Management of Groundwater Resources in Somalia

by

Mohamed Ali Moallim

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

In

EARTH SCIENCES

January, 1993
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Management of groundwater resources in Somalia

Moallim, Mohamed Ali, M.S.

King Fahd University of Petroleum and Minerals (Saudi Arabia), 1993
MANAGEMENT OF GROUNDWATER
RESOURCES IN SOMALIA

BY

MOHAMED ALI MOALLIM

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JANUARY, 1993
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN 31261, SAUDI ARABIA

COLLEGE OF GRADUATE STUDIES

This thesis, written by MOHAMED ALI MOALLIM under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate studies, in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in GEOLOGY.

THESIS COMMITTEE

[Signatures and dates]

Dean, College of Graduate Studies

24-1-1993

Date
This Thesis is Dedicated

to My Loving Uncle, Brothers, Sisters,

Family and all Faithful Muslims.
ACKNOWLEDGMENT

First of all I Thank "ALLAH" The ALMIGHTY for the help and guidance HE has showered on me. Thanks are also to our Prophet Mohammed (peace be upon him) who encouraged us as muslims to seek knowledge and stressed that science and islam are never separable.

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ملخص الرسالة

اسم الطالب: محمد علي معلم
عنوان الرسالة: إدارة برامج مصادر المياه الجوفية
التخصص: علوم الأرض
التاريخ: 2 يناير 1993

تعتبر للمياه الجوفية مصدرًا ثابتاً في بلد جاف مثل الصومال التي لا تتلقى سوى متوسط أمطار سنوي لا يتجاوز ال 100مم. وتعتبر مسألة انجاز تخطيط وإدارة برامج مصادر المياه الجوفية فيما يتعلق بالقدرة التخزينية وتطوير الطبقات المائية وتوزيع واستعمال المياه من الأشياء الهامة بالنسبة للصومال. وقد تم في هذا البحث عمل توليف وجمع البيانات الهيدروولوجية المتنوعة ثم تبع ذلك تحديد الخواص الهيدرولوجية في الصخور المائية وتحليل وتفسير ابعادها الهيدروولوجية وهذه الابعاد مهمة لتحديد الانتجية وتعديل تصرف الصخور المائية. وقد تم تقييم الوضع الهيدروولوجي العام بما في ذلك المعلومات عن إعادة التعبئة والحركة وتواجد المياه الجوفية وتفريغ وتعبئة الصخور المائية.

وقد تم تطوير البيانات المتوفرة بغرض تقدير طلب المياه خلال فترة محددة بعشرين سنة (1990م - 2010م) بالنظر إلى معدل الاستهلاك في القطاعات المتنوعة مثل (الحلي - المواشي - الزراعي - الصناعي) بالتناسب مع معدل النمو السنوي فيها.

كما تم تطبيق المياه السطحية لاستخدامها بجانب المياه الجوفية في البلاد. وقد دلت النتيجة على توفر مصادر مياه كافية لغزالة للمياه خلال الفترة المعنية ولكن بالنظر لطلب المياه مستقبلا يجب أن يатегن أن مصادر المياه محدودة ولن تكون كافية لمعالجة المتطلبات في حالة اعتماد البلاد كليا على المياه الجوفية.

أخيراً تم إعداد خطة شاملة لتطوير وتوزيع الصخور المائية مستقبلاً.

درجة الماجستير في العلوم
جامعة الملك فيصل للبترول والمعادن
المملكة العربية السعودية - الرياض
4 يناير 1993م

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THESIS ABSTRACT

NAME OF STUDENT : MOHAMED ALI MOALLIM
TITLE OF STUDY : MANAGEMENT OF GROUNDWATER RESOURCES IN SOMALIA
MAJOR FIELD : EARTH SCIENCES
DATE OF DEGREE : JANUARY, 1993

Groundwater is a critical resource for an arid country like Somalia which receives an average annual rainfall of about 300 mm. Implementation of planning and management program for groundwater resources in terms of storage capacities and development of the aquifers, and the distribution and use of water are vital issues for Somalia. Synthesis and compilation of scattered hydrogeologic data processed by determination of hydraulic properties of various major aquifers, analysis and interpretation of their hydrologic parameters was performed. These parameters are important for indicating the productivity and behavior of the aquifers. General hydrogeological situation including information on recharge, movement, groundwater occurrence, discharge and storage of the aquifers has been assessed.

Available data have been developed in order to estimate the optimal demand for water resources during a projected period of twenty years (1990-2010), considering a rate of consumption for the various sectors (domestic, livestock, industrial and agricultural) in accordance with their projected annual growth.

Evaluation and assessment of available surface water for conjunctive use and groundwater resources in the country have been made. The results indicate the availability of water resources meeting the demand for water during the projected period. However, long-term forecasting shows that the available groundwater resources are limited and will not be sufficient to satisfy the growing demand if the country is to depend solely on groundwater. Finally, a comprehensive plan for future development and distribution of water resources is presented.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHIRAN, SAUDI ARABIA

JANUARY, 1993
I. INTRODUCTION.

1.1. Purpose and Scope.

The purpose of this study, which is based on the data acquired from various sectors including Ministry of Mining and Water Resources, National Water Development Agency, Department of Earth Sciences of Somali National University, Ministry of Planning and Ministry of Agriculture, is to synthesize the available data on groundwater resources in Somalia and compile them, interpret and develop a comprehensive plan for groundwater development and management in the country. Results of this initial step for groundwater management in Somalia are of importance for groundwater managers to optimize the use of the aquifers in the country. Results of this research will also be important for the assessment and determination of groundwater scarcity problems in the country. This research includes:

- Stratigraphic review using available descriptions in the literature and interpretation of lithological logs.
- Delineation of the easily accessible major aquifers, study of their behavior using available pumping test data and assessment of available groundwater resources in the aquifers.
- Present and future groundwater resource demand in the country.
- Comparison between available groundwater coupled with surface water and water demand in the country.
- Evaluation of groundwater quality in the aquifers in order to determine the
pattern of water quality and its suitability for different uses.

- Application of management techniques for optimization of groundwater resource in order to propose a comprehensive plan for development of the groundwater resources in the country.

- Conclusions and recommendations about groundwater potential, behavior and utilization of the aquifers in terms of groundwater occurrence, storage, chemical quality and future investigations.

1.2. Geographical location of Somalia:

The Somali Democratic Republic lies at the Northeast tip of Africa and is known as the horn of Africa. It extends from the tip corner of East Africa at the Gulf of Aden, running down like a figure seven in a southerly direction to the equator. It is limited by the Latitudes 12° North and 1°30' South and the Longitudes 41° East and 51°30' East. Somalia occupies an area of nearly 638,000 sq.km (262,000 miles). Somalia has a border with the Gulf of Aden (Red Sea) in the Northeast, Jabouti in the North, Ethiopia and Kenya to the West and Southwest and the Indian Ocean to the South and Southeast (Fig. 1.1).

1.3. Topography.

The topographic relief of Somalia is much greater in the North than in either the Central or Southern areas (Fig. 1.2). The Central and Southern features of Somalia are mainly plains with elevations of less than 350m above sea level, except for a range of hills near Obbia (East of Central Somalia) which
Fig. 1.1. Regional geographical relations of Somalia (Barnes, 1976)
rises to an elevation of more than 400m. The elevation of Somali land steadily rises from Galkaio (in the Central region) towards the North and Northeast attaining more than 2000m above sea level. The highest peaks in the country are Surad (2500m) and Bahaia (2200m) located in the mountain range parallel with the Northern coast of the Red Sea.

The Nogal valley in Northern Somalia also exhibits comparatively great relief, with the floor of the valley at an elevation of 350m above Sea level and the Northern and Southern escarpments in the same area rising to more than 800m. The Houd plateau, just North of the Nogal valley, rises to an elevation of 1000m approximately 50km North of Gardo town but decrease to 500m farther Northeast, and again rises towards ranges on the North. The two rivers in Somalia, Jubba and Shabelle, are in the southern half of the country and originate from the highlands of Ethiopia, following the lowest topographical trend towards the Indian Ocean.

1.4. Population:

The last census program conducted in 1989 (unpublished) revealed that the country’s population reached about 8.0 million and increases by about 2.5 percent each year. Nearly three quarters of the population live in the rural areas scattered throughout the country and shifts from place to place, especially in the rangeland, depending on the seasonal changes, while the rest live in small villages and towns. A large proportion of the population is engaged in herding sheep, cattle and camel; and migration patterns are interregional. The distribution of human and animal populations of the country are included in Table 1.1.
Fig. 1.2. Topographic map of Somalia (World Atlas, 1983).
1.5. Land use:

Only about 14% of the total surface area in the country is suitable for irrigation. A small portion (1.7%) of this fourteen percent is cultivated by the private sector and individuals (Table 1.1). Large irrigated agricultural schemes are less practiced in Somalia because of unavailability of the required cultivation utilities. Rain-fed collective farming is the main agricultural system in the country. This system is suitable and preferred by the people because it is simple and requires manpower only. Forestry and rangeland occupies about fifty nine percent of the total surface area of the country. The remaining twenty seven percent includes villages, towns, cities and deserts.

1.6. Previous studies:

Groundwater resource studies of Somalia have been conducted by various consultants, government agencies, companies and the National Water Development Agency (NWDA) of Somalia. These studies were carried out in different areas of the country in order to determine the boundaries of the major basins and to develop the water resources of the country.

Faillace (1964) conducted a study on the surface and groundwater resources of the Shabelle valley. This report provided a very general estimation of the volume of water in the river in certain locations and outlined the change of groundwater quality away from the banks of the river. The report also discusses the increase of depth of the hand-dug wells away from the river.
Table 1.1: Surface Area, Population and Landuse in Somalia

<table>
<thead>
<tr>
<th>Region</th>
<th>Surface Area (approx) $\text{km}^2$</th>
<th>Population</th>
<th>Area (1000 ha. or 1000 $\text{km}^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Human</td>
<td>Animal</td>
<td>Suitable for Agriculture</td>
</tr>
<tr>
<td>Northern</td>
<td>306000</td>
<td>14343250</td>
<td>8850 or 88.50</td>
</tr>
<tr>
<td>Central</td>
<td>141400</td>
<td>10130350</td>
<td></td>
</tr>
<tr>
<td>Southern</td>
<td>190000</td>
<td>16905090</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>638000</td>
<td>41378690</td>
<td></td>
</tr>
</tbody>
</table>
A. P. Popov and A. L. Kidwai (1973) conducted a comprehensive groundwater investigation of the whole country. This project, (parts I, II, unpublished), included development of groundwater basins, distribution of the aquifers, recommendation for drilling wells in certain areas and assessment of groundwater quality.

Faillace (1984) submitted a report on the appropriate technology for the development of water resources in Somalia. He provided the favourable conditions for the groundwater development in the shallow aquifers by means of appropriate and low cost technology. He recommended the drilling of the deeper aquifers in the large villages and towns as well as agricultural areas where a large volume of water is required rather than drilling wells in the rural areas where people are temporarily settling and shifting after a short period of time, and because of high cost of construction and maintainance of the wells.

Pozzi, R. et. al (1987) investigated the water resources in the Central region. They discussed paleogeographical influences on the water resources in arid and semi-arid land with special emphasis on Central Somalia. Their investigation revealed the presence of enough groundwater in the region but its quality is generally poor (TDS = 2000 to 4000 mg/l) and potable water is practically unavailable in many areas of the Central region, especially in the shallow aquifers.

Faillace (1983), under a contract with the ministry of minerals and water resources of Somalia, carried out a comprehensive groundwater study in Northern Somalia. This was an investigation of development and supply of potable groundwater for large towns in the North as well as the possibility of developing
water resources for agricultural areas, especially in Aragavo. He concluded that this area has promising potential aquifers like Aurado and Taleh and recommended proper evaluation of hydrogeological studies, including geophysical work. Drilling exploratory/production wells should be conducted in order to delineate the extension of the aquifers in the area and assess their yield and quality.

Louis Berger International Inc., 1985, under contract with the ministry of minerals and water resources, conducted a comprehensive groundwater development in the Bay region. The intention of the project was to survey the major aquifers in the area and to report on their water quality. The study revealed the presence of several productive aquifers with variable water quality.

The German Agency for Technical Cooperation (GTZ), 1979, under the supervision of the ministry of minerals and water resources, undertook the development of groundwater in some areas of Somalia. The main purpose of the project was to drill wells for water supply of the towns of Dusa-Marceeb, Galkaio, Garowe and Gardo in order to provide sufficient potable water for these towns.

German Water Engineering (Linger, 1985-1989) conducted an extensive hydrogeological exploration in the Gedo and Bakol Area (Western flank of the Southern region). The objective of the study was to develop groundwater resources and solve the problem of scarcity of water in the area. The company recommended installation of a project aimed at drilling new deep wells and improvement of the hygienic quality of the numerous hand dug shallow water
wells, cisterns and surface reservoirs.

1.7. Climate.

Records from different meteorological stations in the country have shown the climatological pattern in Somalia. The climate of Somalia is characterized by high temperature variations, high evaporation rates, high relative humidity and low precipitation. All these factors describe the aridity of the country and classify it as an arid to semiarid region.

1.7.1. Air temperature.

Four periods of climatical change within the year are experienced in Somalia: Two wet seasons (April to June and October to December) and two dry seasons (January to March and July to September). The highest air temperature occurs between February and April, and during this period the maximum temperature reaches up to 37 degrees celsius, particularly in March. The lowest air temperature occurs between May and July and during this period reaches about 25 degrees celsius (Fig. 1.3) and occurs in the middle of May. The monthly mean temperature is about 27 degrees celsius (Pozzi, R. 1980) throughout the country except for the coastal area of the Northern region near Berbera and Bosaso in which the rate of daily mean air temperature drops to about 15 degrees celsius during the winter (December) and rises up to 40 degrees celsius during the summer (September).
1.7.2. Precipitation:

The prominent characteristic of the rainfall in arid countries like Somalia is its variability from place to place and from year to year. The rainfall distribution is uneven throughout Somalia and scant in the Central region. The rainfall is concentrated in two wet seasons. These wet seasons extend from April to June and from October to December. However, the calculated mean annual precipitation ranges from 200mm in the Central region to 600mm in the Southern region. The mean annual precipitation in the Northern region varies from 400mm in the mountainous area (Borama and Aragavo) to 200mm in the lowlands (Fig. 1.4). Generally, the nature of the precipitation in the country is in torrents except for some areas which rarely receive unexpected local showers.

The mean annual precipitation rate in the country over 28 years is approximately 300mm (Fig. 1.5). The maximum annual precipitation rate recorded in the period between 1955 to 1982 was 623.90 mm in 1981 and the minimum was 58.5 mm in 1974.

1.7.3. Relative humidity:

Mean monthly relative humidity is about 70% (Popov 1974). The relative humidity is high during rainy seasons (April to June and October to December) and reaches about 90%; while in the dry seasons (July to September and January to March) it decreases to 30% (Fig. 1.6). Relatively high humidity in the wet seasons or rainy period is probably an important factor in reducing evaporation rates.
1.7.4. Evaporation:

The rate of potential evaporation is influenced by climate, soil and the condition of vegetation in the area. Studies on the evaporation rate in the country were carried out by different companies and United Nations Development program (UNDP) experts under the supervision of the Ministry of Minerals and Water Resources of Somalia.

