Schists, Gneiss and Granite.

The Nubian Sandstone formation constitute a sequence of interbedded sandstones and mudstones laid down in a depositional environment that is dominated by multiple braided channels, bars and floodplain. The sequence is also known as Gedaref Formation. The formation rests unconformably on the basement rocks and is overlain and/or intruded by basaltic rocks. The Gedaref Formation may be overlain limited areas by the Umm Ruwaba Formation. Recent deposits comprise the Kerib Formation and black cotton soil of Quaternary age. The Kerib formation is a sloping land in which both topsoil and subsoil have been removed to expose a surface of abundant calcium carbonate concentrations (Figure 4.20).
Figure 4.18: Annual Rainfall Distribution in the Gedaref Basin Region
Figure 4.19: Topography of the Gedaref Basin
4.6.4. Groundwater Flow, Quality and Development

Groundwater occurs within the Gedaref formation as well as the fractured and weathered zones of the Basalt under semi-confined conditions. The thickness of the saturated layer ranges from 200 to 500 m and the depth water range from 50 to 75 meters.

The main recharge zone to the aquifer appears to be at the Ethiopian side of the border with limited local recharge at the area of outcropping of the water bearing formation.

Water quality is reported to be fresh in the Gedaref formation parts of the basin where TDS values 400 – 500 are recorded while higher values TDS > 800 are expected to be within the basalt formation. Areas that are in contact with the basement complex may exhibit higher salinity values.

Groundwater Development in Gedaref Basin is currently practiced to meet domestic supply as well as the livestock watering. It estimated that current abstraction amount to about 52,000 m³/day, rendering the total annual abstraction from the basin at about 19 Million m³/year.
Figure 4.20: Geology of the Gedaref Basin
4.7. East Kordofan Basin

4.7.1. Location and Extent

The East Kordofan Basin extends from the central Sudan in south east direction where it straddles the Sudan South Sudan international border into the Sudd Area. (Figure 4.1). The part of the transboundary basin within Sudan extends over a length of about 450 Km and covers an area of about 68,000 Km². The basin is formed of a number of subasins which constitutes the northern extension of the White Nile Rift System and the western extension of the Blue Nile Rift System. The Central African Shear Zone does constitute the northern boundary of the basin.

4.7.2. Climate and Topography

The climate in the area of East Kordofan Basin is characterized by a semi-arid climate in the northern part to a semi humid climate in the southern part. Rainfall occurs during the summer period commencing in May in the southern part and June in the Northern part with 80% of the total annual precipitation falling during the months of July, August and September. The total annual rainfall increases progressively from about 300 mm in the north of the basin to about 600 mm in the southern part (Figure 4.21).

The air temperature ranges between 30 to 40 °C in summer but can decrease to a minimum of about 12 °C in winter (Figure 2.2 and Figure 2.3). The evapotranspiration rate is around 190 mm/month during the summer season (April-September) with a total of 2288 mm per year.

The topography of the basin is sloping from the North in a south east direction with a relatively steep gradient in the upper half and a small gradient in the southern half as it approaches the border with South Sudan. High ridges can be found at the northern border of the basin. The ground elevation varies from a high of about 1000 m.a.s.l in the north to about 355 m.a.s.l close to the border of South Sudan (Figure 4.22).
Figure 4.21: Annual Rainfall Distribution in the East Kordofan Basin Region
Figure 4.22: Topography of the East Kordofan Basin
4.7.3. Geology and Hydrogeology

Based on the literature, the geology of North Kordofan State can be itemized from younger to older into

- **Superficial Deposits**  
  → **Late Pleistocene- Recent**
- **Um Ruwaba Formation**  
  → **Late Tertiary Pleistocene**
- **Nubian Sandstone Formation**  
  → **Mesozoic - Cretaceous**
- **Nawa Formation**  
  → **Paleozoic**
- **Basement Complex**  
  → **Pre Cambrian – Cambrian**

**Basement Complex**

The basement complex is the oldest and most extensive rock unit in the basin area. The basement rock crop out around along the northern, southern and western boundaries of the project area. They are mainly granitic gneisses that are migmatized in some parts.

**Nawa Formation**

Nawa formation is the oldest sedimentary rock in the project area, it was first found in water wells around Nawa village north of Er Rahad. It consists of gently dipping unmetamorphosed grits, sandstones and mudstones overlying the basement rocks and occurring along fault contacts with the basement. The sandstones are sometimes cross bedded, whereas thin intercalations of limestones and secondary aragonites also occur. The source rock for the Nawa formation is believed to be the adjacent Nuba Mountains as indicated by the presence of mostly unearthed micas and feldspars. It is believed that the Nawa formation may underlie in some areas the dominant Umm Ruwaba formation.

A cover of recent superficial deposits and sand dunes of variable thickness overlies the Um Ruwaba Formation. The dunes are aeolian deposits elongating north-south and migrating southward as result of desertification, while the superficial deposits are mainly wadi fills. The greatest expanse of these deposits is in the north of the study area where the dunes are most prevalent. The sands are medium to coarse grained, well rounded and well sorted with high infiltration rates that enhance groundwater recharge of the shallow aquifer zones.
The northern part of East Kordofan basin is known as Bara Basin which is one of the most important groundwater basins in south-central Sudan in terms of groundwater availability, water quality and degree of utilization. Groundwater in Bara Basin occurs in the layer of Um Ruwaba formation as well as in the layer of superficial deposits overlaying it and to lesser extent in Nawa Formation and the Nubian Sediments in the far North thus forming two aquiferous layers. Depth to groundwater is controlled by topography, basement configuration, the existing pumping regime and proximity to the recharge sources.

The upper unconfined aquifer is limited to the northern part of the basin, and depth to water varies from 8 m to about 50 m. The lower main aquifer has a thickness varying from 70 meters to more than 300 meters. The upper aquifer is separated from the main aquifer by an aquitard that for the most part hydraulically separates the two aquifers. The Bara Basin itself covers about 60% of the area of East Kordofan Basin within Sudan.

The basement configuration divides the Bara basin into three hydraulically connected subbasins namely El Beshiri (Bara sub-basin), Um Ruwaba and Hashaba (Figure 423).

El Beshiri sub-basin lies within the thick sediments of Bara Graben. The sub-basin can be considered as two separated overlaying aquifers, with the main bottom aquifer under confined to semi confined conditions.

Um Ruwaba sub-basin lies to the south of El Beshiri sub basin and is basically a single layered aquifereous zone under confined to semi confined conditions.

Hashaba sub-basin lies in the eastern part of the study area and is a single aquiferous zone under semi-confined to unconfined conditions.

Proper pumping tests were conducted in 1985 (Geotehnika, 1988), the tests were localized south of Bara town. The obtained results showed that the mean transmissivity of the aquifer in the investigated area was 406 m²/day and that the mean value of the storage coefficient is $3.7 \times 10^{-4}$.

Published results of hydrogeological parameters pertaining to the study area (Abdalla, 2006) do report an average hydraulic conductivity of 0.59 m/day (i.e. a transmissivity of about 90 m²/day given the cited average aquifer thickness of 150 m) and a storage coefficient of $1.7 \times 10^{-4}$. It can be stated in general that the hydraulic conductivity values in Bara Basin vary within a range of 0.5 m/day to 6.0 m/day.
Figure 4.23: Sub-basins of the East Kordofan Basin
Surface runoff constitute the major source of recharge to the Bara Basin including its lower aquifer. Major water courses in the area after flowing for a short stretch on the surface basement percolate in the dunes and enter the water bearing Um Ruwaba Formation when it encounters the down thrown side of a fault.

Figure 4.24 shows the location of the major recharge water courses in the area of study. These water courses constantly recharge the lower aquifer of Bara Basin despite the seasonal character of rainfall in the area. These water courses are non-perennial in nature, they however possess large catchment areas and they are most likely to form seasonal streams with irregular short duration flows between the months of July and August. One of the most prominent of these streams is Khor Abu Habil which is one of the largest non-perennial streams in Sudan.

It should be noted that despite the proximity of the White Nile to the eastern side of the aquifer, recharge from this water course in an east-west direction was not detected. This is attributed mainly to the deposition of thick clays between the river and the water bearing geologic formation in the East Kordofan Basin. However, recharge from the south across the border of South Sudan is perceived and this is expected to cause stagnant zones in the areas of the aquifer close to the international boundary with South Sudan.

4.7.4. Groundwater Flow

Groundwater flow of the upper unconfined aquifer are different from those of the main lower confined aquifer. Groundwater flow in the upper aquifer system flows from the west and northwest to the east (Figure 4.25). The highest hydraulic head value is about 500 meters above sea level, while the lowest value is 370 meters above sea level.

Groundwater in the lower aquifer generally flows from the northwest to the southeast with variable hydraulic gradients. The highest hydraulic head value in the northwest corner of the aquifer is about 480 meters above sea level and it apparently drain into the Sudd Area in South Sudan. The regional groundwater contour map for the lower aquifer identify a significant flow from Khor Abu Habil, as well as inflows from the north eastern border of the basin. If the basin is hydraulically linked to the White Nile System in South Sudan, recharge from the south may occur. The flow from South to North will most likely counteract the natural flow regime in the East Kordofan Basin and is bound to cause stagnant fronts within the basin which may increase the salinity in these areas. (Figure 4.25). It should be noted that the groundwater contour map presented herein was limited to the northern part of East Kordofan Basin (i.e. within Bara Basin) due to the lack of data in the southern part.
Figure 4.24: Average Groundwater levels and Depth to Groundwater for the East Kordofan Basin
Figure 4.25: Groundwater Flow of the upper Unconfined Aquifer for Bara Basin (East Kordofan Basin)
4.7.5. **Groundwater Quality**

Total dissolved solids in the project area were subsequently calculated from the recorded well readings within Bara Basin and were found to range from 80 to 6900 mg/l. The average value of TDS for the study region was found to be 1132 mg/l. Further statistical analysis of the results did indicate that 61% of the results have a TDS value less than 1000 mg/l and that 81% of the samples have a TDS of less than 1500 mg/l. In addition, the mapping of the results has indicated that most of the samples with TDS more than 2500 mg/l are localized in the south east part of the Bara Basin in Hashaba sub basin (Figure 423). These results are attributed to increased salinities resulting from the creation of stagnant zones in that part of the Aquifer.

4.7.6. **Groundwater Development**

The development of groundwater in Bara Basin include open shaft wells, driven wells as well as boreholes. Groundwater development for irrigation purposes is practiced by digging large diameter (4 m) open shaft wells and equipping them with diesel centrifugal pumps. These irrigation wells known locally as Matara, tap the shallow aquifer to depths of up to 8 meters through a 2 to 4-inch diameter driven pipe.

The use of the Matara system is practiced mainly around the town of Bara where the depth to water table of the upper aquifer is generally less than twelve meters.

Development of the lower Bara Basin aquifer is currently practiced through deep boreholes (100 m – 400 m) of 6 inch to 8-inch diameter installed with diesel driven and vertical turbine pumps or by electrical submersible pumps with electrical generating sets. These boreholes are usually equipped with elevated storage tanks and limited water distribution systems for domestic (human and livestock) consumption in what is known as a wateryard. Some agricultural developments also tap the lower aquifer for irrigation through deep boreholes.

The most significant development of the lower aquifer of Bara Basin is by all means El Obeid water supply project which comprises forty boreholes and a pipeline from the well fields to El Obeid town. The well field (named AlSidir) was initially developed to produce 18,000 m³/day using 18 wells, the field had been expanded to forty wells and current abstraction rates are estimated to be 30,000 m³/day. The total daily abstraction from the basin for domestic supply and livestock watering is estimated to be about 82,000 m³/day including the AlSidir Well field.

The use of the lower aquifer for agricultural is not well documented, horticulture production tapping this water resources started to appear in recent years using drip and sprinkler irrigation. It is estimated that the agricultural production using groundwater within Bara Aquifer can reach 6000 Ha consuming about 72 Million m³/year. These estimates put the total current abstraction from East Kordofan aquifer within Sudan at 102 Million m³/year.
5. AQUIFER PROPERTIES

Properties of the main aquifers within the eastern Nile basin in Sudan are summarized in the Table 5.1.

Table 5.1: Properties of the Main Aquifers within the Eastern Nile in Sudan

<table>
<thead>
<tr>
<th>Aquifer type</th>
<th>Aquifer subclass</th>
<th>Aquifer extent, thickness, saturated thickness, depth to water level</th>
<th>Storage (BCM)</th>
<th>Renewable storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement</td>
<td>Gnesissic-Metasedimentary Group</td>
<td>Extent: Precambrian basement rocks over which all other younger sediments had been deposited. Groundwater Occurrence: GW occurs in fractured weathered jointed and faulted zones as well as within the pediment deposits in unconfined conditions. Importance: Low Potential: Very Low Thickness: 5 to 70 m Saturated Thickness: 5 – 20 m Depth to Water Table: 4 – 60 m Yield: low 0.2 – 1.0 l/s Hydraulic Conductivity: Low to Very low. Transmissivity: Recharge: Variable (depending on precipitation) Storativity:</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Basement</td>
<td>Greenschist Complex</td>
<td>Extent: Consolidated Sediments, with continuous aquifers of sub-regional to regional extent. Area ≈ 350,000 Km² Groundwater Occurrence: GW occurs in confined and semiconfined conditions. Importance: Very High Potential: High to Very High Thickness: 50 to 1000 m Saturated Thickness: 20 – 1000 m Depth to Water Table: 2 – 100 m Yield: Low to Very High from 20 – 100 l/s</td>
<td>6000</td>
<td>NA</td>
</tr>
<tr>
<td>Aquifer type</td>
<td>Aquifer sub class</td>
<td>Aquifer extent, thickness, saturated thickness, depth to water level</td>
<td>Storage (BCM)</td>
<td>Renewable storage</td>
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</table>
| **Volcanic Rocks**     | Fractured and Weathered Basalt     | **Extent:** Fractured and Weathered Basalt, forming continuous to sub-continuous aquifer aquifers of local to regional extent. (≈10,000 Km²)  
**Groundwater Occurrence:** GW typically occurs in unconfined conditions.   
**Importance:** Medium to High  
**Potential:** Low to High (Variable)   
**Thickness:** 200 - 500m   
**Saturated Thickness:** 10 – 300 m   
**Depth to Water Table:** 50 – 70 m   
**Yield:** Low to High  
**Hydraulic Conductivity:** Low  
**Transmissivity:** Low (100 m²/day)  
**Recharge:** Variable (depending on precipitation)  
**Storativity:**  
Storage Coefficient:  
Specific Yield: 0.7 NA | 0.7 | NA |
| **(Unconsolidated Sediments)** | Um Ruwaba and Gezira formations | **Extent:** Unconsolidated Sediments, with continuous aquifers of local to regional extent. (≈ 120,000 Km²)  
**Groundwater Occurrence:** GW occurs in confined and semiconfined conditions.  
**Importance:** High  
**Potential:** Low to Medium  
**Thickness:** 10 to 350 m | 75 | NA |
<table>
<thead>
<tr>
<th>Aquifer type</th>
<th>Aquifer sub class</th>
<th>Aquifer extent, thickness, saturated thickness, depth to water level</th>
<th>Storage (BCM)</th>
<th>Renewable storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Water Availability &amp; Conjunctive Use Assessment in the Eastern Nile Aquifer Type</td>
<td>Aquifer sub class</td>
<td>Aquifer extent, thickness, saturated thickness, depth to water level</td>
<td>Storage (BCM)</td>
<td>Renewable storage</td>
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<td></td>
<td></td>
<td>Saturated Thickness: 10 – 150 m</td>
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<td>Depth to Water Table: 0 – 100 m</td>
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<td></td>
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<td>Yield: low to Medium from 2 – 20 l/s</td>
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<td></td>
<td>Hydraulic Conductivity: low to Moderate (0.5 – 20 m/day).</td>
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<td></td>
<td>Transmissivity: 2 – 500 m²/day (low to moderate)</td>
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<td></td>
<td></td>
<td>Recharge: Moderate</td>
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<td></td>
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<td>Storativity:</td>
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<td></td>
<td>Storage Coefficient: 10⁻³– 10⁻¹</td>
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<td></td>
<td></td>
<td>Specific Yield: 0.1</td>
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<tr>
<td>Gezira Formation</td>
<td>Extent:</td>
<td>Unconsolidated Sediments of silts and clays, with continuous aquifers of local to regional extent. (Area ≈ 19,000 Km²)</td>
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<td></td>
<td></td>
<td>Groundwater Occurrence: GW occurs in unconfined conditions.</td>
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<tr>
<td></td>
<td>Importance:</td>
<td>Medium</td>
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<td></td>
<td>Potential:</td>
<td>low to Medium</td>
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<td></td>
<td>Thickness:</td>
<td>5 to 80 m</td>
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<td>Saturated Thickness: 5 – 60 m</td>
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<td>Depth to Water Table: 5 – 50 m</td>
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<td></td>
<td>Yield:</td>
<td>low to Medium from 2 – 20 l/s</td>
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<td></td>
<td>Hydraulic Conductivity: low to Moderate (0.5 – 15 m/day).</td>
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<td></td>
<td>Transmissivity:</td>
<td>2 – 500 m²/day (low to moderate)</td>
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<td>Recharge:</td>
<td>Moderate</td>
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<td>Storativity:</td>
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<td>Storage Coefficient:</td>
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<td></td>
<td>Specific Yield:</td>
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<tr>
<td>Loose quaternary sediments</td>
<td>Extent:</td>
<td>Unconsolidated Sediments of silts and clays or sands, forming continuous aquifers of local extent.</td>
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<tr>
<td>Superficial alluvial / aeolian deposits</td>
<td>Importance:</td>
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<td>Groundwater Occurrence: GW occurs in unconfined conditions.</td>
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<td>Storage (BCM)</td>
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<td>Renewable storage</td>
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<td>Aquifer type</td>
<td>Aquifer subclass</td>
<td>Aquifer extent, thickness, saturated thickness, depth to water level</td>
<td>Storage (BCM)</td>
<td>Renewable storage</td>
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<td>Wadi deposits</td>
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<td><strong>Saturated Thickness:</strong> 5 – 50 m</td>
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<td><strong>Depth to Water Table:</strong> 0 – 20 m</td>
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<td><strong>Yield:</strong> Low to Medium from 0.01 – 20 l/s</td>
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<td><strong>Hydraulic Conductivity:</strong> Low to Moderate (0.5 – 15 m/day).</td>
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<td></td>
<td><strong>Transmissivity:</strong> 500 – 1500 m²/day (Moderate to High)</td>
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<td></td>
<td><strong>Recharge:</strong> Variable (depending on precipitation)</td>
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<td><strong>Storativity:</strong></td>
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<td><strong>Storage Coefficient:</strong></td>
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<td></td>
<td></td>
<td><strong>Specific Yield:</strong></td>
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</table>

* Estimates of groundwater storage are cited for areas of the aquifers within the Eastern Nile Basin.
6. WATER QUALITY – SALINITY

6.1. General Salinity Conditions on Aquifer by Aquifer Level

Salinity is one of the major limitations in the full exploitation of groundwater in the Eastern Nile. Salinity has its origin from both natural and anthropogenic sources. The salinity of the major aquifers within the Sudan can be characterized as follows:

- **Basement Aquifers:** Groundwater quality ranges from fresh to brackish.
- **Nubian Sandstone Aquifers:** Groundwater quality is generally fresh, although salinity increases down-gradient and there are local pockets of higher salinity.
- **Umm Ruwaba Aquifers:** Groundwater quality is usually good and fresh
- **Recent Deposits Aquifers:** Water Quality is generally good.
- **Volcanic Aquifers:** Water Quality is typically fresh in shallow zones to brackish in the deeper aquifer zones.