McDonald (1977) conducted a recording of potential rate of evaporation in some parts of the Southern region. The average potential evaporation rate in the Southern region was 2000mm per year. Popov (1974), also, recorded evaporation data in the Central and Northern regions of the country and the average potential evaporation rate was 2000mm per year to 2500 mm per year.

The mean maximum rate of potential evaporation of the country is approximately 2300mm per year. Comparison between the average potential evaporation rate (2300mm/a) and average precipitation rate (300mm/a) indicates that the evaporation exceeds 6 times the precipitation rate. This reveals that a potential annual water deficiency of no less than 2000mm exists throughout the country (Fig. 1.4).
Fig. 1.3 - Mean Air Temperature.
Fig. 1.4. Evaporation & Rainfall (mm) in Somalia (Louis Berger Inc., 1985)
Fig. 1.5 - Graph showing mean annual precipitation (mm).
Mean Monthly Relative Humidity (%).  Mean Annual Relative Humidity (%).

Fig. 1.8 - Graph For Relative Humidity.
II. GEOLOGY OF SOMALIA
(SEATIGRAPHIC REVIEW).

2.1. General.

The geological setting of the country was controlled by the different phases of geological evolution that led to the formation of the different lithotype and associated structures in the country.

The description of the geologic sequences is based on the extensive research so far conducted by different geologists by means of surface and subsurface investigations and interpretation of some lithological logs provided by petroleum companies. However, a clear picture of nomenclature, description and limits of some geologic units have not been finalized yet. Most of the formational names were derived from names of towns nearest to the type sections.

These previous investigations have revealed the presence of three major lithotypes in the country: The crystalline basement of Precambrian age, sedimentary rocks of Mesozoic and younger ages, and volcanic rocks which started erupting in the Late Cretaceous period. The description of these lithotypes is presented in the stratigraphic column of Somalia (Fig. 2.1).

2.2. Crystalline Basement (Precambrian).

The crystalline Basement of Precambrian age crops out in two major locations in the country (Fig. 2.2): The Bur Acaba area (Southwest of the Southern
Fig. 2.1. Stratigraphic Column of Sanatote

(Prepared for this study)

<table>
<thead>
<tr>
<th>Era Units</th>
<th>Rock Units</th>
<th>Hydrologic Units</th>
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<tr>
<td>Lower Cambrian</td>
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<tr>
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<tr>
<td>Devonian</td>
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<tr>
<td>Carboniferous</td>
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<tr>
<td>Mississippian</td>
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<td></td>
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<tr>
<td>Permian</td>
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</tr>
<tr>
<td>Triassic</td>
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<tr>
<td>Cretaceous</td>
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<tr>
<td>Tertiary</td>
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</tr>
<tr>
<td>Quaternary</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precambrian</td>
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</tbody>
</table>

* Unit 5A, 5B, and 5C forms Yucca-Merced Aquifer System
region); and the far North near the Red sea coast (Northern region). Although unmappable basement crops out in the Nogal uplift at the Southern edge of the Northern region (Beltrandi & Pyre, 1973).

The crystalline basement, in both North and South, consists of metamorphic rocks intruded by granite or granodiorite. Metamorphic rocks comprise gneiss, schists, quartzite and marble.

Gabbro, granite and diorites of huge extension were identified in the Northern region while a banded ironstone has been identified in the Southern region (Beltrandi and Pyre, 1973). The strike of the crystalline basement in the North of Somalia is predominantly North-South, whereas in the South it ranges from Northwest-Southeast to North-South.

The outcrop of the basement in the Bur Acaba area is of very ancient origin, for it was a peneplain in the Early Jurassic time. One of the intrusive bodies in the area has been dated as Early Cambrian (Beltrandi and Pyre, 1973). On the other hand, the crystalline basement of the Northern region is believed to have been exposed as a result of separation of the Arabian plate from the African plate during Late Cretaceous to Middle Tertiary period (Swartz and Arden, 1960).

2.3. Volcanic rocks.

Basalt flows, which started erupting since Late Cretaceous, are present in the country, especially in the subsurface except small extensions in certain locations (Stefnini, 1933; Barnes, 1976). It is believed that the outpouring of these
Fig. 2.2. Geological Map of Somalia (Stefnini, 1933; Barnes, 1976)
basalts was associated with a different succession of movements which occurred in the region since Late Cretaceous especially during the development of the East African Rift valley and the formation of the Gulf of Aden. The basalts in the Northern region were associated with flows that covered extensive areas of Ethiopia and latter have been severely eroded leaving only remnants of the original flows. These flows have been dated as Oligocene to Miocene (Mohr, 1963), while basalts in the East African Rift valley have been dated as Late Cretaceous to Oligocene (Swartz and Arden, 1960).

Two types of basalts were recognized in the Central region. One type is interbedded in the sediments and the other crops out on small scale. The first one is an augitic basalt in subaquatic environment, for it has a typical fluidal structure and desquamation type surface. The age of this type is believed to be Late Cretaceous because of the associated sediments (Piccoli, 1980). The other type is an olivine basalt which intruded in the sequence up to the surface. The age of the second type is Late Tertiary on account of its stratigraphic position (Piccoli, 1980).

The basalt flows in the south of the country are present at Lugh and along the road from Lugh to Baidoa (Southwest of the Southern region). It is described as a series of gypsum bearing sedimentary rocks capped by lava, volcanic ash, and tuff, which was in turn capped by a thick basalt flow (Fig. 2.4) that has been assigned to Late Tertiary to Quaternary. In the Sinclair well, Merca 1, South of the capital, Mogdishu, several flows of light-gray sepiolitic basalt are interbedded with the Late Cretaceous to Tertiary shale.
2.4. Sedimentary Rocks.

The deposition of the sedimentary rocks in Somalia was influenced by the palcorelief inherited from orogenic activity followed by an extensive cycle of erosions. However, the stratigraphic sequence (Paleozoic to Recent) in Somalia is not continuous because Paleozoic and Triassic deposits are missing and, therefore, Early or middle Mesozoic are lying on the basement at different locations in the country. It is very difficult to hypothesize whether this major nonconformity is due to different phases of Paleozoic and Triassic erosions or to complete nondeposition over an emergent area. However, in the Paleozoic and early Mesozoic times the African plate and the Arabian plate were part of the same plate. Nevertheless, the supply source of the Paleozoic and Triassic sediments was coming from Northeast, that is from Tethys, and decreasing toward Yemen.

The last deposition of the Paleozoic sedimentary unit in the Arabian plate was Khuff Limestone (Permian) which changes into clastics towards the Southwest of Saudi Arabia. This latter formation is not present in Yemen. In Ethiopia, on the other hand, glacial deposits of lower Paleozoic age and of various lithology are present. In Kenya, also, Paleozoic sedimentary rocks are found. Therefore, it seems that, at least in the Paleozoic, Somali land was a relatively positive area. But in the Triassic period, according to Merla and Minucci (1938), the first erosional cycle was active in Somalia and the absence of the Triassic sedimentary rocks in Somalia was caused by this severe erosion. This fact can be related to the preservation of thick Triassic sedimentary rocks in downfaulted troughs or grabens in some parts of Yemen and Ethiopia which are bordering Northeast and North to Northwest of Somalia respectively.
2.4.1. Adigrat Formation (Early Jurassic)

The Adigrat Formation is the basal part of the Jurassic rocks and conformably overlies the crystalline basement, especially in the Northern part of Somalia. This formation was named first by Blanford (1870) and latter studied by Arkell (1956) followed by various geologists. The Adigrat formation, whose type section is near Berbera town in the Northern region, consists of fine to coarse-grained, varicolored quartzitic, micaceous, crossbedded, unfossiliferous sandstone, locally grading upward into sandy limestone with intercalation of shale (Swartz and Arden, 1960). Locally a pebbly conglomerate is present at the base. The lithology of the formation changes away from the type section and down to the south where the content of shale increases.

The thickness of the formation at the type section is about 200 meters but lithological logs available indicate that the thickness of the formation decreases to the South of the Northern region and is missing in the Central and Southern regions (Fig. 2.3).

The sequence of the unit shows that the lower part was deposited under subaerial environment of fluvial type while the upper part was deposited under marine-littoral conditions.

2.4.2. Mansa-Guda Formation (Early Jurassic).

The Mansa-Guda Formation lies conformably on the crystalline basement in the Southwest of Somalia. The unit was first recognized and named by Ayres
(1952) in Kenya near the border between Somalia and Kenya. The Mansa Guda Formation crops out in the border of Kenya at Tarbaj area near the border between the two countries and is hidden in the subsurface on the basement at Southwestern flank of Southern Somalia. It comprises mainly variegated, often crossbedded quartz grits and sandstone with little intercalation of shale and limestone.

The thickness of the formation varies from 600 meters in the Southwest of Somalia and thins out towards North in the Kenyan territory (Thompson, 1960). The depositional environment of the formation is continental to littoral.

2.4.3. Hamanley Formation (Early Jurassic).

Available lithological logs indicate that the Hamanley Formation overlies the Adigrat Formation and is overlain by Urandab Formation. The Hamanley Formation is described, in its type section in Ogaden (Ethiopia) near Hamanley, as white to buff, well bedded limestone, prevalently oolitic and fossiliferous. Local variations include a back reef facies in the west of Ogaden and North of Somalia (dolomites, oolitic limestone and anhydrites). Facies of dark limestone and marls were found in the Northeast of the Shabelle valley (Giro well 1, Obbia well 1) in the Somali Embayment (Hilaal, 1977)

The thickness of the formation increases from the type section in Ethiopia towards Somali Embayment (Fig. 2.3) in the Central region and reaches about 2100 meters in the middle of the Embayment (Barnes, 1976). The Hamanley Formation is rich in fauna which includes foraminera, corals, brachiopods, lam-
illibranch and ammonites. The facies are mainly neritic with lagoonal episodes, and episodes of a deeper sea were found in Central Somalia (Barnes, 1976).

2.4.4. Sawer Formation (Early Jurassic).

The Sawer Formation is present in the Borama area (Northwest of the Northern region) and extends up to Zeila town (Red Sea coast) only as the first calcareous unit of Mesozoic sediment (Abbate, 1974). The Sawer Formation is underlain by the Adigrat Formation and is overlain by Daghani Formation in the type locality. It consists of distinctly bedded, coarse grained limestone and sand marls followed by micritic light and gray limestone, locally dolomitized and gypsiferous. The character of the unit is relatively constant in the type locality area.

The thickness of the formation varies from 140 meters to 210 meters with the maximum corresponding to the type section. The depositional environment of the formation is shallow marine.

2.4.5. Baidoa Formation (Middle Jurassic)

The type section for this formation is near the town of Baidoa. The Baidoa formation is divided into three members (Fig. 2.4). These, from older to younger, are the Uaney Member, Baidoa Member, and Goloda Members.

Outcrops of the Uaney Member have not been found in the area because it is covered by the other members, but it is identified by using lithological logs. The lowest part of the Uaney Member consists of green sandstone, dark marls,
limestone and varicolored shale deposited conformably over the basement near Baidoa town. The upper part is made of dark to red shale of several tens of meters thick with a layer of limestone at the top. Lithological logs collected from wells drilled in the area indicate that the total thickness of Uaney Member is 90 meters.

The Baidoa Member conformably overlies the Uaney Member and comprises mainly gray limestone with a few intercalations of black shale and marl. This limestone is deeply weathered, karstified, and exhibits abundant sinkholes. Variation of thickness was observed from lithological logs but the average thickness of the member is about 90 meters.

The Goloda Member consists of light-gray crystalline limestone with oolitic beds and coquina layers. Lithological logs have indicated that thin intercalation of black marls are common in the member. These logs also show that dolomite beds of white to gray are regionally present in the member.

The uppermost beds of the Goloda Member are resistant to erosional effects and form hills in the area. On the other hand, the middle part of the member, exposed in the Qansax Dheere area, Southwest of Baidoa town, is deeply karstified with numerous sinkholes and dolines. This part has also undergone intense weathering forming several meters of caliche (hard soils). The thickness of the member attains 650 meters in the middle of the Lugh-Mandera basin, Southwest of Baidoa town. In the type section at Baidoa town, it is about 350 meters thick.
Fig. 2.3. Cross section along SW-E to S-N of the country

(Prepared for this study)
2.4.6. *Annole Formation (Middle Jurassic)*.

The Annole Formation conformably overlies the Baidoa Formation (Fig. 2.4) and mainly comprises, in its type section, black marls and shale with intercalation of blue compacted limestone. The intercalated limestone shows, locally, signs of karstification on a small scale.

The thickness of the formation varies laterally and vertically. It is about 350 meters thick at the type section. The Annole Formation is limited geographically in the Southwestern flank of the Southern region.

2.4.7. *Bihendula Formation (Middle Jurassic)*.

The type locality of the unit lies near Bihendula in the Berbera area (Red Sea) in the Northeast of the Northern region. It comprises fine-medium grained limestone, sometimes recrystallized and dolomitized, clay, marl and marly limestone. The unit has a distinctive stratification. The limestone microfacies are generally micritic with bioclasts, peloids and quartz grains. Initially, the depositional environment was lagoonal and latter it turned into marginal (Bruni and Fazzoli, 1976). At Bihendula, the type section, the thickness of the unit is about 125 meters.

2.4.8. *Urandab Formation (Late Jurassic)*.

The Urandab Formation rests conformably on the Hamaney Formation and its type section was found near the village of Urandab in Ogaden, west of Central Somalia, on the Ethiopian border. It is fairly uniform in lithology and is
Fig. 2.4. Stratigraphic column of Southwest of Somalia (Piccotti, 1980)
made up of dark laminated shale, gypsiferous in their lower part and interbedded with marly limestone in the upper part. The Urandab Formation is present in Sinclair wells (Obbia 1, Giro 1, and Maray Asha) in the subsurface as basinal dark-gray and gray limestone stringers.

The thickness of the formation increases from the type section in Ethiopia towards the Central region of Somalia (Somali Embayment), and it reaches up to 600 meters (Hilaal, 1977). Lithological logs also indicate this increase (Fig. 2.3), but toward the North of Somalia the formation is missing. The absence of Late Jurassic in these wells may be a result of Post-Jurassic erosion which was very extensive in Northern Somalia (Barnes, 1976). The geographical distribution of the unit is limited between the West of Somalia (Ogaden region near the border between Somalia and Ethiopia) and Central Somalia, and has characteristic fossils like belemnites and ammonites and belongs to a neritic environment (Migliorini, 1956).

2.4.9. Ugeit Formation (Late Jurassic)

The type section for this formation is near the Ugeit town located north of Baidoa. This formation is bounded only in the Southwestern flank of the Southern region. The Ugeit formation is divided into two members (Fig. 2.4). These, from older to younger, are the Guroa and Mugdille members.

Guroa Member, in the type section, is made of marl with less local intercalation of limestone. This member has a thickness of about 200 meters. The Mugdille Member comprises limestone interbedded by sandstone in local scale. This is followed by prevailing sandstone facies at the upper part of the member.
The thickness of the Mugdille Member is about 450 meters.