6.2. Salinity in Groundwater Basins

The salinity of the major identified basins in Sudan within the Eastern Nile was ascertained from existing chemical analysis results of wells within each basin. The point data was analysed to generate salinity maps for each basin. The extent of these maps was limited to parts of the basins by the data availability. The salinity of the groundwater within each basin is summarized hereinafter:

**Nubian Sahara Basin**

Stagnant zones due to basement contact or other flow conditions are likely to cause an increase in groundwater Salinity. The groundwater flow pattern in the basin suggests the presence of such saline zones. Notwithstanding these zones the water quality of the Nubian Sahara Basin in general is excellent as reported in the literature with TDS values of about 500 mg/l.

**Nubian Nile Basin**

Total dissolved solids in the Nubian Nile Basin were found to range from 112 to 5590 mg/l. The average value of TDS for the study region was found to be 685 mg/l. Further statistical analysis of the results did indicate that 84% of the results have a TDS value less than 1000 mg/l. In addition, the mapping of the results has indicated that the areas in the north of the Basin exhibited low TDS values (< 500 mg/l) indicating a strong recharge influence of the River Nile. A front of fresh water also appears to be advancing through the south west corner of the basin toward the Nile in a NE direction indicating the existence of subsurface flow of fresh water in this direction underneath the main wadis in the area (Wadi AlMuqadam). In general, the salinity increases away from the Nile. An exception can be found in area of stagnant zones caused by the existence of two water fronts moving in opposite directions which appears near EdDebba town and in the upper west side of the basin in the interaction area between the Nubian Nile and the Nubian Sahara Basins. Stagnant zones also occur in the areas of contact with the Basement which appears near Merowe town (Figure 6.1)
Atbara Basin

Studies of the Atbara Basin area report the total dissolved solids less than 400 mg/l in the area along the River Nile which is a sign of hydraulic interaction with the river. Areas close to Sabaloga outcrop report TDS values of 2000 mg/l. Areas towards the center of the Basin are also reported to exhibit salinity as the TDS values reach 1500 mg/l. Values of TDS at the southern boundary of the aquifer close to the identified recharge zones are reported to be fresh (TDS < 800 mg/l). The reduced salinity towards the southern border are attributed to the potential impact of recharge from surface runoff.

Blue Nile Basin

Statistical Analysis of the Total dissolved solids (TDS) in the Blue Nile Basin was conducted using 811 samples from wells distributed within the basin. The results were found to range from 98 to 4200 mg/l and the average value of TDS for the Basin was found to be 520 mg/l. Further statistical analysis of the results did indicate that about 90% of the results have a TDS value less than 1000 mg/l. The mapping of the results has indicated that the areas of the basin along the Blue Nile has a TDS value of less than 300 mg/l and that the TDS in most of the basin is less than 500 mg/l. Saline zones within the basin were identified at areas of out-cropping basement (e.g. near Sabaloga in the north and at the south west of the basin), as well as in the area close to the White Nile in the west and North west parts of the basin. The saline zones are attributed to either to the existence of stagnant zones due to basement contact or interaction with White Nile. The groundwater flow in the areas adjacent to the White Nile may be impeded by the existence of thick low transmissivity clays or the existence of an opposite flow emanating from the river. This is bound to create the stagnant zones that in turn can cause the witnessed increased salinities. (Figure 6.2).

Gedaref Basin

Water quality is reported to be fresh in the Gedaref formation (Nubian Sandstone) parts of the basin where TDS values 400 – 500 are recorded while higher values TDS > 800 are expected to be within the basalt formation. Areas that are in contact with the basement complex may exhibit higher salinity values. (Figure 6.3).

East Kordofan Basin

Analysis of the values of the total dissolved solids of Bara Basin in the northern part of East Kordofan Basin has shown that their values range from 80 to 6900 mg/l and the average value was found to be 1132 mg/l. Further statistical analysis of the results did indicate that 61% of the results have a TDS value less than 1000 mg/l and that 81% of the samples have a TDS of less than 1500 mg/l. In addition the mapping of the results has indicated that most of the samples with TDS more than (2500 mg/l are localized in the south east part of the Bara Basin in Hashaba sub basin (Figure 423). These results are attributed to increased salinities resulting from the creation of stagnant zones in that part of the Aquifer. (Figure 64).
Figure 6.1: Total Dissolved Solids (TDS) for Nubian Nile Basin
Figure 6.2: Total Dissolved Solids (TDS) for Blue Nile Basin
Figure 6.3: Total Dissolved Solids (TDS) for Gedaref Basin
Figure 6.4: Total Dissolved Solids (TDS) for East Kordofan Basin
7. GROUNDWATER POLLUTION ISSUES

The inefficient liquid and solid waste disposal practices constitutes a serious and significant risk to the quality of groundwater in Sudan. The use of on-site disposal systems (septic tank and disposal well or pit latrines) as a sanitation system is predominant in Sudan urban centres and villages. The direct injection or seepage of municipal liquid waste to the shallow free water can lead to the contamination the shallow groundwater of the underlying aquifers. Indeed, bacteriological pollution of shallow wadi bed aquifers is commonly reported. The modelling of groundwater contamination from septic tank effluent in Khartoum has shown that in addition to the lateral migration significant contamination from ammonia can reach to 75 meters below the water surface within 10 years.

Lack of land fill sites culminated the practice of dumping or throwing solid waste disposal in the watershed or in the courses of seasonal streams, thus leading to the pollution of the shallow underlying aquifers. Signs of Groundwater contamination from agrochemical practices including the intensive and uncontrolled use of pesticides and fertilizers was detected in open wells in Gezira Scheme and Kassala which are known areas of intensive agriculture. Areas where the depth to water is small (less than 5m) and the soil permeability is relatively high are more susceptible to contamination.

Industrial waste can contain highly toxic compounds such as heavy metals and radioactive material. The increase of industrial activities and subsequent increase of industrial waste accompanied by the spread of improper waste disposition practices is another serious threat to groundwater quality.

More recently the oil exploration and production have imposed a major threat to the groundwater resources in the development areas due to the huge volume of produced oil contaminated water which is in many cases improperly disposed.

The spread of unregulated mining activities during the past five years has increased the uncontrolled use of hazardous chemicals such as cyanide and mercury and is believed to pose an imminent and long-lasting threat to groundwater quality.

Cases of wide spread contamination within the identified groundwater basins in the eastern Nile include the widespread nitrate pollution reported to occur in the Umm Rawaba basin (East Kordofan). Excess Fluoride (more than 2 mg/l) found in association with basalt in Gedaref.
8. PALEOHYDROLOGY

The Sahara Desert is currently one of the most arid places on the planet earth. However, there was a period in time during which North and East Africa received substantially more precipitation than at the present. This period which occurred approximately 15,000 to 5,000 ago (15 – 5 Ka) is referred to as the African Humid Period (AHP). During this period the Sahara Desert contained large and small lakes and was nearly completely vegetated with grasslands, shrubs as well as some woodland vegetation.

The changes that took place since the AHP and which were caused by gradual shift in the orientation of Earth’s axis of rotation include the following

**Change in precipitation rates:** Precipitation in the area between 15 – 25 ° N in Africa which include the area of Northern Sudan was estimated to range from 175 - 600 mm for 6 ka as opposed to range of 0 – 100 mm in modern times.

**Drying of Lakes:** Large lakes that occupied multiple deflation basins were in existence and which were a source of recharge for the underlying formations gradually dried out between 5.6 ka until as recently as 1 ka.

**Rise in Dust Flux:** The area of North Africa witnessed a significant increase in dust flux indicating the start of the desertification process. The period from 14.5 ka to 13 ka witnessed relatively low sand flux. A progressive increase of Dust fluxes can be traced to the period from 12 – 6 ka this was followed by an abrupt rise at ~ 5.5 ka doubling thereafter over a period of only few centuries. The rise of the dust flux was not limited to the Northerner Africa, rather it could be traced south to 12° N.

**Displacement of Vegetation Zones:** The most extensive vegetative cover across the Sahara occurred between ~10–8 ka when Tropical-associated species extended as far north as 20–25˚N thus including all of the modern Sudan. At 6 ka, sites throughout the modern Sahara show evidence for grasses and shrubs typical of subtropical steppe which extended to 30˚N and savanna environments which extended to approximately 20˚N across most of North Africa. The vegetation displacement started at 6 ka with an extensive increase of regional grasslands and local wadi vegetation. The transition to more xeric species occurred gradually after 4.7 ka, with desert flora becoming fully established only after 2.7 ka (Kröpelin et al., 2008)

**River Discharge:** The River Nile discharges were much higher from 10 – 8.5 ka than today’s discharge. The river witnessed a gradual decrease in between 8 – 4 ka.

**Drying of Seasonal Streams:** Several currently inactive river drainages in the Sahara were active during the AHP. One such drainage is the lower Wadi Howar in the Nubian desert of northern Sudan. Here, a variety of geologic and faunal evidence points to this drainage having been active during much of the AHP (Pachur & Kröpelin, 1987). This watercourse extended over 400 km from the current terminus of the upper Wadi Howar to the Nile, connecting the eastern central Sahara to the Nile. Remote sensing data and GIS analysis also indicate the existence of large relict drainages in both the western and northern Sahara.