2.4.10. Gabredarre Formation (Late Jurassic).

The Gabredarre Formation was recognized by the AGIP (Private Oil Company) mission (1938) and latter was investigated by Merla (1948) and Azzaroli and Merla (1960). The type section of the formation was found near the Gabredarre town, Ogaden, near the border between Somalia and Ethiopia and is made up of light coloured, compact limestone with oolitic levels and intercalation of anhydrite and shale. Locally, arenaceous and marly limestone with ammonites occurs. The transition from the underlying Urandab Formation is sharp at the location of the type section (Ogaden) and is more gradual in Central Somalia.

The thickness of the formation varies from 410 meters at the type locality to 629 meters at the well of Gumbro 1, in Ethiopia, and 347 meters at a well near Obbia in Central Somalia (Barnes, 1976).

2.4.11. Garbaharre Formation (Late Jurassic).

The Garbaharre Formation lies conformably on the Ugeit formation (Fig. 10) and was first investigated by Dixey (1948) in the Lugh-Mandera basin and latter by Barbarieri (1968) and then Piccoli (1980). The Garbaharre Formation is divided into two members. These are Busul Member (lower) and Mao Member (upper).

The Busul Member comprises mainly sandstone intercalated by dolomitic
limestone, biostormal and micritic limestone. The lithology and the thickness of the Busul Member vary laterally as well as vertically. The thickness, at the type section, is about 280 meters.

The lithology of the Mao Member consists of alternation of limestone and dolomite, sandstone, shale, and anhydrite. The thickness as well as the lithology of the unit changes laterally. In places where this member is thinnest (Dolo and near Mandera town), it consists totally of anhydrites (Fig. 2.5). The thickness of the member is about 350 meters at the type locality.

The Garbaharre Formation, which crops out and is limited in the Lugh-Mandera basin in Southwest of the southern region, has a neritic to littoral, brackish and continental environment.

2.4.12. Daghani Formation (Late Jurassic).

The Daghani Formation was studied first by Macfadyan (1933) and latter by Bruni and Fazzoli (1976) and is known in the West of Northern Somalia. The unit overlies the Sawer formation and is overlain by the Gawan Formation.

Lithologically, there are varicolored shale, subordinate marls, rare calcarenites and local intercalation of thin gypsum levels.

The thickness of the unit varies from a minimum of 30 meters near Borama to 300 meters down to the South near Bihendula. Facies are open sea (Bruni and Fazzoli, 1976).
Fig 2.5. Three parallel local cross sections of Southwest of Somalia (Piccotti, 1980)
2.4.13. Gawan Formation (Late Jurassic).

The termination of the Jurassic sequence in the Northwestern flank of the Northern region is capped by the Gawan Formation and is overlain by the Jesomma Formation (Late Cretaceous). This huge disconformity between them is due to different cycles of erosion in the Mesozoic time.

The Gawan Formation consists of well bedded limestone, occasionally marls occur in the base with intercalation of thin beds of shale. The average thickness of the unit is about 150 meters.

Fossils so far identified in the unit are saccocoma radiolarian, lamillibranch, ostracods and therefore, the depositional environment is from open sea to marginal and lagoonal (Abbate, 1974 ; Abukar, 1977).


The Amber Formation is the base of the Cretaceous succession, especially in Southern Somalia and was found first by Weir (1929) under Merchan Sandstone, but in a later investigation conducted by Barbarieri (1968) the formation was given the current name (Amber Formation). Between El-Wak and Fah-fah Dhun, the Amber Formation lies conformably on the Ugeit Formation (Fig. 2.5) and is limited in the Mandera-Lugh basin. The lithology of the Amber formation, in its type locality, comprises mainly sandstone and silt, occasionally with limestone, marly and shale intercalation.

The thickness of the formation varies from 150 meters in the Mandera area
at the border between Kenya and Somalia to 450 meters in the Lugh-Mandera basin in Somalia (Barbarieri, 1968). The fauna in the formation indicate that the facies are littoral and deltaic, passing to continental in the parts of the pure sandstone (Piccoli, 1980).

2.4.15. Main Gypsum Formation (Early Cretaceous).

The Main Gypsum Formation represents thick bedded, crystalline gypsum intercalated by limestone, calcarenite, sandstone and shale. Occasionally thin dolomite beds are intercalated in the thick variegated gypsum.

In the type locality at Gabredarre, the thickness is 200 meters but thicknesses of up to 400 meters have been recorded in its extension in Ogaden, in Ethiopia (Barnes, 1976). In the East of the Central region and Northern Somalia, the main gypsum formation is replaced by Cotton Formation (Azzaroli and Fois, 1964 and Barnes, 1976). In the Southwestern part of Somalia, the unit lies conformably on the Garbaharre Formation (Fig. 2.4).

2.4.16. Cotton Formation (Early Cretaceous).

The Cotton Formation represents the Lower Cretaceous in the subsurface and was found in Agip well 1 in the Cotton area, the type locality, in the Northern region. Also, available lithologic logs from the Central region of Somalia (Mary Asha Well 1) have indicated the presence of a thin layer of Cotton Formation. The Cotton Formation is made of a forereef limestone and medium depth neritic shale. The thickness of the formation varies from place to place; however, the average thickness is 200 meters.
2.4.17. Mustahil Formation (Late Cretaceous).

The Mustahil Formation crops out in the Faf depression (Fig. 2.3) near Mustahil town (type locality) at the border between Ethiopia and Somalia. The Mustahil Formation, characteristically, exhibits upward grading facies. It comprises cream coloured limestone, gypsiferous marls and clay, in the base, grading upward to reef limestone and gypsum. This is due to the fact that the unit lies stratigraphically between two gypsiferous formations (Main Gypsum Formation and Ferfer Gypsum Formation), but North of Latitude 6 degrees North, it is overlain by transgressive Jesomma sandstone, where the extension of Ferfer Gypsum Formation is not present.

The thickness of the formation varies between 150 meters to 400 meters in its extension. The facies of the formation is marine, with frequent variations of depth evidenced by alternating changes from infralittoral to lagoonal environment (Hilaal, 1977).

2.4.18. Ferfer Gypsum Formation (Late Cretaceous).

The Ferfer Gypsum Formation occupies the Faf depression in the South of Ethiopia and extends as far South as Beletuen in Somalia. The type locality for the formation is near the Ferfer town located at the border between Somalia and Ethiopia. The unit is made up of gypsum alternating with marls, limestone and dolomite in small quantities. The thickness of the formation varies from 100 meters to 400 meters as indicated by lithological logs collected from the wells drilled in Central and Northern Somalia (Barnes, 1976). The depositional
environment is similar to Main Gypsum Formation: lagoonal, evaporitic with variations of salinity degree (Hilaal et. al., 1977).

2.4.19. Beletuen Formation (Late Cretaceous).

The Beletuen Formation crops out in the Shabelle basin between Bulo Burde in Somalia and the Faf depression in Ethiopia and extends, in the subsurface, under the Central and Northern regions as indicated by available lithological logs. The unit consists mainly of fossiliferous limestone with small intercalations of sand, sandy marls and gypsiferous limestone.

The thickness and lithology of the formation varies from the type locality, Beletuen town, towards southeast. The Beletuen Formation thickens in this direction from its type section, in part because of facies changes in the underlying Ferfer Formation, which resulted in environmental changes towards the Somali Embayment (Barnes, 1976). However, the average thickness is about 200 meters. The depositional environment, as interpreted from its content of fauna, is sublittoral (Hilaal et. al., 1977).

2.4.20. Jesomma Formation (Late Cretaceous).

The Jesomma Formation, in its type section near Bulo Burde in the Central region, mainly comprises intensely coloured red, purple, brown and yellow sandstones of fine to coarse grain sizes. Occasionally, gypsum intercalations occur at the base. The unit is widely exposed, from the Hargeisa area in the Northern region down to Shabelle basin in the Central region (Fig. 2.3). It transgressed on the stratigraphic succession of Somalia in the Late Cretaceous (Hilaal et. al.,
1977). The thickness of the unit varies from 250 to 400 meters. However, the maximum thickness corresponds to the type locality.

The Jospharma Formation is considered one of the potential aquifers in the country with good water quality (LBI, 1985).

2.4.21. Sagale Formation (Early Paleocene).

The Sagale and Maray Asha Formations (believed to be a deeper facies of Aurado Formation in the subsurface) were established to represent Early Paleocene at a joint meeting of geologists in December, 1958, in Mogdishu, Somalia (Barnes, 1976).

The Sagale Formation forms the beginning of the Cenozoic succession in Somalia and is found in the subsurface wells (Sagale well 1 and Maray Asha well 1) in the Central and Northern regions. Especially, in the Sagale well 1, it lies at a depth interval between 1124 to 1286 meters. The unit is made up of dark-gray shale, speckled white with many chalky foraminiferal tests. Silty to fine inclusions are present locally. The thickness of the unit varies generally from the type locality. However, the average thickness is about 162 meters. Lack of subsurface data make it impossible to draw a clear picture of the extension of the formation. The depositional environment has been is interpreted as deep water marine facies based on the fauna studied in the unit (Goloborotalia Velascoensis, Goloborotalia Crasea and Anomalia Granosa)(Hilaal, et. al. 1977).
2.4.22. *Maray Asha Formation (Early Paleocene)*

The type locality for this formation was found in the Maray Asha well in the Central region and represents a transitional zone between the shale of the Sagale Formation and the overlying Aurado Formation. The unit consists mainly of marls, at the base, followed by shale and siltstone. It is present at depth in the interval between 436 to 632 meters where medium depth foraminifera (Rubulus and Cibicides) have been identified (Barnes, 1976). The thickness of the formation is about 192 meters, although some variation was observed.

2.4.23. *Aurado Formation (Middle to Late Paleocene).*

The Aurado Formation is overlain by the Taleh Formation and underlain by the Maray Asha Formation. The type section of the unit lies in the South of Berbera near the Red Sea. The lithology of the formation is a finely crystalline, compact hard, usually tan to light-brown limestone with local intercalation of thin gray shale. The unit extends over most of Northern and Central Somalia. In the South, the unit was found in the subsurface as indicated by lithological logs (Fig. 2.3).

The thickness of the formation at the type locality is about 550 meters but varies in the subsurface, reaching up to 1400 meters in the South at Merca well 1 drilled by Sinclair Petroleum Company. The Aurado Formation is equivalent, in lithology and age, to Umm Er Radhuma Formation in the Arabian plate (Beydoun, 1970). The Aurado Formation forms one of the potential aquifers in the country with good water quality.
2.4.24. Taleh Formation (Early to Middle Eocene).

The Taleh Formation, in its type section, in Nogal Valley, consists of well bedded anhydrite in the upper part with intercalations of dolomite, cherty limestone, marl and shale beds which increases and dominates in the rest of the formation. It merges by intercalation into the overlying Karkar Formation (Migliorini, 1956). There is a lateral change in the unit indicating changes in the depositional environmental. Towards the coast of Indian Ocean, the Taleh Formation disappear underneath the Karkar Limestone. Near the coast, Sub-surface exploration has shown that the upper evaporitic facies is replaced by dolomite, shale and limestone of vari-coloured and size, and farther south, Obbia, by calcareous sandstones and shale (Azzaroli and Fois, 1964; Barnes, 1976). The thickness of the formation varies with the change of lithology, but at the type locality it is 270 meters. The Taleh Formation is the African counterpart of the Rus Formation of Saudi Arabia (Beydoun, 1970).

The Taleh Formation is a potential aquifer and supplies large areas in the central and northeastern part of the country, but the quality of water in the southern part of the aquifer is low due to the presence of anhydritic lithology (LBI, 1985; Faillace, 1982).

Karkar Formation (Middle-Late Eocene)

The type locality of this formation is in the hills of Karkar, which lie in the Southern margin of the Darror depression in the Northern region. The unit, which lies conformably on the Taleh Formation, is made up of bedded nodular and chalky limestone with local intercalations of compacted limestone and shale.
The Karkar Formation is rich in fauna: Foraminera, Coral, Echinoids and Mollusks (Migliorini, 1956). The thickness of the unit, in its type section, is about 400 meters although it varies as indicated by lithological logs collected from the wells drilled in the extension of the unit. The distribution of this formation extends from the Southern edge of the Northern region (Latitude 6 degrees North) to the Northeast edge of Somalia (Fig. 2.2). But in the subsurface, available lithological logs indicate that this formation is present in the Merca well 1, about 110 kilometers South of Mogdishu (the Capital).

2.4.26. Hafun Formation.

The Hafun Formation overlies conformably the Karkar Formation and, in its type locality, Ras Hafun, consists of coarse glauconitic sandstone with quartz followed by marl limestone and sand in the lower part, organic limestone in the middle, and organic limestone intercalated by shaly levels, marls and sand in its upper part. The lithology and thickness of the formation varies away from the type locality and the maximum thickness is about 160 meters. The unit is restricted in the East of the Northern region near the coastal area of the Indian Ocean between Galad and Bender Baila in the Northern region of Somalia. The depositional environment is infra littoral-marine.

2.4.27. Guban Formation.

The Guban Formation extends along the coastal area of Berbera up to Cape Garda Fui (Northern region) in a discontinuous manner. At the type section, Bender Zaide, the Guban Formation consists of sandstone with reddish quartz
followed by lenses of fossiliferous marly limestone. Locally, lenses of coarse boulder conglomerates are interbedded in the marly limestone and conglomerate develops largely above them. Isolated sections of the formation were found in the North. This is due to the system of faults developed in the area. The maximum thickness of the unit recorded is 150 meters.

The fauna in the unit indicate that the depositional environment is infralittoral-marine.

2.4.28. Scuscuiban Formation.

The Scuscuiban Formation is a lagoonal environment and restricted in the Darmor depression in the Northeast of Somalia along the coastal belt. The unit, in its type locality, is made up of marl, marly sandstone, shale and occasionally limestone and gypsum. Facies variation were observed along its extension. The maximum thickness of the formation is 100 meters.

2.4.29. Upper Conglomerate Formation.

The unit overlies conformably the Scuscuiban Formation and in some places rests on the Guban Formation where the extension of Scuscuiban is absent. It forms the cap of the sedimentary succession in the Northern region. The lithology of the formation varies according to the local conditions and comprises mainly coarse limestone conglomerates and poorly cemented rounded pebbles. Minor boulders were evident in some parts. They were developed at the foot of the scarps of the mountains of Northern Somalia. The distribution of the unit gives evidence that the fault scarps of the Gulf of Aden system developed by
uplifting of the Somali Plateau during the Early and possibly Middle Miocene (Azzaroli, 1957).

2.4.30. Obbia Formation.

The type locality of the Obbia Formation is near Obbia town which lies at the Eastern margin of the Central region near the Indian Ocean. In its type section, it consists predominantly of white to gray, some tan, granular, organic limestone and glauconitic sandstone with some intercalations of gypsum in the lower part. Intercalation of marl, shale and silt were observed at different levels of the unit. At the type locality, the Obbia Formation is highly karstified especially the limestone beds. The distribution of the formation is limited along the coastal strip of the Indian Ocean and is continues down to Kismania (south) in the subsurface except West of Obbia (Central region) where this unit crops out (Fig. 2.3). The average thickness of the formation is about 500 meters.