The paleohydrodogy of Sudan explains the conditions that formed the groundwater basins of today and shows the impact of today’s environment and conditions on these non-renewable resources.
9. TRANSBOUNDARY AQUIFERS

Three of the six main identified groundwater Basins in Sudan that lie within the Eastern Nile Basin are transboundary Basins. These are:

The Nubian Sahara Basin which is part of the Nubian Sandstone Aquifer (NSA) that Sudan shares with Egypt, Libya and Chad. The area of the aquifer within Sudan comprises about 17% of its total area and the area of the aquifer that falls within the Eastern Nile comprises only 4% of the total area of NSA. The management of the Nubian Sahara Basin must essentially be conducted as part of the overall management of the NSA as a transboundary non-renewable aquifer which will require the cooperation of the four countries that shares it. The fact that two of the four countries are not within the Nile watershed will effectively put the management of the Nubian Sahara Basin outside the realm of the Eastern Nile and River Nile cooperation protocols and agreements. The four NSA countries have already embarked as of 1999 on a process to cooperate on the management of the aquifer system through the Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System (JASAD-NSAS). The mission of the Joint JASAD-NSAS is to provide the regional legal and institutional mechanisms necessary to formalize regional cooperation in the management of the NSA.

The East Kordofan Basin is part of a regional Um Ruwaba Aquifer that is shared with South Sudan with only 68,000 Km² within Sudan. The two countries (Sudan and South Sudan) also, share Recent deposit aquifers. Indications are that the part of the aquifer within Sudan (Bara Basin) receives its annual recharge from non-Nilotic sources and the there is a hydrogeological divide between the East Kordofan Basin in Sudan and the Sudd Basin in South Sudan. The divide is indicated by the existence of saline regions close to the international boundary. Nevertheless, field investigations are required to better characterize the interaction between the Sudan/South Sudan parts of the aquifer.

The Gedarif Basin in Eastern Sudan with its volcanic and Nubian Sandstone Aquifer are shared with Ethiopia. Indications are that the most of the renewable recharge to the basin come from the Ethiopian side of the border. This is indicated by the NW flow trend within the basin.

Currently there are no institutional setups between Sudan and South Sudan or Sudan and Ethiopia for the joint or shared management of the transboundary aquifers between the respective countries.
10. GROUNDWATER SURFACE WATER CONNECTION

The Blue Nile contributes about 70% of the River Nile waters. It flows out from Lake Tana in the north western part of Ethiopia at Bahir Dar. The river cuts its way into Cenozoic basaltic highlands forming deep gorges and capturing the runoff of most of the Blue Nile Basin and flowing into the flat plains of Sudan.

The Blue Nile River is characterized by very high discharges during the wet seasons (July – September) and very low discharges during the dry season. It flows from the Ethiopian highlands into the flat savannah of south eastern Sudan, where it does constitute the most important source/drainage feature of the area. The Blue Nile and White Nile make their confluence in Khartoum forming the Main Nile which flows through Sudan into Egypt.

Surface water groundwater interaction will be viewed along five hydrologic sections stretching over a distance of 2500 Km from the Sudanese-Ethiopian border to the Sudanese Egyptian Borders. The five sections are

- Blue Nile segment covering the distance from the Sudanese Ethiopian border to Khartoum (800 Km)
- Khartoum-Atbara Segment (350 Km)
- Atbara-Merowe Segment (500 Km)
- Merowe-Dongola Segment (400 Km)
- Dongola-Wadi Halfa Segment (450 Km)

Blue Nile Segment

In this segment the Blue Nile and its two main tributaries (Rahad and Dinder Rivers) flows through the Blue Nile Basin. The basin has a flat terrain and is occupied by tertiary unconsolidated sediments and Mesozoic consolidated sediments in the lower part.

There is ample evidence that the Blue Nile and to a lesser extent its tributaries the Dinder and Rahad rivers do contribute to the recharge of the underlying Blue Nile groundwater basin.

This is validated through the interpretation of stable isotope composition of groundwater in the basin as reported in existing studies. In addition, reports of the groundwater levels in the basin have revealed the existence of a lagged correlation between the hydrographs of the River flow and groundwater level. While being the source of recharge during the flood season, the Blue Nile become a gaining river and acts a drainage during the low season.

Khartoum – Atbara Segment

The River Nile emerge from the sixth cataract North of Khartoum and cut into the Nubian Sandstone in a North – North East direction towards the confluence location with the Atbara River. The River Nile
form the hydrological divide that separates the Nubian Nile Basin from the Atbara Basin. Groundwater level maps do indicate that existence of recharge from the River Nile to both basins.

**Atbara – Merowe Segment**

The River Nile moves through the basement complex in the Atbara – Merowe Segment in a North, north west direction towards the 5th Cataract towards the town of Abu Hamad before turning to a South West direction towards Merowe. The deflection of river’s course is attributed to the tectonic uplift of the Nubian Swell.

**Merowe – Dongola Segment**

After clearing the basement complex at Merowe, the Nile gradually change it course from the south west to its original north course as it travels in a North/North-west direction cutting into the Nubian Sandstone of the Nubian Nile Basin. Recharge to the Aquifer in this segment had been confirmed by isotope studies. The area between Edebba and Dongola in particular receives significant recharge. The segment ends at the basement complex outcrops about 60 Km North of Dongola town (at Abu Fatma). These outcrops constitute the northern boundary of the Nubian Nile Basin. Even though the basin become a shallow unconfined aquifer (50 m – 100 m) North of Dongola, it has a very high yield as well as recharge potential. This is attributed to the existence of tertiary volcanic sills that has apparently caused the silicification of the Nubian Sandstone during its activity and the formation of secondary porosity cracks during its cooling process.

**Dongola – Wadi Halfa Segment**

In this final segment the Nile flows through a basement complex formation in a North-East direction towards the Sudan/Egypt international boundary.
11. GROUNDWATER ABSTRACTION

Groundwater provides an important source of water supply in Sudan. About 80% of the inhabitants depend on groundwater for their living most of the year. The persistence of drought and erratic nature of rainfall in the country over the past few decades have emphasized the importance of groundwater as a reliable source. The development of groundwater in Sudan for domestic supply and livestock watering had been practiced for hundreds of years in various parts of the country using dug wells. These open shaft wells are still a major water source in addition to hand pumps in remote settlements or small villages in various parts of Sudan. The technique is not limited to areas with shallow water tables, indeed deep shaft wells were found in areas with relatively deep depths to groundwater (20 meters). Since groundwater quantities developed by this technique are very low, the technique of open shaft well is being replaced by more hygienic and efficient systems such as tube wells and public water supply systems in larger settlements. Communities within Sudan are increasingly relying on groundwater for domestic supply as in most cases it is the only available perennial water source. Communities residing near surface water perennial sources are also relying on groundwater for their domestic supply due to the infeasibility of constructing water treatment and conveyance systems (Figure 1.11).

Smallholders residing along the River Nile generally abstract water for irrigation directly from the river by using small diesel pump. The delivery head of these pumps usually allow for the irrigation of areas within 300 m to 500 m from the river banks. Smallholders beyond this limit usually resort to the use of groundwater for irrigation.

Groundwater abstraction for irrigation purposes started in the forties of the last century by digging large diameter (4m) open shaft wells and equipping them with animal driven wooden wheels locally known as ‘Matara’ or ‘Sagia’. In the mid-sixties and to cope with increasing water demands the Mataras were equipped by diesel driven centrifugal pumps. In order to cater for seasonal groundwater level fluctuations and to tap the rich deep aquifer zones the Mataras were outfitted with 2” – 3” driven pipes to depths of up to 8 m. The system is presently called driven wells on Matara, and able to reach maximum depths to groundwater of about 20 m.

The use of the driven wells within the Nile irrigated schemes is not uncommon due to the steadiness they provide in irrigation permanent crops. However, it must be noted that the limited suction head of the diesel driven centrifugal pumps (< 6m) is affected by seasonal groundwater level fluctuations (2 – 4 m) along the Nile banks and the increased depth to groundwater along the upper terraces. The pump efficiency significantly decreases with increasing pumping depth. In addition, the low yield of driven wells (< 30 m³/h) does not provide enough water for extensive agricultural development.

Drilling of deep boreholes for irrigation purpose started in Sudan in 1956 by drilling 12” diameter boreholes (100-200 m depth) with high yield. The use of deep boreholes for irrigation has witnessed significant expansion since that time. Investment in medium and large scale agricultural projects using groundwater and sprinkler irrigation started to spring in various parts of the country particularly the Northern State. This expansion is driven by the economic redound brought by these investments as well as the improvement of infrastructure in the form of electricity and roads which allow for the feasible implementation and operation of such projects.
The relentless expansion of groundwater development is expected to cause a serious strain on the groundwater levels in the area. Such development must be carefully monitored and regulated so as to avoid the depletion and or contamination of groundwater resources.

Data pertaining to groundwater development in Sudan within the Eastern Nile Basin was compiled during the course of this study. The data included the number and yield of domestic supply wells within the aquifers of interest as well as the areas irrigated by groundwater using groundwater. The domestic supply data was obtained from the relevant authorities within the federal government agencies as well as the authorities within the relevant states. The obtained data reveal that the total annual abstraction for domestic supply is limited to about 200 Million m$^3$.

Table 1.11: Abstraction for Domestic Water Supply from Groundwater Basins in Sudan within the Eastern Nile Basin

<table>
<thead>
<tr>
<th>Basin</th>
<th>Abstraction Rates for Domestic Water Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m$^3$/day</td>
</tr>
<tr>
<td>Nubian Sahara</td>
<td>40</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>164,000</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>245,000</td>
</tr>
<tr>
<td>Atbara</td>
<td>10,000</td>
</tr>
<tr>
<td>Gedaref</td>
<td>52,000</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>82,000</td>
</tr>
<tr>
<td>Basement</td>
<td>50,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>603,040</strong></td>
</tr>
</tbody>
</table>
Figure 1.11: Groundwater Wells for Domestic Supply in the Eastern Nile Region in Sudan
12. AREA UNDER GROUNDWATER IRRIGATION

The areas of agricultural development in Sudan within the Eastern Nile Basin were ascertained during the course of this project through the analysis of Landsat satellite imagery acquired in 2018 for the whole of the study area. The analysis included the identification and classification of the permeant agricultural areas from the remote sensing data and the distinction through the analysis of satellite imagery and other soft data between the agricultural areas irrigated from groundwater and those irrigated by direct conveyance from other surface water sources. The identified agricultural areas within the extent of the study area for each groundwater basin are given in Table 12.1. The total areas under groundwater irrigation are estimated to reach about 130,000 Ha, primarily (90%) within the Nubian Nile and Blue Nile groundwater basins. These areas can be grouped into two categories, areas the rely solely on groundwater for irrigation and areas that partially rely on groundwater for irrigation. Most of the areas that fall under the first category are found within the Nubian Nile Basin and are estimated to account for about 50% of the area under groundwater irrigation within the Basin, while most of the areas under groundwater irrigation within the Blue Nile Basin fall under the second category.

Table 12.1: Agricultural Areas Irrigated by Groundwater

<table>
<thead>
<tr>
<th>Basin</th>
<th>Areas Under Groundwater Irrigation (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>40</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>77,500</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>40,000</td>
</tr>
<tr>
<td>Atbara</td>
<td>5,000</td>
</tr>
<tr>
<td>Gedaref</td>
<td>-</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>6,000</td>
</tr>
</tbody>
</table>

Estimates of the daily and annual abstraction rates for agricultural purposes were subsequently made on the basis of a crop water requirements of 18,000 – 20,000 m³/year/Ha for areas with low precipitation and high temperature rates (i.e Nubian Nile, Nubian Sahara and Atbara Basins), while a lower crop water requirement between 10,000 to 12,000 m³/year/Ha was adopted for the other three basins. The applied rate depended on the climatic condition, annual precipitation rates, the length of the rainy season as well as the prevalent cropping pattern.

The total annual abstractions for each basin for both agricultural and domestic requirements were estimated for each of the six aquifers within the study area (Table 12.2).
Table 12.2: Total Annual Withdrawals from Groundwater Basins within the Study Area

<table>
<thead>
<tr>
<th>Basin</th>
<th>Annual Abstraction Rates for Agriculture Mm$^3$/year</th>
<th>Abstraction Rates for Domestic Water Supply m$^3$/day</th>
<th>Total Estimated Annual Groundwater Abstraction Mm$^3$/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>0.8</td>
<td>40</td>
<td>1.0</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>1,400</td>
<td>164,000</td>
<td>1,460</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>400</td>
<td>245,000</td>
<td>490</td>
</tr>
<tr>
<td>Atbara</td>
<td>95</td>
<td>10,000</td>
<td>100</td>
</tr>
<tr>
<td>Gedaref</td>
<td>0</td>
<td>52,000</td>
<td>19</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>70</td>
<td>82,000</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1965.8</strong></td>
<td><strong>553040</strong></td>
<td><strong>2,170</strong></td>
</tr>
</tbody>
</table>

The total annual abstraction from the groundwater basins within the study area is about 2.2 billion m$^3$ per year more than 65% of which is from the Nubian Nile Basin. Groundwater abstraction for irrigation purposes account for about 99% of the total abstraction (Figure 12.1).
Figure 121: Delineated Agricultural Areas that depend on Groundwater for the Nubian Nile Basin in the year 2019.
13. THREATS TO GROUNDWATER RESOURCES

Sudan is endowed with significant groundwater resources, which can be utilized for meeting the ever-growing water demand for domestic, industrial and agricultural uses. These resources however are facing the following threats:

- **Groundwater Depletion**

  Overexploitation of groundwater resources can cause significant drawdowns and lead over time to a significant increase in the cost of groundwater abstraction and potentially to the depletion of these resources. Cases of unfettered extensive groundwater development for agricultural purposes is noticeable in many areas of Sudan. This is clearly noticeable in the Northern State and West Omdurman (Khartoum State) which tap the Nubian Nile Basin.

- **Groundwater degradation**

  Over abstraction, poor management and inadequate development of groundwater resources can lead to degradation of groundwater quality by inducing changes in groundwater flow patterns to and from adjacent aquifer systems. Cases of introducing salinity or contamination through the improper development of overlying aquifers are present in Khartoum and North Kordofan. The prevalence of such practices may lead to the large-scale degradation of pristine aquifers.

- **Recharge Decline (Reduction of Reliable Yield)**

  Human intervention in the training or control of surface water courses may inadvertently impact the ground-surface water interaction regime and lead to the decline of recharge of groundwater. The control of ephemeral streams in semi-arid areas is known to impact the recharge of the shallow aquifers in contact with the stream. It is had been argued for example that the training efforts of the Gash River in Eastern Sudan has adverse effects on the potential recharge of the Gash Aquifer the primary water source for Kassala city.

  In the context of the of the Eastern Nile, it is argued that the significant upstream interventions in the Blue Nile flow is bound to impact the groundwater recharge to the Blue Nile and Nubian Nile groundwater basins. Recharge decline may also be potentially caused by climate change and the subsequent change of the surface runoff and river flows that contribute to the groundwater recharge.

- **Groundwater contamination**

  Groundwater contamination is a significant threat to groundwater quality in Sudan. Microbial contamination from municipal practices, chemical contamination from agricultural and industrial activities pose a clear and imminent threat to the groundwater quality in all of the urban and development centers of Sudan.

Mitigation of the aforementioned threats to groundwater resources is only possible through the effective management of these resources. The challenges facing the implementation of adequate management whether legal, institutional or financial, must be identified and addressed to reduce the threat to groundwater resources.
14. GROUNDWATER MONITORING PRACTICES IN SUDAN

14.1. Overview

Groundwater is a hidden resource the occurrence and movement of which can only be ascertained through the careful interpretation and analysis of water level measurement from observation wells. Long-term, systematic measurements of water levels provide the essential data needed to evaluate changes in the resource over time, to assess the impact of hydrologic stresses on aquifers, develop ground-water models and forecast trends, as well as to design, implement, and monitor the effectiveness of ground-water management programs.

The design of monitoring network for any aquifer or basin is about deciding the number and location of observation wells as well as the type of measurement to be conducted and its frequency. Decisions about the areal distribution and depth of completion of observation wells should consider the physical boundaries and geologic complexity of aquifers under study. Water-level monitoring programs for complex, multilayer aquifer systems for example require measurements in wells completed at multiple depths in the different geologic units. Large, regional aquifers such as those identified within Sudan during the course of this study require vast networks of observation wells distributed within the extent of each basin.

Selection of the number of observation wells is one of optimization. The objective is to ascertain the required information while using the minimum number of observation wells. This can result in a significant reduction in the cost of installation and operation of the monitoring network.

The frequency of water-level measurements is among the most important components of a water level monitoring program. Although often influenced by economic considerations, the frequency of measurements should be determined to the extent possible with regard to the anticipated variability of water-level fluctuations in the observation wells and the data resolution or amount of detail needed to fully characterize the hydrologic behavior of the aquifer.

Measurement of groundwater levels and quality in Sudan relies to a great extent on sampling existing wells. For obvious cost control measures rarely are observation wells constructed and dedicated for groundwater monitoring. This implies that the areal extent of the monitoring is limited to the inhabited areas of the aquifer which may render large areas of the aquifer unmonitored. The potential impact of this practice can be easily visualized in the cases of Nubian Sahara, Nubian Nile and Atbara basins where the human settlements are localized close to the River Nile. Monitoring systems are thus mainly designed by designating some of the inventoried wells in the aquifer for periodic measurement. Measurements usually include depth to groundwater and limited water quality parameters namely the electrical conductivity (EC) and the PH. The monitoring well selection criteria include a number of factors including:

- The well is accessible and can be regularly monitored;
- The details about the depth and construction of the well are sufficiently known;
- The details of the screen setting are roughly known;
- The well is complete and the water is clean or can be cleaned by purging;
The hydraulic contact with the aquifer is good (the water level should recover within minutes after purging).

Systematic groundwater monitoring in Sudan is greatly hampered by budget constraints and the absence of a clear well stated monitoring plan for the different aquifers by the relevant authority namely the Groundwater Directorate and its regional offices. The absence of logistics such as transportation, fuel and accommodation costs are often cited as reasons for cancelling or limiting groundwater monitoring campaigns. These costs are not trivial given the geographic extent of the aquifers and the roughness of the terrain that has to be covered. For many years the groundwater measurement effort within a basin had been limited to the compilation of the data obtained from newly drilled wells.

Most of the serious and semi-comprehensive groundwater monitoring efforts in Sudan were financed by international development funds, or as a part of a major national development project. While these campaigns established spatially extended networks, rarely did the monitoring of these networks extend beyond the project period, and while the observations wells remained in place, the routine and continuous measurement of these wells was abandoned. Two examples of such cases are the monitoring networks of the Nubian Nile Basin and that of Bara Basin within East Kordofan Basin.


A program of groundwater level monitoring including continuous recording and periodic measurements was carried in Dongola Basin within the hydrogeological investigations of the Nubian Sandstone Aquifer project 1984-1986 by Bonifica of Italy. The campaign included 106 observation points most of which were concentrated in a narrow strip along the River Nile with only few wells located in a larger distance from the river. A number of factors adversely affected the accuracy of the groundwater measurements at the time due to the facts that measurements were carried out with bailers instead of light meters and the lack of precise knowledge of the monitoring reference point elevations. The measurement activities stopped after 1986 and were partially and intermittently continued between 2001 – 2003 for few observation wells in the Dongola area.