2.4.31. Somal Formation.

Interpretation of lithological logs indicates that the Somal Formation is confined in the subsurface between Johar and Kismania (Southern region) along the coastal area. In the type locality, near Qorioley town, the unit consists of marls, shale and silt with intercalations of limestone beds and sandstone. The lithology of the formation varies from the type section towards Kismania (South) because dominance of shale beds was observed in the wells drilled near Kismania (Barnes, 1976). The thickness of the unit is about 470 meters at the type section but little increase was reported in the well drilled for petroleum exploration by
Sinclair near Brava, about 70 kilometers South of Qorioley.

2.4.32. **Merca Formation.**

The Merca formation caps the sedimentary sequence of the Tertiary period in Southern Somalia and extends from Johar, located at 120 kilometers North of the capital, Mogdishu, to Kismania, 500 kilometers south of the capital. In its type locality, the unit comprises mainly porous sandstone intercalated by thin layers of limestone followed by limestone with intercalation of shale which generally caps the whole Tertiary succession. The average thickness of the formation is about 600 meters.

Merca Formation is a potential aquifer with good water quality. This aquifer supplies the capital, Mogdishu and its vicinity (Dal Pra et. al, 1983).

2.4.33. **Superficial Deposits (Quaternary).**

Quaternary sedimentary rocks in Somalia were not regionally investigated and precise dating is not available at the present, but aeolian sand and reef deposits are active especially along the coastal areas. The most conspicuous Quaternary formation with continental facies in Somalia is dune sand extending for more than 1000 kilometers from Obbia (Central region) to Jumbo (Southern region) in the coastal area (Jobstribizer and Omar Shire, 1970). According to Stefnini, 1930, recent subsiding movements were evidenced by a deep indented fringing reef with traces of a drowned valley in some parts of the country, particularly in the far Southeast and far Northeast in the coastal area.
2.5. Structural Setting.

The relevant structural settings in Somalia were formed during different stages of the geological evolution and are summarized as follows (Fig. 2.6).

The Bur uplift, located in the Central of the Southern region, is an ancient crystalline basement outcrop which remained probably above the sea level since the beginning of sedimentation in Somalia, with the exception of Callovian of Jurassic time, because sedimentary rocks of this age lie on the basement. Sedimentary rocks in the area dip about 5 degrees in every direction from the uplift. Down to the far Southwest of the Bur uplift, near the border between Somalia and Kenya, the Lugh-Mandera basin was developed during the Jurassic time in consequence of large regional faults subjected to the area during Jurassic movement (Fig. 2.5). It shows the development of the Jurassic sequence in the area and spatial relationship of the sediments in the basin (Beltrandi and Pyre, 1973).

The Tertiary basin lies at the South and Southeast of the Bur uplift and was developed due to the subsidence caused by the regional fault of Tertiary age which is parallel with the Indian Ocean coast. The sediments in the basin dip towards the Indian Ocean and the axis of the basin is offshore. Occupying most of the Central region, but recognized only in the subsurface, is the Somali Embayment, a large region of deep water Mesozoic deposition. The axis of the basin trends Northeast-Southwest.

The Nogal uplift in Northern Somalia trends Northwest-Southeast and
Fig 2.6. Regional Structural map of Somalia (Barnes, 1976)
extends up to the Northwest of the Northern region. This positive structure is due to the presence of an ancient crystalline basement which influenced Mesozoic deposition (Fig. 2.3). Down to the North, from the Nogal uplift, probably the youngest structural feature in Somalia, is the uplift region along the Northern coast which locally exposes basement rocks. Such positive structure was apparently caused by the movement when the Arabian plate finally separated from the African plate in Miocene time (Swartz and Arden, 1960).


Somaliland was a peneplain of an ancient crystalline basement by the end of the Paleozoic or probably the Triassic period. The first major event recorded in the history of the sedimentary evolution in Somalia was the cyclic invasion of the sea from the Northeast, East and Southeast. Transgressions and regressions of the Post-Triassic sea led to the deposition of Jurassic sedimentary rocks over most of Somalia with the exception of the positive areas (Bur uplift and Nogal uplift). Regionally, the Jurassic sediments lie conformably almost horizontally on the basement rocks with great nonconformity. Such rocks sedimentary rocks which covered this peneplained region were not folded except on a local scale, but apparently were subjected to isostatic adjustment, creating highs and lows, the highs being eroded and the lows creating basins. Faults of regional scale have been identified in the Jurassic sequence with a trend of Northeast-Southwest. This was followed by Post-Jurassic erosion which removed a considerable thickness of sediments from the highs (Barnes, 1976). The Jurassic episode was followed by a number of Cretaceous transgressions and regressions which left its
sediments all over the country with the exception of certain parts which had been subjected to epeirogenic uplift and have remained above the sea level since. On the other hand, after a period of post-Cretaceous erosion, the area downwarped to allow the invasion of the Paleocene and Eocene Seas to Northern and Central Somalia. After the Eocene the Nogal area was upwarped (Fig. 2.3), and hence no marine sedimentation took place except along a narrow strip of the coastal area in which Oligocene-Miocene sediments can be found: This was probably related to the uplifting and faulting of the mountains along the Northern coast of Somalia during the Middle Tertiary. Such event is believed to have been caused by the final separation of the Arabian Plate from the African Plate (Swartz and Arden, 1960).
III. HYDROGEOLOGY.

3.1. Introduction

The assessment of groundwater depends, to a considerable extent, on the local conditions as well as regional variations and distribution of the water bearing units. Therefore, a proper understanding of distribution and general framework of the aquifers in the country is important in order to quantify the groundwater resource. The major objective of this chapter is to describe, assess and quantify groundwater potential of the major accessible aquifers in terms of groundwater occurrence, availability and aquifer storage capacities. In addition, determination of physical characteristics of the aquifers like transmissivity and storage coefficient will be conducted using available pumping test data. These parameters are important in determining the natural flow of water through an aquifer and its response to abstraction. Surface water, which is generally confined in the Shabelle and Jubba rivers, has been given special consideration in terms of quantity and contribution to water demand.

3.2. Surface Water

Because of its arid to semiarid climate, Somalia will become increasingly dependent on water resources. The availability of these resources varies from being insignificant in some regions, to reasonably productive in other regions of the country. This has caused severe problems regarding the demand, quality and quantity of water available. Various studies of water resources have been
previously carried out by Somali government organizations, particularly by the Ministry of Minerals and Water Resources, companies operating in private sector, National Water Development Agency, and various consultant organizations operating in Somalia. Results of these studies indicated low availability of surface water in Somalia except for the two perennial rivers, Shabelle and Jubba, whose catchment areas are mostly in Ethiopia. These rivers run from their headwaters in Ethiopia through Somalia and discharge into the Indian Ocean near Kismania in the south of the country. The flow rate of these rivers, Jubba and Shabelle, depends on the intensity of the rainfall received during the year. Serious inventories of flow rate measurements were performed at various stations along Jubba and Shabelle rivers and the results obtained have shown various levels of flow rates, depending on the period of recording and altitude of the station. McDonald (1977) measured the flow rate of Jubba river at Sakow, in the southwest of Somalia, during an intensive rain period and obtained a flow rate of 1780 m$^3$/sec. In an up stream station at Bardere area, they calculated an average annual flow rate of $7.8 \times 10^8$ m$^3$ and reported that the flow rate of Jubba at this location, especially at Bardere dam, could reach 4000 to 12000 m$^3$/sec. during intensive rain season. Pozzi (1980), also, reported that the flow rate of Jubba river decreases to 100-125 m$^3$/sec. at Bardere during the dry season. Studies on flow rate measurements of Shabelle river at various stations have been conducted by Dal Pra (1983) and the results indicate that the mean flow rate of Shabelle river is about 55 m$^3$/sec. All the previous calculations were based on short-term records. No consistent long term records of flow rate.
measurements are available. FAO (1979), released a record of long-term mean flow rate data for Jubba and Shabelle rivers (Table 3.1).

Table 3.1: Mean flow rate of the Jubba and Shabelle rivers (Louis Berger International, 1985).

<table>
<thead>
<tr>
<th>River</th>
<th>Station</th>
<th>Year</th>
<th>Mean Flow (m³/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jubba</td>
<td>Lugh G.</td>
<td>1957-79</td>
<td>192</td>
</tr>
<tr>
<td>Shabelle</td>
<td>Beletuen</td>
<td>1957-79</td>
<td>68.3</td>
</tr>
<tr>
<td>= =</td>
<td>Bulo Burti</td>
<td>1957-79</td>
<td>66.4</td>
</tr>
<tr>
<td>= =</td>
<td>Mahadey W.</td>
<td>1957-79</td>
<td>58.8</td>
</tr>
<tr>
<td>= =</td>
<td>Balad</td>
<td>1957-79</td>
<td>46.90</td>
</tr>
<tr>
<td>= =</td>
<td>Afgoye</td>
<td>1957-79</td>
<td>46.1</td>
</tr>
</tbody>
</table>

The minimum flow rates of Shabelle and Jubba rivers are 13 and 125 m³/sec. respectively during dry season and the maximum flow rates could reach 149 and 12000 m³/sec. respectively during an intensive rain period (McDonald,
Both rivers, Jubba and Shabelle, have an average flow rate of 192 and 57.3 m³/sec. respectively.

Intermittent streams are found in the mountainous area. These streams flow only during the rainy season and convey water relatively short distances before they become dry due to evaporation and infiltration into alluvium.

Based on the extreme low flow conditions in both Shabelle and Jubba rivers, the amount of water available annually for use is $410 \times 10^6$ m³ for Shabelle and $3937.5 \times 10^6$ m³ for Jubba, forming a total volume of $4347.5 \times 10^6$ m³. This reflects the presence of large amount of surface water in the rivers. This volume of water can irrigate more than 80,000 ha per year of agricultural land if it is planned to produce perennial or seasonal crops from that land. So proper planning and distribution of surface water in the rivers can increase production of food to encounter the increasing shortages and to settle people in such areas. This will help in alleviating the reoccurring hunger episodes that are hitting the population frequently.

3.3. Groundwater.

Studies of various aquifers were conducted as a part of various phases of groundwater development schemes in the country. Shallow wells with depths ranging 10 to 20 meters and deeper wells with depths ranging 70 to 400 meters were drilled striking water of various quantity and quality at different depths throughout the country. Groundwater in the most shallow aquifers is highly
saltish with total dissolved solids between 500 to 5000 mg/l. The presence of large gypsiferous rocks together with high evaporation rate is the main reason for the high salt concentrations (Pozzi et. al, 1987). Therefore, it is essential to exploit the low mineralized and economically sustainable deeper aquifers. Deeper aquifers (deeper than 400m) are not considered yet because their development is not feasible under the present state of economic standards of the country. However, the major groundwater resource withdrawals in most of the country depend on the deeper aquifers (<400m). In addition, temporary shallow hand dug wells with low productivity and quality are in use in the rural areas because they are much cheaper and easier than the deeper wells in terms of operation and maintainance.

Aquifer systems in the country are distributed in relation to their geological conditions (lithology and structural evolution). Therefore, there are two different types of aquifers in the country: Unconsolidated and consolidated aquifers.

3.3.1. Unconsolidated Aquifers.

Unconsolidated aquifers are generally found throughout the country, especially along the coastal belt (Fig. 3.1). They are areally limited with an average width of about three to five kilometers while their length could run up to ten to twenty kilometers. These aquifers are recharged by direct infiltration from the rainfall and surface runoff that flows over the valleys during the rainy seasons. The volume of groundwater stored in these aquifers is controlled by the nature of the sediments, their areal extension and the volume of pore space within the sediments. The expected withdrawal from these type of aquifers is very low.
Fig. 3. Location of Unconsolidated aquifers in Somalia

(After Pozzi, 1983; Faillace, 1982; GTZ, 1979; LBI, 1985.)
compared to that from consolidated aquifers because the thicknesses and areal extensions of unconsolidated aquifers are smaller than those of consolidated aquifers. Exploitation of alluvial aquifers requires careful management since water quality could deteriorate with continuous withdrawal especially since most of them lie along the coastal line of the Indian Ocean and Red sea. Permanent dewatering of these aquifers could cause a loss of balance between the interface of freshwater and saline water and lead saline water intrusion or upwelling of connate water into the aquifers. The water quality of these aquifers varies from good to poor as indicated by numerous existing wells used for drinking and for livestock. The presence of gypsum and saline soils, which are easily soluble with rain water in most of the country, has influenced the quality of water in these aquifers (GTZ, 1979; Pozzi, 1983; Pozzi et. al, 1987). Moreover, the annual recharge volume of these aquifers is estimated as $288 \times 10^6$ m$^3$ by using the mean annual precipitation (300 mm) received by the country, the areal extension of the aquifers ($192 \times 10^4$ m$^2$) and infiltration rate of 5%.

The calculation of volume of water in storage of unconsolidated aquifers is based on the estimated total areal extension, average saturated thickness of the aquifers and assumed average specific yield (0.07) referenced from Raghunath (1982). The thickness of these aquifers varies from 12 to 40 meters (LBI, 1985; Pozzi, et al 1983; Faillace, 1982). Therefore, an average saturated thickness of 25 m is used in order to calculate the total volume of water in storage by applying the following formula (Toth, 1982).

\[ V = A \times b \times S_y \] ..........................(1)

-55-
Where $V = $ Volume in storage ($m^3$).

$b = $ Average saturated thickness of the aquifers (m).

$S_y = $ Average specific yield of aquifer material ($\%$).

hence, the total volume is

$$V = 192 \times 10^4 \times 25 \times 0.07 = 33.6 \times 10^9 \ m^3$$

The amount of water in storage ($33.6 \times 10^9 \ m^3$) of the unconsolidated aquifers replenished by annual recharge of $288 \times 10^6 \ m^3$ can cover part of growing demand of the country and can be used to convert the nomadic life to settlements and agricultural society in order to reduce famine in the country. The volume of water in these aquifers manifests the presence of large amount of groundwater in the country in spite of difficulties of water shortage in some parts. This is due to lack of development of the aquifers and proper plan of water distribution.

3.3.2. Consolidated Aquifers.

The distribution of the principal aquifers in the country is shown in figure 3.2. Figure 3.3 shows a hypothetical spatial relationship between the aquifers in the country, and the degree of development of each aquifer.

The major aquifers are the Baidoa, Jesomma, Aurado, Taleh, and Merca aquifer. Consolidated rocks such as conglomerate, sandstone, limestone and
Fig. 3.2. Outcrop map of principal aquifers in Somalia

(from Stefini, 1933; Barnes, 1976)
Fig. 3.3. Hydrogeological cross section of Shanxi
(see Fig. 3.2.)
dolomites mainly form these major aquifers. These formations are usually found below the unconsolidated sediments and are economically important for forming good aquifers which could store valuable amounts of water. Their value as aquifers depends to a large extent on the degree of cementation and fracturing to which they have been subjected. However, the knowledge of discharge, recharge, effect of lithology on hydraulic characteristics, porosity, permeability, groundwater movement, transmissivity and storage coefficient of these aquifers is essential for the assessment of each aquifer in terms of response to abstraction, volume in storage, safe yield and hydraulic behavior of the aquifer. Evaluation and determination of groundwater of individual aquifers are presented in the following sections.

3.3.2.1. Baidoa Aquifer

1. Recharge

The Baidoa limestone aquifer receives its recharge from direct infiltration of rainfall during rainy seasons in the outcrop area. Infiltration of water into the limestone aquifer takes place mostly by direct runoff into the enlarged fracture systems which act as conduits. The less availability of surface drainage courses on the aquifer outcrop indicate that there are abundant openings and sinkholes that readily accept infiltration of rainfall. The aquifer's response to recharge, as observed from water level measurements in some wells tapping the aquifer, varies from rapid (within hours) to moderate (as much as couple of months). Observation of water levels in some wells showed rapid response to intense
precipitation events and delayed response to precipitation of lower magnitude. In some areas a thin layer of soil overlies the outcrop. Two soil infiltration tests were performed in the Baidoa town area by Hunting Technical Services, Ltd. Infiltration rates were 18.2 cm per hour in sandy clay loam and 7.5 cm per hour in light clay loam. These rates are greater than average infiltration rates for similar materials (USDA Technical Bulletin 729) but negligible in comparison with the rate of direct runoff into sinkholes. In addition, infiltration studies conducted by BRADP (1985) on the soils overlying the aquifer in the vicinity of the Baidoa town yielded rates between 13.56 cm per hour and 0.2 cm per hour with a mean of 6.9 cm per hour (LBI, 1985). The results of the infiltration tests depend on the state of the soil at the time of measurement or its infiltration capacity and intensity of rainfall because infiltration often begins at a high rate (20 to 25 cm/hr) and decreases to a fairly steady rate (1.25 cm/h) as rain continues (Raghunath, 1982). Infiltration rate measurements obtained at various locations within the Baidoa aquifer vary from high to moderate depending on soil state and rainfall intensity. In addition, minimum recharge to the aquifer takes place from infiltration through soil or alluvium and maximum recharge takes place along the fractures in the outcrop area. Most recharge occurs early in the precipitation event when the soil is dry and has greater shrinkage fractures and openings.

Estimation of groundwater recharge to the aquifer was made by Louis Berger International in 1985 using a mean annual precipitation of 0.6 m over all the areal extension of the outcrop of the aquifer and calculated a recharge rate of five percent. This value is comparable with other values obtained from studies
conducted in other parts of the world with similar soil and climatic conditions (Chew, 1964). Accordingly, the estimated recharge volume to the Baidoa aquifer is about $115.5 \times 10^6$ m$^3$/year. The annual withdrawal from the aquifer is about $1.3 \times 10^6$ m$^3$ or only about 1.13% of the estimated recharge volume (LBI, 1985). This manifests that the Baidoa aquifer is sustainable and beneficial in terms of economy and abstraction because large volumes of water remain in storage.

2. Movement.

Groundwater flow is generally from areas of low head to areas of high head or from areas of recharge to areas of discharge. In the Baidoa aquifer, groundwater flows through karst zones, along bedding planes, open joint sets and fractures of the formation. Figure 3.4 shows the general flow pattern in the aquifer. The flow is normal to the groundwater divide which coincides with the topographic divide of the Shabelle and Jubba rivers. The flow of groundwater in the aquifer is almost west toward Jubba river with slight deviation to the southwest, but some flow occurs towards the east, beyond the escarpment, where it emerges as springs or enters the alluvium and contributes to the river flow as underflow. Groundwater flow rates are variable and depend on the extent of fractures and faults present and the degree of karst development in the aquifer. The transmissivity values obtained from wells tapping the aquifer along the flow direction ranged widely over short distances. The lack of uniformity reflects the typically uneven karst development and the influence of faults and fractures (LBI, 1985).
Fig. 3.4. Groundwater Movement in the Baidoa Aquifer and Drainage

3. Discharge.

Natural discharge of groundwater could be observed at springs along the limestone escarpment and inferred as underflow in the alluvium east of the escarpment. Nearly all natural groundwater discharge from the springs run through the valleys and is ultimately dissipated as evapotranspiration. Groundwater which flows towards Jubba and Shabelle rivers is discharged as base flow in these rivers.

4. Production.

The Baidoa aquifer has not been discovered until recently. Before the beginning of groundwater development projects in 1975, the major water supply in Baidoa area came from shallow hand dug wells and surface reservoirs. The National Water Development Agency of Somalia drilled several wells in Khansah Dheere and Baidoa town area for the first time in 1975. The estimated total rate of production of these wells was 0.03 cubic meter per second. Louis Berger International conducted another study on the aquifer in which they drilled a number of wells at different locations over the aquifer's areal extent, namely: Sarmaan Dheere, Khansah Dheere, Guduudo Dhuunte, Baidoa, Hareero Jecfo, Maleel and other places. The total production rate of these wells was estimated to be about 0.040 cubic meter per second. The discharge rate results obtained from the tested wells show that the production capacity of the aquifer is higher than the present annual withdrawal (1.3 × 10⁶ m³). In addition, only about 1.13% of the total annual recharge amount is withdrawn from the aquifer due
to scarcity and uneven distribution of wells in the aquifer. Therefore, it is recommended to increase the distribution of the wells in the aquifer in order to abstract more needed water that is being stored in this aquifer.

5. Hydraulic Properties.

The Baidoa limestone aquifer was deposited under geologic conditions which played an important role in the development and distribution of the aquifer characteristics. In the lower part of the formation, limestone and sandstone together with large amounts of marl and shale were deposited as indicated by cuttings from wells drilled near the Baidoa town. The rest of the formation is generally characterized by deeply weathered and karstified limestone with small intercalation of shale, marl and sandstone. Near Khansah Dheere town, the upper part of the formation has undergone intense weathering. Carbonate rocks are partially dissolved by downward percolating water, causing development of karstification and sinkholes. Karstification and fractured zones are common in the northwestern part of the aquifer, especially in the recharge area near Baidoa town. Less karstified areas of the aquifer, especially in some parts of Golodo member, yield less water to the wells due to low permeability. Areas characterized by fractures, widened fissures, karstification and sinkholes have high transmissivity caused by the development of secondary permeability. This karstification has caused the development of secondary permeability which enhanced the productivity in some parts, especially in the northwestern part of the aquifer.
6. Pumping Tests

A pumping test program of several wells has been conducted by Louis Berger International in some parts of Baidoa aquifer in order to determine the transmissivity (T) of the aquifer. No observation wells were drilled in the Baidoa aquifer. The recorded drawdown from the pumped wells (fully penetrated the thickness of the aquifer) was used for calculation of transmissivity. This parameter is important for the evaluation of the aquifer productivity. The Results of the tests and pumped wells are presented in Table 3.2 and the well locations are given in Fig. 3.5.

Pumping Test At Baidoa: A pumping test was performed on a production well (no. 11) in USAID compound at Baidoa. Drawdown was monitored at the same well. The duration of the pumping test was 16.7 hours with a constant discharge rate of $3.7 \times 10^3$ m$^3$/sec. The recorded drawdown is plotted against time on semilog paper. The drawdown is shown on the linear scale (vertical) in meters and time in minutes on the horizontal logarithmic scale (Fig. 3.6). From the graph, the transmissivity was calculated by applying Jacob's equation (Kruseman and De Ridder, 1970; Freeze and cherry, 1979; Fetter, 1982), stated as:

$$T = \frac{0.183 \times Q \text{ (m}^3/\text{sec})}{\Delta s \text{ (m)}} \text{ ..................................(2).}$$

where $T$ = Transmissivity in meter square per second.
\[ Q = \text{Discharge rate in cubic meter per second.} \]
\[ A_s = \text{Drawdown per log cycle in meter} \]

The calculated transmissivity value in this locality is $4.84 \times 10^{-3}$ m$^2$/sec. This value indicates that the Baidoa aquifer is transmissive in this locality. The high productivity of the aquifer in this locality is attributed to the development of secondary permeability caused by the fractured rocks, sinkholes and solution cavities.

**Pumping Test At Sarmaan Dheere:** At this location, production well no. 10, was pumped at a constant discharge rate of $7.4 \times 10^{-3}$ m$^3$/sec. for a period of 24 hours. Water level in the production well was measured at frequent intervals. Recorded drawdown during the progress of the pumping test is plotted against time (Fig.3.7) in order to calculated the transmissivity of the aquifer at this locality from the plot. The calculated transmissivity value in this locality is $2.52 \times 10^{-2}$ m$^2$/sec. This value indicates that the Baidoa aquifer is highly transmissive in this locality due to the hydraulic characteristic of the formation; the development of the secondary permeability is the main cause of productivity in this locality.

7. **Storage coefficient of the aquifer.**

According to Lohman, 1972, the values of storage coefficient in most confined aquifers fall within the range $10^{-3}$ to $10^{-1}$ while specific storage of unconfined aquifers fall within the range $10^{-2}$ to $10^{-1}$ (Hamill and Bell, 1986).
Table 3.2: Pumping Test data and results for the Baidoa aquifer.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Location</th>
<th>Test duration (hrs)</th>
<th>Average discharge (l/s)</th>
<th>Calculated transmissivity (m²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Sarman dheere</td>
<td>24</td>
<td>7.4</td>
<td>$2.52 \times 10^2$</td>
</tr>
<tr>
<td>11</td>
<td>USAID Comp.</td>
<td>16.7</td>
<td>3.7</td>
<td>$4.84 \times 10^3$</td>
</tr>
<tr>
<td>12</td>
<td>Harcero Jeefo</td>
<td>5</td>
<td>3.2</td>
<td>$2.53 \times 10^5$</td>
</tr>
<tr>
<td>16</td>
<td>Taflow</td>
<td>24</td>
<td>4.3</td>
<td>$2.4 \times 10^4$</td>
</tr>
<tr>
<td>18</td>
<td>Guduudo DHunte</td>
<td>24</td>
<td>3.2</td>
<td>$1.32 \times 10^4$</td>
</tr>
<tr>
<td>20</td>
<td>Durai A. Gelle</td>
<td>79.3</td>
<td>3.2</td>
<td>$2.3 \times 10^4$</td>
</tr>
<tr>
<td>42</td>
<td>Bulo Fur</td>
<td>24</td>
<td>3.2</td>
<td>$4.14 \times 10^4$</td>
</tr>
<tr>
<td>46</td>
<td>Khansah Dheere</td>
<td>24</td>
<td>3.2</td>
<td>$1.2 \times 10^4$</td>
</tr>
<tr>
<td>47</td>
<td>Awshinile</td>
<td>24</td>
<td>3.2</td>
<td>$2.6 \times 10^4$</td>
</tr>
<tr>
<td>51</td>
<td>Mintaan</td>
<td>12</td>
<td>4.3</td>
<td>$2.74 \times 10^4$</td>
</tr>
<tr>
<td>52</td>
<td>Maleel</td>
<td>11.5</td>
<td>7</td>
<td>$3.41 \times 10^3$</td>
</tr>
<tr>
<td>54</td>
<td>Isgeed</td>
<td>24</td>
<td>4.7</td>
<td>$8.1 \times 10^5$</td>
</tr>
<tr>
<td>55</td>
<td>Marti Moog</td>
<td>24</td>
<td>6.3</td>
<td>$1.3 \times 10^4$</td>
</tr>
</tbody>
</table>
Fig. 3.5. Schematic Well Location Map for the Baidoa Aquifer.
Fig. 3.6. Pumping Test at Baldea Area, Usaid Compound, Well # 11
However, the storage coefficient of the Baidoa aquifer is not determined using pumping test data because of lack of observation wells. Instead it is computed by applying Jacob's method which considers water under artesian condition to be released from storage by compression of water bearing material (aquifer) and by expansion of water itself. Under unconfined condition, however, water drains from the pore spaces. Thus, the storage coefficient is a function of elasticity of water and aquifer skeleton and can be calculated by (Jacob Bear, 1950; Hantush, 1964; Jacob Bear, 1979)

\[ S = \gamma_w \times b \times (\alpha + n \times \beta) \] .............................(3).

where \( S = \) Storage coefficient (dimensionless)
\( \gamma_w = 9.8 \times 10^3 \text{ N/ m}^3 \) (unit weight of water).
\( \alpha = 10^{-9} \text{ m}^2/\text{n} \) (compressibility of the matrix).
\( \beta = 4.4 \times 10^{-10} \text{ m}^2/\text{n} \) (compressibility of water).
\( n = 20 \% \) (average porosity)
\( b = 90 \text{ meters} \) (average aquifer thickness).

The values used for the above parameters (\( \gamma_w, \alpha, \beta \) and \( n \)) are typically for limestone aquifer material (Freeze and Cherry, 1979). The storage coefficient, considered as representative of the aquifer, has been calculated using the above equation (3) and was found to be \( 7.50 \times 10^4 \). This value lies in the range indicated by Lohman, 1972, for confined aquifers.
8. Analysis of Pumping test Results.

The accuracy of the evaluation of the aquifer parameters (transmissivity and storage coefficient) are essential for aquifer assessment and depends on the nature of the data used. The results of all pumped wells indicate varying pattern of the Baidoa aquifer characteristics (Table 3.2). The transmissivity values obtained from the pumping test results show a range of variations throughout the areal extension of the aquifer. The well at USAID compound (W11), Baidoa town, has high transmissivity and appears to have good production rate. At Sarmaan Dheere (W10), northwest of the Baidoa town, the Baidoa aquifer is highly transmissive. This well is the most productive well among the wells tested so far in the Baidoa aquifer. The productivity of the aquifer in this area is due to the development of secondary permeability caused by the presence of solution cavities and sinkholes. Local variations of transmissivity are evident in area between the two localities (W11 and W10). This is the result of uneven distribution of secondary permeability and presence of faults. The result of the test at Awshinile (W47) shows abrupt decrease in transmissivity of the aquifer. The decrease is due to change in lithology and textural properties of the formation in that area.

Variations in transmissivity also exist farther north of the Baidoa aquifer at Maleel (W52), Mintaan (W51), and Marti Moog (W55). These variations are caused by local changes in the secondary permeability of the formation (LBI, 1985). In the south of the Baidoa aquifer, where the distribution of the wells is uneven, the transmissivity values obtained from pumping tests are compara-
tively low. In Khansah Dheere (W46), the cone of depression increases rapidly with time (Fig. 3.8) due to low transmissivity. This indicates an immediate exhaustion of the aquifer at this locality.

The transmissivity of the baidoa aquifer changes within short distances because the development of the secondary permeability caused by fractures and sinkholes is not distributed homogeneously in the Baidoa aquifer. The productivity is high in the northwestern part of the aquifer. In addition, the average transmissivity \( (2.71 \times 10^3 \text{ m}^3/\text{sec.}) \) calculated on the basis of results from wells tested so far indicates that the Baidoa aquifer is a transmissive aquifer and can supply large volumes of water in the region.