The Nubian Nile Aquifer monitoring network was reinitiated in 2004 as part of Merowe Dam construction effort. The new monitoring program included the installation of 38 new observation wells as well as the incorporation of the operational wells deemed suitable for the monitoring process. A surveying campaign was carried out to ascertain the precise location and altitude of the monitoring wells. The monitoring network included a total of 70 wells and covered an area of about 12,000 Km$^2$. The monitoring program lasted for a duration of six months following the completion of the network installation (February 2005 to July 2005). The network was operated by the GWWD office in the Northern State for an additional six months after which the monitoring became intermittent due to lack of logistical funds. In 2017 two monitoring campaigns involving about 180 wells were conducted as part of a research project financed by the ministry of higher education in Sudan (Figure 14.1). The campaign included the sampling of 185 wells covering an area of about 40,000 Km$^2$. The network remains the largest and most active groundwater monitoring network in Sudan.
14.3. Bara Basin Monitoring Network

Bara Basin which lies in the northern part of East Kordofan Basin enjoyed a monitoring program that was established in the 1970s for exploratory purposes over EL Beshiri and Um Ruwaba Sub-basins. The network was expanded in 1985 to more extensively cover the area around Bara town (El Beshiri subbasin) and gradually expanded over time with the coverage being limited basically to El Beshiri and Um-Ruwaba Sub-basins. The monitoring program witnessed its zenith during the period from 2000 to 2009 following the commissioning of Alsidir well field as the program included 50 wells tapping the top and lower aquifers over El Bishiri and Um Ruwaba basins. The program logistics were supported during this period by the IFAD. The funding for the monitoring program was left to a very limited and dwindling government budgets after the termination of the project. This led to the disbandment of the monitoring program as of 2010 (Figure 14.2).
Figure 14.1: Distribution Nubian Nile Aquifer Monitoring Network 2017

Legend
- Monitoring Well 2017
- River Nile
- Nile Nubian Aquifer
Figure 14.2: Distribution of Bara Aquifer (Eastern Kordofan) Monitoring Wells 2009
14.4. Current Status

It is without doubt that the establishment of a fully functional monitoring program for any groundwater basin is a prerequisite for the establishment of any scientific and serious effort to manage its development. The status of the monitoring networks for the six identified Eastern Nile groundwater basins within Sudan are as follows:

- There are no established monitoring networks in four of the eastern Nile groundwater basins within Sudan (namely Nubian Sahara, Atbara, Blue Nile and Gedaref).
- An extensive currently unoperated network exist for the Nubian Nile Basin the network. The network can be reinitiated with limited effort.
- The Bara Basin network that had not been operated for about nine years and may be potentially rehabilitated to cover the East Kordofan Basin.

The future operation of any of these networks should seriously consider the option of installation of automatic measurement systems equipped with telemetry to improve data acquisition frequency and reduce the cost of the system operation.

Groundwater monitoring is not merely the process of recording observation well readings. It also includes the documentation, maintenance analysis and communication of the compiled data and information. The system operation requires a well-trained support staff, that is capable of managing the collected data as well as direct and enhance the operation of the monitoring system.
15. GROUNDWATER GOVERNANCE

15.1. Institutional Setup and Water Legislation

15.1.1. Institutional Setup

The responsibility of the water resources monitoring, development and management in Sudan at the time of independence (1956) was under the responsibility of the Ministry of Irrigation and Hydroelectric Power which was later renamed as the Ministry of Irrigation and Water Resources.

It should be noted that the responsibility of the exploration and assessment of groundwater was historically vested with the Department of Geology and Mineral Resources (now the Geological Research Authority of Sudan). However, since 1964 the National Rural Water Corporation (NRWC) became entrusted with the exploration, assessment and development of groundwater resources. The focus of the agency was mainly the development, operation and maintenance of water supply facilities for rural human and animal supply through the drilling of deep boreholes as well harnessing surface waters. The NRWC operated under different names and ministries until its dissolution in 1994.

The ministry of Irrigation and Water Resources witnessed significant administrative mandate changes between 1999 and 2012 that included the establishment of an independent Dam Implementation Unit (DIU) responsible of the technical, administrative and financial issues pertaining to the design of and implementation of dams as well as major irrigation projects. In 2012 the administration of irrigation infrastructure in the government irrigation projects was transferred to the Ministry of Agriculture, thus practically limiting the role of the Ministry of Water Resources to the task of overall planning and management of Sudan Water Resources. Less than six months later by the end of 2012 the ministry of electricity and dams (including the DIU) were consolidated with the Ministry of Water Resources to form the Ministry of Water Resources and Electricity. (MWRE). Few years later the administration of the irrigation sector was returned to its parent ministry and the Ministry of Water Resources, Irrigation and Electricity was formed it became the agency entrusted with the monitoring, assessment, planning and development of the water resources in Sudan at the national level. In September of 2019 and following significant political changes, the governance of electricity was removed from the ministry and it was renamed the Ministry of Water Resources and Irrigation. While the new ministry is expected to undergo major restructuring, the current organizational structure of the ministry and its departments as inherited from the previous political regime is shown in Figure 15.1.

The ministry organ responsible of management of groundwater resources in Sudan is the Groundwater Directorate within the General Directorate of Groundwater and Wadis. The mandate of the directorate is to develop the national groundwater resources, monitor the usage of groundwater and coordinate the development of groundwater resources, particularly in the case of cross-state groundwater basins. It should be noted that at least one other department within the ministry namely the Dams Implementation Unit which reports directly to the minister also conducts groundwater monitoring and assessment tasks with little coordination with the Groundwater Directorate.

The planning of management and development of transboundary aquifers on the other hand is the responsibility of the of the Water Resources Technical Organ which coordinates with groundwater directorate and directly reports to the minister.
Figure 15.1: Hierarchy of the Ministry Irrigation Water Resources and Electricity of Sudan
15.1.2. Water Management Policy

The first water policy, strategy and plan was formulated in 1913 by the colonial powers and was geared like the other policies during the colonial period towards the development of large scale irrigation schemes (e.g Gezira Scheme). The first water policies in the post-independence era was formulated following the 1959 Nile Waters Agreement and was also geared towards the development of surface waters for hydroelectric power generation (e.g. Roseriess Dam) as well as the provision of sufficient waters for the development of large-scale irrigation projects (e.g. El Managil Extension, El Gunaied Sugar Project). These policies were revised in 1978 and the Master Plan of the Nile Water was prepared. These plans and policies were focused on Surface waters and did not give any consideration to the development of groundwater resources.

In 1992 a comprehensive review of water policies and legislation was conducted by the Ministry of Irrigation and Water Resources. The result was the formulation of the National Comprehensive Strategy (NCS) for Sudan from 1992 to 2002. The strategy continued to consider the water resources sector as a subsector of the agricultural sector, it however identified its policy objectives and strategies for groundwater development which included the full and efficient utilization and development of groundwater resources to eliminate thirst and completely eradicate water scarcity for human and animal life.

In 1999 the Ministry of Irrigation and Water Resources (MIWR) recruited a multidisciplinary team to evaluate the implementation of the NCS and prepare the 2000 National Water Policy (NWP). The input of a large number of stakeholders was solicited for the preparation of preliminary NWP draft, and a national workshop with wide multisectoral participation was conducted for its evaluation and improvement.

The National Water Policy (NWP) was incorporated as part of the comprehensive national Quarter Century Strategy (2002 – 2027) of which the water resources was only one sector. The QCS goals particularly pertaining to groundwater included:

- The expansion of groundwater for irrigation and addressing the problems of excessive drawdowns and groundwater deterioration
- Mitigating the environmental pollution hazard

Additional goals pertaining to water resources in general and other sectors and applicable to groundwater included

- The need to enhance regulation and coordination between the different users and avoid fragmentation of government responsibilities and institutions in the different states of Sudan.
- Mitigating the environmental pollution hazard
- The formulation of a regulating body to establish the appropriate enforcement mechanism for the management and development of water resources and to enforce the Environment Protection Act of 2000.
- Enhancing the capacity in water resources management and development in the federal and states’ governments.
The outcome of the QCS led to the formulation of the Integrated Water Policy Strategy (IWPS) which came into existence in 2007. The policy gave the highest priority to the development of water resources including groundwater to meet the basic human needs and to encourage the participation of users such as the private sector in this endeavor. The strategic actions of the policy identified project plans to meet the increased demand for water according to the set priorities, and has put a target for the minimum available per capita water use for urban and rural areas. The policy stressed the importance of implementation of the existing water acts and identified measures to be undertaken to strengthen the water resources management so as to address the problems of overexploitation, water quality control and demand management.

15.1.3. Sudan Water Legislations

The history of water legislation in Sudan dates back to the year 1939 with the enactment of the Nile Pump Control Act, a number of legislations were passed and implemented thereafter. The main theme of the national water legislations in Sudan between 1939 and 1995 focused on the regulation of the use of surface waters particularly the River Nile and its main tributaries for irrigation and drainage. It was not until the enactment of the 1995 Water Resources Act did the Sudanese legislator address the regulation of the development of the groundwater resources. The national water laws and regulations that have been drafted between 1939 and 1995 are listed in Table 15.1.