Long term water level data records are not available for analysis of fluctuations in the Baidoa aquifer, but short term (over one year) measurements of water level data have been recorded by Louis Berger International (1985-86). The data of nine observation wells scattered along the areal extension of the aquifer are available for analysis. Figures 3.9 and 3.10 show water level hydrographs for various wells in the Baidoa aquifer. Water level measurements in these wells have shown seasonal fluctuations varying from one place to another depending on the amount of recharge available, amount of withdrawal and available time for recovery of the wells after the ceasing of pumping stress.
\[ q = 3.2 \times 10^{-3} \text{ m}^3/\text{sec.} \]

\[ r = \frac{0.103 - \frac{Q}{\Delta s}}{5.0} \]

\[ T = 1.2 \times 10^{-4} \text{ m}^2/\text{sec.} \]

Fig. 3.8. Pumping Test At Khansah Dheere, Well No. 46.
Hydrograph of observation well no. 11 (Fig. 3.10) shows the influence of short term seasonal variations on the water level. This well receives recharge, sometimes during rainy season, as it is located near the recharge area of the aquifer where fractures and solution cavities are present. Well no. 47 shows similar pattern, but it is far from the recharge area. Presence of faults, which could act as a conduit, is suspected in the area. Well no. 63 indicates, also, high fluctuations in water level. This well is located near the recharge area as well and the increase of water level is due to interception of recharge during the rainy season as water decreases slightly during the dry season. Water level hydrographs of wells 1, 46, 52 and 71 indicate a similar pattern of water level variations, although they are located at various parts of the aquifer. This shows a trend of fluctuations in storage and groundwater movement in the aquifer at these various locations.

Water level hydrographs for well no. 18 and 76 show similar pattern of water level fluctuations, although slight variations exist in the magnitude of the results at the end of the recorded pattern (Fig. 3.10). The difference in magnitude of the results is due to the amount of withdrawal from the aquifer and available recovery time before the measurement of water level.

Groundwater levels recorded from the Baidoa aquifer were influenced by the seasonal cycles like recharge, movement, evapotranspiration and withdrawal rate from the wells and showed a fluctuation of about 10m. This reveals the extent and capability of the storage of the aquifer to respond to abstraction from the aquifer.
Fig. 3.9. Hydrographs of Wells Showing Seasonal Water Level Variations in the Baidoa Aquifer.

Fig. 3.10. Hydrographs of Wells Showing Seasonal Water Level Variations in the Baidoa Aquifer.
10. Aquifer Storage.

The total usable amount of water in storage in the Baidoa aquifer can be calculated under two conditions based on aquifer characteristics. An average depth (pumping thickness) of 200 meters below the surface is utilized due to economic limitations.

A. Under confined condition.

The amount of water in storage between the potentiometric surface and the upper confining bed can be calculated when the area, average storage coefficient and the difference in head between the potentiometric surface and the top of the upper confining layer are known (Fig. 3.11).

\[ V_1 = S_a \times A \times H \] .................................(4A).

where \( V_1 \) = Volume of water in Storage (m³).

\( A \) = Estimated aquifer area (m²).

\( H \) = Total head change (m) which is equivalent to vertical distance between the upper confining bed and potentiometric surface.

\( S_a \) = Average storage coefficient (dimensionless).

\[ V_1 = 37850 \times 10^6 \times 7.5 \times 10^{-4} \times 90 = 2.555 \times 10^9 \text{ m}^3 \]

B. Under unconfined condition.

When potentiometric level drops to the top of confining bed, the aquifer
Fig. 3.11 Schematic illustration of confined part of the Baidoa aquifer.
behaves as an unconfined aquifer because water is drained from the pores by gravity. Therefore, the amount of water available in storage in the aquifer between the bottom of confining bed and maximum depth of economic pumping wells (200 m) is calculated according to the equation

\[ V_2 = S_y \times A \times B \]  

where \( V_2 \) = Volume of water in Storage (m³).

\( A \) = Estimated aquifer area (m²).

\( B \) = Saturated thickness (m) of the aquifer (to a depth of 200).

\( S_y \) = Average specific yield (%).

\[ V_2 = 37850 \times 10^6 \times 0.02 \times 80 = 60.6 \times 10^9 \text{ m}^3 \]

The assumed average specific yield used in this calculation is referenced from Raghunath (1982). The total usable economic storage in the Baidoa aquifer is

\[ V_t = V_1 + V_2 = 2.555 \times 10^9 \text{ m}^3 + 60.6 \times 10^9 \text{ m}^3 = 63.20 \times 10^9 \text{ m}^3 \]

3.3.2.2. Jesomma Aquifer.

1. Recharge.

The Jesomma aquifer has an extensive outcrop in the Southwestern portion of the Central region near the border between Ethiopia and Somalia and part of Northwest of the Northern region (Fig.2.2). In addition, the Jesomma aquifer
has outcrop in the Ethiopian highlands where substantial recharge from much higher precipitation is available. The recharge volume received annually by the aquifer in its outcrop in Somalia is relatively less compared to the recharge volume received in the Ethiopian highlands due to less annual rainfall in Somalia, especially in the outcrop area. Moreover, the Jesomma aquifer deepens towards the Indian Ocean, in the Somali territory, and therefore the amount of recharge into the aquifer becomes minor, especially in the east. The extent of the recharge in the outcrop area is estimated as $258 \times 10^6$ m$^3$/year by using the areal extension of the outcrop $(17181 \times 10^6$ m$^2$), average annual precipitation (300 mm) and infiltration rate of 5%. Infiltration rate was calculated by Louis Berger international in 1985. This infiltration rate is also true for other studies from other parts of the world with similar soil and climatic conditions (Chew, 1964). The replenishment of this volume into the aquifer results in a rise of water level. The annual withdrawal from the aquifer is not available to compare with recharge, but the recharge volume is large enough to increase the storage and balance the abstraction from the aquifer.

2. Movement.

Groundwater movement usually takes place from areas of high head to areas of low head. However, the flow in this deeper aquifer is towards the southeast coinciding with the regional dip of the formation. Water in the aquifer, originating from the recharge area at distant outcrops, moves downward through the aquifer. Moreover, analysis of water samples collected from various wells in the Jesomma aquifer indicated an increase in sulfate and chloride ions.
and decrease in bicarbonate and calcium cations towards southeast (LBI, 1985). The predominance of chloride and sulfate along these direction towards the deeper parts of the aquifer indicates a trend in the general chemical changes that occur as water moves through the rocks from recharge areas to residence areas. The rate of movement has not been measured in the past and lack of data makes it impossible to estimate the rate of movement in the aquifer.

3. Discharge.

Natural discharge from the aquifer is almost minimum except from small springs scattered around Jesomma village (fig. 3.12). These springs provide the only means of natural discharge into a thin alluvial channel that surfaces downstream and disappears after a relatively short distance as a result of evaporation and seepage. The discharge from the springs continues for a short period of time and normally occurs during or immediately after events of intensive rainfall.

4. Production.

The Jesomma aquifer has been first recognized by Macfadyan in early 1960 in the Northwest of the Northern region (Fig. 3.12). It has been exploited for water supply in the towns of Gebilay, Togwajale and Hargeisa. Six wells with depths ranging from 70 to 135 m were drilled in Togwajale. The total production of these wells was estimated as 0.42 m³/sec. In Hargeisa area, eleven wells were drilled later. Eight of which were producing water and the rest were
abandoned due to difficulty in drilling caused by tendency collapse of loose sand beds. The total yield of these wells was 0.25 m³/sec. (Faillace, 1983). The discharge rate of the aquifer in the Hargeisa area is less than the discharge rate in Togwajale area. The decrease in productivity of the aquifer is due to lithological changes in the formation. Intercalation of fine material increases towards Hargeisa in the east, hence decreasing the permeability of the formation. Later drilling on the Jesomma aquifer has been performed by the National Water Development Agency of Somalia for augmentation of water supply in the Central region (Gulane, Mataban, Guri’al, Jesomma, Mahas - 1970) and other locations in the region. The average production of each of these wells was estimated at 6 × 10⁻² m³/sec. German Technical Cooperation (GTZ) also drilled two wells in the Jesomma aquifer in 1984 to supply water for Buroa town. The total production of these wells was about 0.1 m³/sec. The results obtained from these locations show that the Jesomma aquifer is highly productive, especially in the southern part, and can supply enough water to the region.

5. Hydraulic Properties.

The Jesomma formation was deposited under regressive conditions in a fluvi- vial environment which influenced the distribution and development of the hydraulic characteristics of the aquifer. The Jesomma formation consists mainly of sandstone with local intercalations of silt, shale and thin beds of limestone. Conglomerates are common locally in the upper part of the formation. The nature of the clastic texture of the formation has caused the development of the primary permeability. In Hargeisa area, the intercalation of silt and clay has
decreased primary permeability of the formation, because the production of the aquifer in that area is lower than the production of the aquifer in other locations. Primary permeability of the formation increases towards the south, where areas of lower cementation exist, as observed from the transmissivity values obtained from various locations. In Buroa, Mataban, and Gulane, the lithology of the formation is less cemented and the composition is dominated by porous texture which increased primary permeability of the formation.

6. Pumping tests

Pumping tests have been performed on the Jesomma aquifer at various locations by various companies and agencies by using constant pumping test. The objective of the tests was to calculate aquifer characteristics (Transmissivity and storage coefficient). The knowledge of these parameters permits the evaluation of productivity and nature of the aquifer. The transmissivity and storage coefficient of the Jesomma aquifer at various locations were calculated by applying Jacob's equation (Kruseman and De Ridder, 1970; Freeze and Cherry, 1979; Fetter, 1982), stated as:

\[ T = \frac{0.183 \times Q \text{ (m}^3/\text{sec})}{\Delta s \text{ (m)}} \]  

(2).

where \( T \) = Transmissivity in meter square per second.
\[ Q = \text{Discharge rate in cubic meter per second.} \]
\[
\Delta s = \text{Drawdown per log cycle in meter} \]

and

\[
S = \frac{2.25 \times T \times t_s}{r^2} \]

..........................(5).

where \( S = \text{Storage coefficient (dimensionless).} \)

\( t_s = \text{time intercept where the drawdown time intercepts the zero drawdown axis in seconds.} \)

\( r = \text{Distance between pumping well and observation well in meter.} \)

The results of these tests and pumped wells are presented in Table 3.3 and locations of the pumped wells are shown in figure 3.12.

Pumping test At Gulane Area: A constant discharge pumping test was performed on the production well having a constant discharge rate of 6.6 \( \times 10^2 \) m\(^3\)/sec. Water level was monitored at an observation well located a distance of 100 meters away from the pumped well. Drawdown data recorded from the observation well during pumping were plotted against corresponding time on semilogarithmic paper (Fig.3.13) in order to calculate the transmissivity and storage coefficient of the aquifer in this locality. The calculated values of transmissivity and storage coefficient are \( 3.7 \times 10^2 \) m\(^2\)/sec. and \( 1.4 \times 10^4 \) respectively.
Table 3.3: Pumping Test data and results for the Jesomma aquifer.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Location</th>
<th>Test duration (hrs)</th>
<th>Average discharge (l/s)</th>
<th>Calculated transmissivity (m²/sec)</th>
<th>Storage coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Gulane</td>
<td>24</td>
<td>66</td>
<td>$3.7 \times 10^{-2}$</td>
<td>$1.4 \times 10^4$</td>
</tr>
<tr>
<td>20</td>
<td>Adan Ival</td>
<td>24</td>
<td>50</td>
<td>$2.7 \times 10^{-2}$</td>
<td>$6.35 \times 10^4$</td>
</tr>
<tr>
<td>24</td>
<td>Jesomma</td>
<td>24</td>
<td>53</td>
<td>$2.5 \times 10^{-2}$</td>
<td>—</td>
</tr>
<tr>
<td>35</td>
<td>Mataban</td>
<td>24</td>
<td>69</td>
<td>$3.83 \times 10^{-2}$</td>
<td>$2.70 \times 10^4$</td>
</tr>
<tr>
<td>38</td>
<td>El-Bilal</td>
<td>16.67</td>
<td>60</td>
<td>$2.75 \times 10^{-2}$</td>
<td>$8.73 \times 10^4$</td>
</tr>
<tr>
<td>46</td>
<td>Guri’al</td>
<td>16.67</td>
<td>66</td>
<td>$2.95 \times 10^{-2}$</td>
<td>$4.6 \times 10^4$</td>
</tr>
<tr>
<td>53</td>
<td>Mahas</td>
<td>24</td>
<td>66</td>
<td>$3.35 \times 10^{-2}$</td>
<td>$7.62 \times 10^4$</td>
</tr>
<tr>
<td>67</td>
<td>Buroa</td>
<td>24</td>
<td>70</td>
<td>$4.27 \times 10^{-2}$</td>
<td>—</td>
</tr>
<tr>
<td>78</td>
<td>Togwajale</td>
<td>24</td>
<td>77</td>
<td>$1.5 \times 10^{-2}$</td>
<td>$1.13 \times 10^4$</td>
</tr>
</tbody>
</table>
Fig. 3.12. Schematic Well Location Map for the Jesomma Aquifer.
Fig. 3.13. Pumping Test At Gulane Area, Well No. 13
These values indicate that the Jesomma aquifer is a highly transmissive and confined aquifer at this locality. The higher transmissivity value of the aquifer in this locality is attributed to the increase in porosity of the formation which in turn enhanced its permeability.

Pumping Test At Mataban Area: A pumping test of the aquifer was performed by National Water Development Agency of Somalia in Mataban area with constant discharge rate of $6.9 \times 10^{-2}$ m$^3$/sec. Drawdown data were obtained from an observation well located at distance of 95 meters from the pumped well. Figure 3.14 shows a graph of drawdown versus time. The transmissivity and storage coefficient were calculated by applying equation 1 and 4 (Jacob’s method). The transmissivity and storage coefficient values calculated from the pumping test data are $3.38 \times 10^{-2}$ m$^2$/sec. and $2.70 \times 10^{-4}$ respectively. These values indicate that the Jesomma aquifer is highly transmissive and confined at this locality which is due to the development of the primary permeability of the formation.

Pumping Test At Guri’al: A constant pumping test was conducted at Guri’al. The pumped well had a discharge rate of $6.6 \times 10^{-2}$ m$^3$/sec. and lasted for a period of 16.67 hrs. Drawdown was monitored at an observation well located a distance of 100 meters away from the pumped well. Recorded drawdown was plotted against time to determine the transmissivity and storage coefficient (T & S ) of the aquifer at this locality (Fig. 3.15). The calculated values of transmissivity and storage coefficient based on the slope of the middle part of time-drawdown graph are $2.95 \times 10^{-2}$ m$^2$ sec. and $4.6 \times 10^{-4}$ respectively. The
\[ Q = 6.9 \times 10^{-2} \text{ m}^3/\text{sec}. \]
\[ r = 98 \text{ m}. \]
\[ t_0 = 28.2 \text{ sec}. \]

\[ T = \frac{0.183}{\Delta S} \]

\[ T = 0.183 \times \frac{6.9 \times 10^{-2}}{0.33} \]

\[ T = 3.03 \times 10^{-2} \text{ m}^3/\text{sec}. \]

\[ S = \frac{2.25 \times T \cdot t_0}{r^2} \]

\[ S = \frac{2.25 \times 3.03 \times 10^{-2} \times 28.2}{98^2} \]

\[ S = 2.7 \times 10^{-4} \]

**Fig. 3.14.** Pumping Test at Mataban, Well No. 35.
Fig. 3.15. Pumping Test At Qurlal, Well No. 48.
The slope of time-drawdown graph is significant for the computation and selection of transmissivity value. Data recorded in the first 10 minutes are not valid when using Jacob’s method because water is pumped from the casing storage (recall that \( U \) in the Theis Equation must be less than 0.05 for Jacob’s method to be valid) and transmissivity value calculated from this data becomes very low. The latter part of the slope indicates the effect of recharge, the transmissivity calculated on the basis of latter part of the slope will be too high to be representative. The middle part of the drawdown represents the true aquifer transmissivity (Driscoll, 1987). However, the transmissivity value of this locality is low compared to Mataban, Gulane and Buroa. The decrease is a result of lithological change which in turn caused a decrease in hydraulic characteristics of the formation.