Table 15.1: List of Sudan Water Legislations

<table>
<thead>
<tr>
<th>Act</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Nile Pump Control Act (1939).</td>
<td>To control the pumping from the River Nile</td>
</tr>
<tr>
<td>The Agricultural Tenants Protection Act (1950)</td>
<td>The protection of agricultural tenants and regulation of pumping from the Nile</td>
</tr>
<tr>
<td>The Fresh Water Fisheries Act (1954)</td>
<td>The protection of the freshwater fisheries of Sudan and to regulate and control fishing</td>
</tr>
<tr>
<td>The Water Hyacinth Control Act (1960)</td>
<td>To control and prevent the spreading of the water-hyacinth in rivers and waterways in Sudan</td>
</tr>
<tr>
<td>The Environmental Health Act (1975)</td>
<td>To preserve public environmental health including provision and preparation of public drainage, drain water and sewage water</td>
</tr>
<tr>
<td>The Irrigation and Drainage Act (1990)</td>
<td>Regulation of all irrigation and drainage activities</td>
</tr>
<tr>
<td>The Water Resources Act (1995)</td>
<td>• Harmonization of existing Laws and Regulations</td>
</tr>
<tr>
<td></td>
<td>• Assigning and streamlining custody of water legislation implementation</td>
</tr>
<tr>
<td></td>
<td>• Redefine Water Resources to include both surface and groundwater</td>
</tr>
<tr>
<td></td>
<td>• Extend custody to all aspects of use of water resources including consumptive use such as hydro-power generation as opposed to previous legal regimes which were confined to irrigation and drainage</td>
</tr>
</tbody>
</table>
The conception and adoption of the Water Resources of 1995 came as a direct result of the implementation of the national comprehensive strategy of 1992, which resulted in the restructuring of the water sector. Under the 1995 legislation all water affairs in Sudan were brought under the umbrella of the Ministry of Irrigation and Water Resources (MIWR) including the policy formulation functions which primarily encompasses the following main functions:

- To assess, formulate and develop the national plan for irrigation
- To formulate policies for the use of water resources and review and update such policies according to new developments.

The 1995 act also established and/or adopted the following institutions:

1. **The National Council for Water Resources (NCWR);** Established in 1995 it is headed by the minister of MIWR with representatives from major suppliers and users of water both on the national and state levels. Its mandate includes:
   - To formulate the general policy for water resources.
   - To formulate a long term federal plan for the optimal and balanced use of water resources and set the national priorities.

2. **The National Water Corporation (NWC);** Already in existence since 1992, the corporation was mandated in 1995 to conduct the following tasks
   - Formulate the general policy for drinking water at the national level and protection of the surrounding environment
   - Propose legislation regulating the use of water for drinking and the implementation of such uses as well as capacity building
   - Management of foreign aid dedicated for drinking water projects.

3. **The Irrigation Water Corporation;** This corporation was established by the Council of Ministers to provide services in connection with irrigation systems to the agricultural corporations for a fee. The agricultural corporations were to collect these service fees from the farmers.

The implementation of the 1995 Water Resources Act faced a number of challenges and obstacles particularly after the full adoption of the federal system in Sudan following the approval and adoption of the 1998 constitution. According to the constitution the federal government is responsible for the planning, regulation and execution of inter-state waters and national electricity projects. On the other hand, each state exercises legislative, executive and planning functions in non-transit waters and electric power within its boundaries. The increased powers of the states ordained by the 1998 constitution and the restructuring process that emanated thereof, resulted in a number of changes that engulfed the institutional setup of the water sector in Sudan. The irrigation water corporation was dissolved in May 1999 and irrigation services at the minor canal level was to be shouldered by the management of the concerned irrigation scheme under the technical supervision of the Ministry of Irrigation and Water Resources. The responsibility for water supply sanitation and Hygiene (WASH) became vested with the Ministry of Water Resources, Irrigation and Electricity (MWRIE) and Ministry of Health. The Drinking Water & Sanitation Unit (DWSU), which operates under MWRIE became responsible for planning,
implementation of national water supply projects, provision of technical support, upkeeping of standards, training and issuing of policies. At the state level; the State Water Corporation (SWC) working under the auspices of the state minister became responsible for water supply planning, construction, operation and maintenance of water infrastructure. The Groundwater and Wadis Directorate (GWWD) which is a traditional organ of the MWRI works closely through its regional offices with the SWC and the Ministry of Agriculture at the state levels in the planning of the state's groundwater resources development activities.

In 2016 the Ministry of Irrigation and Water Resources issued bylaws for the regulation of groundwater utilization under the 1995 Water Resources Act. The bylaws mandated securing the approval of the ministry prior to the drilling and installation of any well. The approval is to include the well location, well design, maximum allowed abstraction rate as well as the drilling contractor.

A licence is to be only issued following the submission of a technical study including an EIA component among other legal ownership documents. The licence is to be initially issued for two years after which it has be annually renewed. The renewal process requires the applicant to submit a technical report on the well including an estimate of the amounts of withdrawals. In addition, the applicant must be adhering to following:

- Environmental requirements
- Pre-approved technical designs and guidelines
- Use of the facility for the intended purpose.

Under these bylaws the licensing authority reserves the right to limit the abstraction rates and was granted unfettered access to the licenced facility for inspection, sampling and testing purposes. The licensing authority was also given the right to mandate the drilling of monitoring well(s) during the installation period of any licenced well. Furthermore, the licensing authority was given the right to immediately revoke groundwater abstraction permits in any of the following cases:

1. Detection of pollution in the well
2. Excessive water abstraction (i.e. exceeding the licensed abstraction rates)
3. If abstraction from the facility is bound to cause irrecoverable damages.

15.1.4. Institutional and Management Assessment

It can be argued that there is no shortage of policies, plans and regulations pertaining to the management of groundwater within Sudan. While prior to 1995 the role of groundwater and the policies coordinating its management were lacking, the issue was addressed in 1995 and the policies related to groundwater development continued to be developed and included in the all the water strategies prepared thereafter. Bylaws pertaining to the regulation and licensing of groundwater development were passed in 2108. What may be lacking is the establishment of the mechanisms and protocols needed to enforce the existing laws. A significant restructuring process appears to be needed to enable the ministry organs to carry the tasks required of them in this regard. Some of the problems that the Groundwater Directorate within the Ministry of Irrigation Water Resources and Electricity need to address include:
Instability due to frequent institutional changes

Diminished capacity to conduct exploration and aquifer assessment research activities due to shortages in qualified and trained staff, equipment and tools as well as the budget limitations.

Lack of coordination and conflicting responsibilities with other MIWRE departments.

Poor linkage and cooperation with other institutions working in the groundwater research and development sector (e.g. research centers, universities, drilling companies), as well as agencies in other sectors related to groundwater (e.g. Petroleum Industry)

Lack of well-developed training and capacity building plans.

Low staff morale and motivations.

Groundwater management may be defined as the actions and activities concerned with allocating and developing groundwater resources to designated end users as well as conserve, protect or improve groundwater basins in terms quantity and quality. This is to be carried out in a holistic approach for each groundwater basin as opposed to an ad-hoc approach (i.e. only when and where the need arises). Some of the factors that constrain the development and utilization of groundwater resources include:

- Poor groundwater information database in terms of data quality and the ability to readily consolidate data for the purpose of planning and management.

- Lack of the basic hydrogeologic data required to adequately map the groundwater basins and plan their development. This may include: Detailed geological data, lithology data, values of hydrogeologic parameters, recharge rates, water level data, water quality data…

- Absence of the monitoring systems necessary to fully ascertain water level and water quality as well as the behavior of the water table to pumping and recharge within the different groundwater basins.

- Lack of information about end user current and projected needs.

- Poor connection and coordination with decision makers and planners to adequately plan or implement projects relying on groundwater (e.g. Agricultural Expansion).

- Poor public awareness about the susceptibility of groundwater resources to depletion and contamination.

The national institutions that are relevant for the development of groundwater resources are not limited to the governance institutions such as the Ministry of Water Resources and Irrigation. The inputs of other institutions that contribute to the enhancement of the knowledge, development of human resources and enabling the environment for groundwater development are needed. A non-comprehensive list of some of these relevant key institutions, their main roles and the challenges they face to fulfil their goal is summarized in Table 15.2.

There are a number of factors that are currently negatively impacting the performance of the intuitions working in the groundwater development and management sector. The most prominent of these however appears to be the lack of coordination and comprehensive national management plan that determines a set realistic goals and objectives and consolidate all the available resources thereafter to formulate and achieve these objectives.
<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universities</td>
<td>▶ Staff shortages</td>
</tr>
<tr>
<td></td>
<td>▶ Absence of national guiding policy projecting needs</td>
</tr>
<tr>
<td></td>
<td>▶ Conducting Research geared towards solving pertinent groundwater problems</td>
</tr>
<tr>
<td></td>
<td>▶ Limited output</td>
</tr>
<tr>
<td></td>
<td>▶ Lack/shortage of research funds</td>
</tr>
<tr>
<td></td>
<td>▶ Lack of access to relevant data</td>
</tr>
<tr>
<td>Technical and Vocational</td>
<td>▶ Shortage of qualified trainers</td>
</tr>
<tr>
<td>Training Institutes</td>
<td>▶ High cost of training per capita</td>
</tr>
<tr>
<td></td>
<td>▶ Absence of well-developed, market geared training programs</td>
</tr>
<tr>
<td></td>
<td>▶ Lack of well-equipped training facilities and environment.</td>
</tr>
<tr>
<td></td>
<td>▶ Absence of assessment or projection of market needs</td>
</tr>
<tr>
<td></td>
<td>▶ Absence of government support for technical training programs</td>
</tr>
<tr>
<td>Specialized Service Providers</td>
<td>▶ Shortage in highly specialized experts</td>
</tr>
<tr>
<td></td>
<td>▶ Shortage and high cost of highly specialized services (e.g. isotope studies,</td>
</tr>
<tr>
<td></td>
<td>▶ Adequate ability to provide routine tests and routinely requested services.</td>
</tr>
<tr>
<td></td>
<td>▶ High cost of investment is specialized equipment and advance training.</td>
</tr>
<tr>
<td></td>
<td>▶ Difficult working conditions</td>
</tr>
</tbody>
</table>

Table 15.2: The Key Institutions, their Main Roles and the Challenges Facing
16. CONCLUSIONS AND RECOMMENDATIONS

16.1. Conclusions

During its recent history, Sudan has put a lot of emphasis on the development of its Nile waters, with little attention paid to groundwater resources. The use of groundwater was confined to the provision of domestic supply and the supplementary irrigation of small-scale agricultural projects. There was no strain on the groundwater resources and little attention was paid to the research, exploration, planning and management of these resources.