7. Analysis of Pumping Test Results.

The interpretation of the results of the pumping tests performed at various locations of the Jesomma aquifer reveals, in general, similar pattern in terms of hydrogeologic characteristics, although slight variations exist among the results. The transmissivity value of the Jesomma aquifer at Guri’al area is low compared to Mataban, Gulane and Buroa area. The transmissivity value increases towards Gulane, southeast of Guri’al, and Mataban, northeast of Guri’al (Fig. 3.12). The relative increase of transmissivity is caused by the nature of the formation which becomes more porous and permeable in these localities. In addition, wells in Guri’al area are utilizing a small part of the thickness of the aquifer, because the average depths of the pumped wells are about 70 meters while
wells tapping the aquifer at Gulane and Mataban penetrate the thickness of the aquifer. Also the depth of the aquifer increases toward northeast and southeast from Guri'al. The transmissivity values of the latter locations are comparatively higher than other locations except at Buroa area (Table 3.3), in the central part of the northern region (Fig.3.12).

At Togwajale area, northwest of the northern region, near the border between Somalia and Ethiopia, the transmissivity of the aquifer is comparatively low. Decrease in transmissivity of the aquifer in that area is attributed to the presence of intercalation of fine matrix material in the formation which caused less development of the primary permeability. Macfadyan (1960) and Morgan (1971) have reported the presence of fine matrix material in the formation in that area. In most wells, the casing had to be driven down in order to stop caving (Faillace, 1983). The average transmissivity of the Jesomma aquifer is about 3.11 \times 10^2 \text{ m}^2/\text{sec}. However, the results of the pumping tests from all locations indicate that the Jesomma aquifer is highly transmissive and confined. Besides, the productivity of the Jesomma aquifer is generally high and increases towards the southern part of the aquifer.

8. Water Level Behavior.

Water level data from several wells tapping the Jesomma aquifer at various locations are available for analysis of long term behavior of the water level in the aquifer. Water level data measurements cover the period from 1965 to 1987 and are not continuous for all wells in the aquifer.
Hydrographs of observation well no. 13 (Gulane) and 35 (Mataban), located in the south of the central region, indicate minor fluctuations in the water level during the period between 1970 and 1983, except during the period of severe drought (1972-1975) which affected the whole country. The steady increase of pumping rate in the drought period caused a measurable decline in water level of 3 about meters in these localities, especially in Gulane area. The water level decline in Mataban area is relatively smaller than in Gulane area (Fig.3.16) due to relatively higher transmissivity of the aquifer in Mataban area.

Water level hydrographs of observation well no. 24 and 46, located in the southwestern part of the aquifer (central region), show significant water level decline during that extended period of drought (1972-75). Significant decline was observed in well no. 24 (Fig.3.17). However, both wells showed recovery later on, because they are located in the shallow part of the aquifer. The recovery of water levels started at the end of 1976 in response to extended heavy rainfall period in Somalia and Ethiopia, where the aquifer recharge area is located. The wet climatic conditions persisted for a long period and caused extensive recharge to occur causing the reversal of water level decline. Figure 3.18 shows a hydrograph for observation well no. 67, located at Buroa in the northern region. It indicates slight decline in the water level during a period of four years (1984-87). This decline is due to large withdrawals from the aquifer. Figure 3.19 shows a hydrograph of observation well no. 78, located in the northwest of the northern region, near the border between Somalia and Ethiopia. It shows slight fluctuations in water level for the first six years, then it maintains a quasi-constant water level. After 1970 and throughout the extended period of drought,
Fig. 3.16. Water Level Hydrographs of Well No. 13 and 35.

Fig. 3.17. Water Level Hydrographs of Well No. 24 and 48.
Fig. 3.18. Water Level Hydrograph of Well No. 67.

Fig. 3.19. Water Level Hydrograph of Well No. 76.
the water in the well started declining and continued until 1975. The magnitude of water level decline reached about 4.5 m. The slight fluctuation in water level in the early years was caused by the balance of the hydrologic situation, but later heavy pumping which coincided with the extension of the drought has caused abrupt water level decline of the aquifer in this locality.

In summary, the water level fluctuations in the aquifer could reach about 10 m in some parts during drought periods. Water level decline in the wells decreases towards the southeastern part of the aquifer. In addition, the results of recharge, production, pumping test and long term water level response to pumping reveals that the Jesomma aquifer has high potential and can supply large volume of water to the country.


The amount of water stored in the Jesomma aquifer was calculated by applying equation 4A and 4B with an average pumping thickness of 210 meters based on the conditions and characteristics of the aquifer.

A. Under confined condition.

Total head drop of 70 meters between the potentiometric surface and upper confining layer, estimated area and average storage coefficient of the aquifer under this condition is utilized in order to calculate the storage of the aquifer in this section (Fig.3.20).
Fig. 3.20 Sketch illustrating the confined part of the Jesomma aquifer
\[ V_1 = 66.56 \times 10^9 \times 4.65 \times 10^{-4} \times 70 = 2.2 \times 10^9 \text{ m}^3 \]

B. Under unconfined condition.

The storage in the aquifer under unconfined condition is calculated using a thickness of 60 meters between the top confining layer and bottom of the pumping thickness, assumed average specific yield (0.03) and area of the aquifer (66.56 \times 10^9 \text{ m}^2).

\[ V_2 = 66.56 \times 10^9 \times 0.03 \times 60 = 119.8 \times 10^9 \text{ m}^3 \]

Therefore, the total usable storage in the Jesomma aquifer is

\[ V_t = V_1 + V_2 = 2.2 \times 10^9 \text{ m}^3 + 119.8 \times 10^9 \text{ m}^3 = 122.0 \times 10^9 \text{ m}^3 \]

3.3.2.3. Aurado Aquifer.

1. Recharge.

The Aurado formation has its extensive outcrop areas in the southwest of the central region as well as northwest of the northern region, near the border between Somalia and Ethiopia. The outcrop extends beyond the border between Somalia and Ethiopia where a substantial recharge from much higher precipitation levels is available. Water samples collected from wells drilled near the border between Somalia and Ethiopia have shown the dominance of bicarbonate
ions which indicate direct recharge from precipitation. Recharge to the aquifer is limited to exceptional precipitation events due to higher moisture deficiency and to the lower depth of the water table, towards east and southeast from the border. In addition, chemical analysis of water samples collected from the wells tapping the deeper parts of the aquifer, towards east and southeast of the border, indicated the dominance of either chloride ions or sulfate ions. This indicates poor recharge and long-term stagnation of groundwater in the host rocks. The major recharge to the aquifer takes place in the highland outcrops in Ethiopia near the border between Somalia and Ethiopia. The extent of this recharge is estimated by using the extension of the outcrop and mean annual precipitation. The outcrop of the formation receives an average annual precipitation of about 300 mm over an estimated area of $29.7 \times 10^3 \text{ km}^2$. An infiltration rate of 5% was calculated for the aquifer by Louis Berger International in 1985. The infiltration capacity is also true for other studies from other areas of the world with similar soil and climatic conditions (Chew, 1964). The annual recharged volume into the aquifer is about $445.6 \times 10^6 \text{ m}^3$. The replenishment of this amount of water into the aquifer results in an increase of water level and storage and maintains the balance of hydrogeologic conditions of the aquifer.

2. Movement.

The entire formation dips gently to the southeast and the deep groundwater flow is related to recharge area in the west and northwest of Somalia and expected to move down through the aquifer towards the Indian Ocean. Groundwater movement in the aquifer coincides with the regional dip of the formation.
The dominant anions in the water samples analyzed by Louis Berger International (1985) and Popov and Kidawi (1973) indicate that the flow of groundwater in the aquifer is towards the Indian Ocean; There is increase in sulfate and chloride ions and decrease in bicarbonate and calcium cations toward this direction. This is the normal chemical evolution which occurs during the movement of water through the host rocks. However, more detailed hydrogeological investigations are required in the future to verify the significance of the rate of movement of water in the aquifer.

3. **Production.**

The Aurado aquifer, one of the major aquifers in the country, was first recognized by Armado Oil Company in 1967, when it utilized the aquifer to supply water for its camps. Later in 1970, several wells were drilled in the aquifer by National Water Development Agency (WDA) of Somalia. German Technical Cooperation (GTZ) conducted inventories and drilled several wells in the aquifer at various locations during the period between 1983 and 1986.

Armado Oil Company drilled several wells in the south and central parts of the Northern region for water supply to their camps. The average production of these wells was estimated at 0.04 m³/sec. (600 gpm). National Water Development Agency of Somalia also drilled wells in the aquifer at various locations in the northern and central regions in response to rising groundwater demands in the rural areas, villages and towns. The distribution of the wells was selected on the basis of necessity for water at each particular location. The average dis-
charge rate of each of those wells was estimated at 0.05 m$^3$/sec. (700 gpm).

In 1983, German Technical Cooperation (GTZ) drilled wells in the aquifer at Dhusa Mareb and Aradabo towns as part of a groundwater development program to supply better quality water to these towns. They reported that the total discharge rate from the aquifer at these localities was about 0.11 m$^3$/sec. (1650 gpm). Local lithological variations exist in the formation, especially in the northeastern part, and the distribution of the wells is not homogeneous throughout the extension of the aquifer. However, tested areas manifested good results in terms of productivity which increases towards southeastern section of the aquifer.


The development and distribution of hydraulic characteristics of the Aurado aquifer is controlled by the nature of geological processes and environmental conditions under which this formation was deposited. The lower section of Aurado formation consists of fine, crystalline, compact, banded limestone. The upper section consists of finer textured limestone with clearer banding. Intercalation of dolomite and fine clastic material are common in the formation. Limestone beds are commonly fractured and karstified. This karstification and fracturing has caused development of secondary permeability of the formation, which offers a good potential for groundwater storage and yield. The hydrologic properties of the aquifer change laterally and is accompanied with change in nature of limestone, intercalation of dolomitic limestone, siltstone and marls.
The transmissivity of the Aurado aquifer is low in the area adjacent to and along the border between Somalia and Ethiopia and high in the eastern and southeastern portion of the aquifer (the deeper part). Pumping test results presented in Table 3.4 show that the average transmissivity of the wells (Galdogob and Bur-Hisso) near the border is low compared to transmissivity of the wells tapping the northeastern and southeastern part of the aquifer away from the border (Aragabo, El-Bur, Gal-Hareere and Hersi Garablo). This increase in transmissivity towards northeast and southeast is due to increase in the secondary permeability of the formation due to lateral change in lithology, karstification and fracturing of the aquifer.

5. Pumping Tests

Pumping tests have been performed in the Aurado aquifer at various locations by Armado Oil Company, National Water Development Agency of Somalia and German Technical Cooperation. The tests were conducted on the production wells and drawdown data were monitored from the corresponding observation wells located at various distances from the pumped wells. Well locations are also shown in figure 3.21. The recorded drawdowns at constant discharge rate from individual wells were plotted on semilog paper. Transmissivity and storage coefficient of the aquifer at these various locations were calculated by applying equations 2 and 5 (Jacob's method). Figures 3.22 and 3.23 show graphs of drawdown versus time at two locations of the aquifer and the results of the pumping tests are presented in Table 3.4.
Fig. 3.21. Well Location in the Aurodo Aquifer
Table 3.4: Pumping Test data and results for the Aurado aquifer.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Location</th>
<th>Test duration (hrs)</th>
<th>Average discharge (l/s)</th>
<th>Calculated transmissivity (m²/sec)</th>
<th>Storage coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>Dhusa M.</td>
<td>24</td>
<td>50</td>
<td>$1.1 \times 10^2$</td>
<td>$1.71 \times 10^4$</td>
</tr>
<tr>
<td>14</td>
<td>El-Bur</td>
<td>33.33</td>
<td>44</td>
<td>$2.52 \times 10^2$</td>
<td>$1.70 \times 10^4$</td>
</tr>
<tr>
<td>21</td>
<td>Gal-Hre.</td>
<td>24</td>
<td>50</td>
<td>$2.30 \times 10^2$</td>
<td>$6.53 \times 10^4$</td>
</tr>
<tr>
<td>30</td>
<td>Galdogob</td>
<td>24</td>
<td>56</td>
<td>$1.03 \times 10^3$</td>
<td>$2.2 \times 10^5$</td>
</tr>
<tr>
<td>44</td>
<td>Ja’ar</td>
<td>20</td>
<td>56</td>
<td>$2.23 \times 10^2$</td>
<td>$5.76 \times 10^4$</td>
</tr>
<tr>
<td>23</td>
<td>Hersi G.</td>
<td>24</td>
<td>56</td>
<td>$2.63 \times 10^1$</td>
<td>$1.92 \times 10^4$</td>
</tr>
<tr>
<td>34</td>
<td>Bur-His.</td>
<td>16.67</td>
<td>69</td>
<td>$8.42 \times 10^3$</td>
<td>—</td>
</tr>
<tr>
<td>37</td>
<td>Gardo.</td>
<td>24</td>
<td>55</td>
<td>$2.35 \times 10^2$</td>
<td>$7.35 \times 10^4$</td>
</tr>
<tr>
<td>45</td>
<td>Aragabo</td>
<td>24</td>
<td>61</td>
<td>$2.94 \times 10^2$</td>
<td>$2.53 \times 10^4$</td>
</tr>
</tbody>
</table>
6. Analysis of Pumping Test Results:

The results obtained from the pumping test data performed at various locations of the aquifer show similar pattern except at two locations: Galdogob and Bur-Hisso. The transmissivity value obtained from the pump test at Galdogob, near the border between Somalia and Ethiopia is the lowest compared to all other locations. The behavior of drawdown recorded from the observation well at Galdogob (W30) indicates that the intake area of the aquifer is not open to the well because the cone of depression increases rapidly with time (Fig. 3.22). In Bur-Hisso area, the drawdown behavior is similar to Galdogob, but it is slightly lower because Bur-Hisso is little far from the Border, where secondary permeability of the formation is low due to lack of karstification. High drawdown in a well decreases the specific capacity of the well and render the efficiency of the well very low. In the southeast of the aquifer, at Hersi Garablo, El-Bur, Ja’ar, Gal-Hareere and Dusa Mareb and in the east and north of the Aquifer, at Aragabo and Gardo, the transmissivity values are higher (Table 3.4). Generally, the transmissivity of the aquifer increases from northwest, near the border, to southeast and east where both the permeability and thickness of the formation are increasing. The average transmissivity of the Aurado aquifer is about $4.52 \times 10^2 \text{ m}^2/\text{sec}$. Besides, the transmissivity and storage coefficient values obtained from the various locations indicate that the Aurado aquifer is highly transmissive and confined. Moreover, the productivity of the Aurado aquifer is generally good and increases towards Hersi Garablo and El-Bur area.
Fig. 3.22. Pumping Test At Galdogob, Well no. 30.
Fig. 3.23. Pumping Test Al’Horal Garablo, Well no. 23.
7. Water Level Behavior.