The available data pertaining to the six major identified basins within the study area were compiled during the course of this study. Data pertaining to groundwater abstraction quantities were generated in part from the analysis of remote sensing data. The available data was used to map and characterize the six basins. The compiled data included, Geological Data (maps, reports, etc.) Hydrogeological data (Water Level data, Water quality data, depth to basement data, lithology data, Isotope analysis, Hydraulic properties, etc.), Development and Management data. The available data differs from one aquifer to another in terms of detail, quality and extent of coverage.

While a significant number of exploratory studies and investigations were conducted within the six basins, the collected data and information is scattered among old reports without the existence of an adequate information database. Recently a large effort was conducted to enter point data pertaining to well observations into spatial databases, which facilitates the analysis of the existing point data to ascertain trends and determine the spatial variation of some parameter such as water level and quality. The case is different for old maps and observations particularly those related to geological observations. A rudimentary analysis of the quality of available data for the six basins considered in this study is presented in Table 16.1, Table 16.2, Table 16.3 and Table 16.4 for the purpose of identifying the gaps in the data needed for the characterization of each aquifer.
### Table 16.1: Geological Data

<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>General Geological map of Sudan, semi detailed geological description of the different formations and the geological features in the basin using general location.</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>General Geological map of Sudan, Semi detailed geological description of the different formations and the geological features in the basin using general location.</td>
</tr>
<tr>
<td>Atbara</td>
<td>General Geological map of Sudan, Very general geological description of the different formations in the basin</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>General Geological map of Sudan, Semi-detailed geological description of some of the formations and geological features in limited parts of the basin.</td>
</tr>
<tr>
<td>Gedaref</td>
<td>General Geological map of Sudan, Very limited geological description of the geological features</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>General Geological map of Sudan, general geological description of the different formations in the basin</td>
</tr>
</tbody>
</table>

### Table 16.2: Hydrogeological Data - Groundwater Inventory and Monitoring System

<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
</table>
| Nubian Sahara  | ▶ No Groundwater monitoring system,  
▶ very limited groundwater level measurements in terms of extent and accuracy, groundwater levels are interpolated using regional groundwater measurements.  
▶ Very Limited/Insufficient groundwater quality data to ascertain general salinity or water quality trends. |
| Nubian Nile    | ▶ Groundwater monitoring system covering about 30% of the Basin area, monitoring system only intermittently operated due to budget constraints,  
▶ Sufficient groundwater level measurements in terms of extent and accuracy generate general groundwater level maps.  
▶ Sufficient water quality measurements to determine very general water salinity trends. |
| Atbara         | ▶ No Groundwater monitoring system,  
▶ limited groundwater level measurements in terms of extent and accuracy, groundwater levels are interpolated using regional groundwater measurements.  
▶ Limited groundwater quality data can be used nevertheless with other maps and soft data to approximately locate saline regions. |
| Blue Nile      | ▶ No formal Groundwater monitoring system.  
▶ Single Low accuracy groundwater level measurements from new wells cover about 70% of the Basin area, temporally inconsistent data can be used to establish groundwater flow trends.  
▶ Sufficient yet temporally inconsistent water quality measurements can be used to determine general water salinity trends. |
<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
</table>
| Gedaref       | - No formal Groundwater monitoring system.  
- Spatially limited single Low accuracy groundwater level measurements from new wells can be used with other soft data to establish average depth water within basin.  
- Spatially limited and temporally inconsistent water quality measurements can be used to determine general water salinity trends. |
| East Kordofan | - Groundwater monitoring system covering about 50% of the Basin area, monitoring system disbanded due to budget constraints,  
- Sufficient groundwater level measurements in terms of extent and accuracy to ascertain groundwater flow trend.  
- Sufficient water quality measurements can be used to determine very general water salinity trends and water quality maps over about 50% of the aquifer extent. |

<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
</table>
| Nubian Sahara           | - Insufficient depth to basement data and/or maps  
- virtually no local pumping tests results to estimate and map hydraulic properties. |
| Nubian Nile             | - Limited depth to basement data and/or maps  
- Results of a number of pumping and recovery tests including limited proper pumping tests exist and can be used to prepare a general and spatially limited map of hydraulic properties. |
| Atbara                  | - Insufficient depth to basement data and/or maps  
- Results of very limited number of pumping tests in terms of number and spatial extent, data insufficient to generate hydraulic property maps. |
| Blue Nile               | - Limited depth to basement data and/or maps  
- Results of a number of pumping and recovery tests within the different formations of aquifer exist thus allowing for the estimation of the range of Transmissivity of the different aquifer layers. |
| Gedaref                 | - Insufficient depth to basement data and/or maps  
- Results of Very limited number of pumping tests in terms of number and spatial extent, data insufficient to generate hydraulic property maps. |
| East Kordofan           | - Limited depth to basement data and/or maps  
- Results of a number of pumping and recovery test including a proper pumping tests exist and can be used to prepare a range of values of hydraulic properties. |
Table 16.4: Hydrogeological Data - Abstraction and Recharge

<table>
<thead>
<tr>
<th>Basin</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nubian Sahara</td>
<td>❱ No monitoring or measurement of abstraction rates</td>
</tr>
<tr>
<td></td>
<td>❱ Absence of local recharge estimation studies.</td>
</tr>
<tr>
<td>Nubian Nile</td>
<td>❱ No monitoring or measurement of abstraction rates</td>
</tr>
<tr>
<td></td>
<td>❱ Isotope Studies to identify recharge sources, without the estimation of recharge potential.</td>
</tr>
<tr>
<td>Atbara</td>
<td>❱ No monitoring or measurement of abstraction rates</td>
</tr>
<tr>
<td></td>
<td>❱ Absence of local recharge estimation studies.</td>
</tr>
<tr>
<td>Blue Nile</td>
<td>❱ No monitoring or measurement of abstraction rates</td>
</tr>
<tr>
<td></td>
<td>❱ Limited Isotope Studies to identify recharge sources without the estimation of recharge potential.</td>
</tr>
<tr>
<td>Gedaref</td>
<td>❱ No monitoring or measurement of abstraction rates</td>
</tr>
<tr>
<td></td>
<td>❱ Absence of local recharge estimation studies.</td>
</tr>
<tr>
<td>East Kordofan</td>
<td>❱ No monitoring or measurement of abstraction rates</td>
</tr>
<tr>
<td></td>
<td>❱ Limited Isotope Studies to identify recharge sources without the estimation of recharge potential.</td>
</tr>
</tbody>
</table>

It is evident that there are a number of factors that constrain the effective management of groundwater resources in Sudan in general including the groundwater basin within the Eastern Nile Basin. Some of the factors that constrain the development and utilization of groundwater are related to the lack of the necessary data as well as the limited understanding of the aquifers dynamics these include:

▶ Poor groundwater information database in terms of data quality and the ability to readily consolidate data for the purpose of planning and management.

▶ Lack of the basic hydrogeologic data required to adequately map the aquifer and plan its development. This may include: Detailed geological data, lithology data, values of hydrogeologic parameters, recharge rates, Water level data, water quality data…

▶ Absence of the monitoring system necessary to fully ascertain water level and water quality as well as the behavior of the water table to pumping and recharge.

▶ Lack of information about end user current and projected needs.

▶ Poor connection and coordination with decision makers and planers to adequately plan or implement projects relying on groundwater (e.g. Agricultural Expansion).

▶ Poor public awareness about the susceptibility of groundwater resources to depletion and contamination.

The obstacles and challenges to the development and implementation of effective management plans for groundwater resources are not only technical, rather they include organizational, institutional and legal factors.

It can be argued that there is no shortage of policies, plans and regulations pertaining the management of groundwater within Sudan. The policies related to groundwater development are well developed and
included in the all the recent water strategies of Sudan. Bylaws pertaining to the regulation and licensing of groundwater development were passed in 2108. What may be lacking is the establishment of the mechanisms and protocols needed to enforce the existing laws. Institutional reform is needed within the Groundwater Directorate, the agency responsible of managing the groundwater resources within the Ministry of Irrigation Water Resources and Electricity in Sudan. Some of the challenges that this agency faces and need to address include:

- Diminished capacity to conduct exploration and aquifer assessment research activities due to shortages in qualified and trained staff, equipment and tools as well the budget limitations.
- Lack of coordination and conflicting responsibilities of other MIWRE departments.
- Poor linkage and cooperation with other institutions working in the groundwater research and development sector (e.g. research centers, universities, drilling companies), as well as agencies in other sectors related to groundwater (e.g. Petroleum Industry)
- Lack of well-developed training and capacity building plans
- Absence of a well-developed and detailed working plans for conducting research and achieving set goals.

16.2. Recommendations

A significant effort can be employed towards improving the understanding and governance of groundwater resources, some of the actions that are believed will contribute the most to this effort are recommended herein:

- A project for compiling and consolidating all the available data pertaining to groundwater resources within Sudan in general and the Eastern Nile Basin in particular in one single database should be initiated.
- The design and implementation of a groundwater monitoring program that include groundwater level and groundwater quality data should be devised for the different groundwater Basins
- A research program geared towards the collection of the missing geologic and hydrogeologic data necessary for the management of each groundwater basin (including recharge assessment) should be planned and implemented.
- Mechanisms for the effective enforcement of existing groundwater regulations should devised and implemented.
- Plans and tools for the effective management including groundwater models should be devised of each groundwater basin with priority given to the most vulnerable or exploited basins.
- Establishment of joint research and collaborative effort with riparian countries for the explorations and characterization of transboundary aquifers
- The systematic and periodic assessment of the capacities of the different national institutions working in or serving the groundwater sector should be conducted with the purpose of upgrading the capabilities of these institutions and stream line their efforts for the effective and sustainable management of groundwater resources.
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ENTRO is an organ established to implement the Eastern Nile Subsidiary Action Program within the framework of Nile Basin Initiative.