Water level data collected from several observation wells tapping the Aurado aquifer are used for analysis of historical behavior of water level in the aquifer. The available data cover the period between 1971-1984 and only a few as far back as 1967.

Hydrographs of observation well no. 14 (El-Bur) and well no. 23 (Hersi Garablo), located in the southeastern portion of the aquifer, indicate similar patterns of water level fluctuations (Fig.3.24). Water level decline was evidenced in these localities during the extended period of drought (1972-75). The decline was higher in El-Bur Area. The water level of these areas would have declined more if the aquifer had not been transmissive in these localities. The drop of water level was caused by the increase of withdrawal from the aquifer during the extended period of drought. Water level maintained a quasi-balance condition in both localities after the drought. This was due to wet climatic conditions which balanced the hydrologic condition of the area and in turn decreased the withdrawal rate from the aquifer.

The hydrograph of observation well no 30 (Fig.3.25), located in the northwestern section of the aquifer, near the border between Somalia and Ethiopia, indicates a continuous water level decline until 1975, but started recovering since. The decline of water level was high because of heavy pumping coupled with lower transmissivity of the aquifer in that area. A hydrograph of observation well no. 34 (Fig.3.26) indicates that the water level in that area was continuously declining until 1975. Water level decline is a result of overpumping

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Fig. 3.24. Water Level Hydrographs of Well no. 14 and 23.

Fig. 3.25. Water Level Hydrograph of Well no. 30.

Fig. 3.26. Water Level Hydrograph of Well no. 34.
caused by the extended drought which affected the whole country. The latter part of the hydrograph indicates slight increase of water level. This is due to wet climatic conditions caused by the rainfall and hence the availability of recharge water decreasing the withdrawal rate from the aquifer.

The water level change in the aquifer could reach 10 to 15 meters in some parts of the aquifer during the dry season, especially in the northwestern section of the aquifer. The Aurado aquifer is a potential aquifer which could supply large irrigation systems and can sustain long term supply because of its high productivity and low water level decline, especially in the southeastern section of the aquifer.

8. Aquifer Storage.

The total usable amount of water in storage in the Aurado aquifer can be calculated under two conditions based on the aquifer characteristics. Average thickness of 250 meters below the surface based on the depth of the pumping wells was utilized (Fig.3.27).

A. Under confined condition.

The amount of water in storage between the potentiometric surface and upper confining was calculated using the estimated area (67.2 × 10⁹ m³), average storage coefficient (3.5 × 10⁻⁴) and head drop (70 m) in the aquifer by applying equation 4A.
Fig. 3.27 Schematic illustration of confined part of the Aunado aquifer
\[ V_1 = 67.2 \times 10^9 \times 3.5 \times 10^4 \times 70 = 1.65 \times 10^9 \text{ m}^3 \]

B. Under unconfined condition.

The storage in the aquifer in this section was calculated using the same area, saturated thickness (90 m) between the upper confining layer and the bottom of economic pumping thickness (250 m) and assumed specific yield (0.02) of the aquifer material. Therefore, the volume of water in storage between the top of confining layer and bottom of the pumping wells was, using equation 4B, found to be

\[ V_2 = 67.20 \times 10^9 \times 0.02 \times 90 = 121.0 \times 10^9 \text{ m}^3 \]

therefore, the total usable economic storage in the Aurado aquifer is

\[ V_t = V_1 + V_2 = 1.65 \times 10^9 \text{ m}^3 + 121.0 \times 10^9 \text{ m}^3 = 122.60 \times 10^9 \text{ m}^3 \]

3.3.2.4. Taleh Aquifer.

1. Recharge

The Taleh aquifer extends from Ethiopia to central Somalia. The Taleh aquifer receives a substantial recharge in Ethiopia where precipitation rate is high. The major recharge into the aquifer takes place in the outcrop area, near the border between Somalia and Ethiopia. The annual recharge rate of the aquifer in the outcrop area is estimated by using the recharge area \( (9522 \times 10^6 \text{ m}^2) \), annual precipitation \( (300\text{mm}) \) and infiltration rate of 5%. This infiltration rate
(5%) is same as the infiltration rates used for previous aquifers and is based on similar conditions. The annual recharge volume is $142.8 \times 10^6 \text{ m}^3$. The replenishment of this volume of water into the aquifer during winter season results in an increase in storage and rise in the water level thus balancing the hydrogeologic condition of the aquifer.

2. Production.

The Taleh aquifer was first tapped by Armado Oil Company (1967), especially in the northeastern part of the aquifer. The company drilled several wells in the aquifer and utilized it for water supply to its camps. The average production rate of each individual well was estimated as $0.03 \text{ m}^3/\text{sec}$ (450gpm) (Popov and Kidawi, 1973).

The National Water Development Agency of Somalia conducted a hydrogeological inventory on the Taleh aquifer in 1970. This was a part of groundwater development program and augmentation of water supply in the central region. They drilled several wells at various locations in the region. The total production of these wells was estimated to be less than $0.15 \text{ m}^3/\text{sec}$.

3. Hydraulic Properties.

The depositional environment and the nature of lithology played an important role for the development of hydraulic characteristics of the Taleh aquifer. The Taleh formation comprises anhydrite and gypsum in the upper part with much intercalation of limestone, marl, dolomite, dolomitic limestone and clay
which dominate the rest of the formation. The Taleh formation changes from an evaporitic nature in the upper part to dolomitic, and dolomitic limestone with much intercalation of marl and shale, especially in the northeast and southeastern section of the aquifer. Large scale karstification and fissures were identified in the lower part of the formation (Pozzi, 1980). Due to the presence of karstification, the Taleh aquifer exhibits high development of secondary permeability. This is the main cause of high transmissivity of the aquifer in certain locations like Balli Busle, Garoowe and Las Gidet (Table 3.5). The transmissivity of the aquifer is low in Kalla Bair and Aragabo area due to intercalation of clay and fine elastic material which caused the decrease of porosity of the aquifer.

4. Pumping Tests

Pumping tests were conducted on the Taleh aquifer at various locations shown on Fig. 3.28. The tests were performed on the production wells and drawdowns were recorded from the corresponding observation wells located at various distances from the pumped wells. The recorded drawdowns at constant discharge rates were plotted on semilog paper. The transmissivity and, wherever possible, storage coefficient were calculated by applying equations 2 and 5 (Jacob's method). The results of these tests are presented in Table 3.5.

5. Analysis of Pumping Test Results

The objective of calculating transmissivity and storage coefficient of the aquifer is to evaluate the potential productivity and nature of the aquifer. The transmissivity values obtained from the locations subjected to pumping mani-
fested varying pattern. The transmissivity is low in Aragabo (W25) and Kalla Bair (W13) area. In the Northern part of the Taleh aquifer at Aragabo, The increase of drawdown with time reflects that the cone of depression extends out in order to abstract more water from the aquifer (Fig. 3.29). This is due to decrease in thickness caused by the uplift of the basement as well as low permeability of the formation. Other localities like Balli Busle (W10), Las Anno (W22), Las Gidet (W17) and Galkaio (W6) have high transmissivity (Table 3.5). The development of secondary permeability caused by the presence of karstification is the main cause of high transmissivity values in this locations. The distribution of the wells in the aquifer is not homogeneous but the productivity of the aquifer is, generally, good in the central and eastern part of the aquifer. The average transmissivity of the Taleh aquifer is about $1.41 \times 10^2$ m$^2$/sec. The transmissivity and storage coefficient are reliable and indicate that the Taleh aquifer is transmissive and confined and can sustain a good supply of water.


Yearly recorded water level data from observation wells tapping the Taleh aquifer are available for interpretation of water level behavior. These water level data have been recorded in the period between 1967 and 1984.

Water level hydrographs of well no. 10 (Balli Busle) and well no. 13 (Kalla Bair) (Figs. 3.30 and 3.31) show slight water level fluctuations in the early years (1970-72) followed by continuous decline in water level until 1976. This large decline was a result of overpumping caused by the extended period of drought.
which effected the whole country. In 1977, water level in the aquifer at these localities started to recover, although it never reached its original level. The recovery of water level was in response to decrease in pumping from the aquifer due to the return of wet climatic conditions which prevailed in that period. Hydrographs of wells no. 14 and 25 (Fig. 3.32 & 3.33) indicate sharp decline in water level which persisted in the Aragabo area for several years, until 1977. The water level decline was very rapid in Aragabo area. The principal cause of water level decline is related to the increase of withdrawal rate from the aquifer during the extended period of drought. In addition, the transmissivity of the aquifer is low in the Aragabo area and such rapid decline is expected in response to overpumping. Water level of the aquifer in these localities began to recover during later years (1978-84) in response to wet climatic conditions which decreased the withdrawal rates from the aquifer. Figure 3.34 shows a hydrograph of well no. 17. This well has maintained a constant water level fluctuation in the early years. This fluctuation indicate a state of hydraulic equilibrium associated with a stable hydrogeologic situation. However, water level started declining in 1972 and continued until 1977. The decline of water level is a result of intensified groundwater abstraction from the aquifer. In 1978, water level began recovering in response to wet climatic conditions and lower rate of withdrawal from the aquifer.

The average water level decline in the aquifer could reach about 16m in the western part of the aquifer. The results of the pumping tests and response of water level in the aquifer show good reliability and possible abstraction of large volume of water from the aquifer, especially in areas with high transmissivity.
Fig. 3.28. Well Location in the Taleh Aquifer
Table 3.5: Pumping Test data and results for the Taleh aquifer.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Location</th>
<th>Test duration (hrs)</th>
<th>Average discharge (l/s)</th>
<th>Calculated transmissivity (m²/sec)</th>
<th>Storage coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Galcao</td>
<td>17</td>
<td>35</td>
<td>$1.15 \times 10^{-2}$</td>
<td>$5.34 \times 10^{-4}$</td>
</tr>
<tr>
<td>10</td>
<td>Balli B.</td>
<td>24</td>
<td>33</td>
<td>$3.5 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Kalla B.</td>
<td>16.67</td>
<td>33</td>
<td>$9.8 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Garowe</td>
<td>24</td>
<td>30</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>22</td>
<td>Las anno</td>
<td>16.67</td>
<td>30</td>
<td>$1.33 \times 10^{-2}$</td>
<td>$4.75 \times 10^{-4}$</td>
</tr>
<tr>
<td>17</td>
<td>Las Gidet</td>
<td>25</td>
<td>40</td>
<td>$1.14 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Aragabo</td>
<td>25</td>
<td>40</td>
<td>$4.6 \times 10^{-3}$</td>
<td>$1.48 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
\[ Q = 4.0 \times 10^{-2} \text{ m}^3/\text{sec.} \]
\[ r = 200 \text{ m.} \]
\[ t_0 = 57 \text{ sec.} \]

\[ r = 0.103 \times \frac{Q}{\Delta \delta} \]
\[ \Delta S = 3.12 - 1.62 = 1.60 \text{ m} \]

\[ r = 0.103 \times \frac{4.0 \times 10^{-2}}{1.60} \]
\[ T = 4.0 \times 10^{-3} \text{ m}^3/\text{sec.} \]

\[ S = \frac{2.26 \times \tau \delta}{r^2} \]
\[ S = \frac{2.26 \times 1.60 \times 10^{-3} \times 57}{200 \times 200} \]
\[ S = 1.40 \times 10^{-5} \]

*Fig. 3.20.* Pumping Test At Aragabo area, Well no. 26
Fig. 3.30. Water Level Hydrograph of Well No. 10.

Fig. 3.31. Water Level Hydrograph of Well No. 13.

Fig. 3.32. Water Level Hydrograph of Well No. 14.
**Fig. 3.33.** Water Level Hydrograph of Well No. 25.

**Fig. 3.34.** Water Level Hydrograph of Well No. 17.
7. Aquifer Storage.

The total usable volume of water in storage in the Taleh aquifer was calculated under two conditions based on aquifer characteristics. Average thickness (pumping thickness) of 200 meters between the surface and bottom of pumping economic thickness was utilized due to economic limitations (Fig. 3.35).

A. Under confined condition.

The amount of water in storage under this condition was calculated utilizing the area \((141440 \times 10^4 \text{ m}^3)\), average storage coefficient \((3.0 \times 10^{-4})\) and water level drop \((80 \text{ m})\) in this section of the aquifer. Substituting these values in equation 4A, the volume in storage is

\[ V_1 = 141440 \times 10^4 \times 3.0 \times 10^{-4} \times 80 = 3.4 \times 10^9 \text{ m}^3 \]

2. Under unconfined condition.

The calculation of stored water in this section of the aquifer is based on same area, saturated thickness of this section \((50 \text{ m})\) and average specific yield \((0.02)\) of the aquifer material. Hence, the volume of water in storage between the top of confining bed and bottom of the pumping wells is calculated by applying equation 4B.

\[ V_2 = 141440 \times 10^4 \times 0.02 \times 50 = 141.40 \times 10^9 \text{ m}^3 \]

Thus, the total usable storage in the Taleh aquifer is

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Fig. 3.35 Sketch illustrating the confined part in of the Taleh aquifer.
\[ V_i = V_1 + V_2 = 3.4 \times 10^9 \text{ m}^3 + 141.4 \times 10^9 \text{ m}^3 = 144.80 \times 10^9 \text{ m}^3 \]

3.3.2.5. Mudug-Merca Aquifer System.

1. Introduction

The Mudug-Merca group forms a multiaquifer system with a variable extension and water quality. The major important and easily accessible aquifer, Merca, which supplies a large volume of water to the capital (Mogdishu) and nearby area, is considered in this section. The reason is that the other aquifers which belong to the Mudug-Merca group are deep and their exploitation is not feasible at this stage of economic conditions of the country. In addition, this group has not yet been considered as a system and therefore data from the group is not available except for Merca aquifer. Special consideration has been given to the relationship between Merca aquifer and Shabelle river, which passes over the western flank and parts of the aquifer, in terms of recharge. Also there is a special relationship between Merca aquifer and sea water intrusion, especially in wells supplying Mogdishu area. These wells are scattered at distances 7 to 25 kms from the shoreline of the Indian Ocean.

2. The relationship between saltwater and freshwater.

Possibility of seawater intrusion in the Merca aquifer was examined by Parsons (1970) and Dal Pra (1986). According to Dal Pra, the freshwater/saltwater interface is deepening from the shoreline towards inland and there is a barrier (groundwater divide) between the Merca aquifer and shoreline, especially in the
northern part of Mogdishu. The tidal influence which disturbs the water level in the shallow alluvial aquifers (8-12 m) near the shoreline (500-1000 m) was observed but no influence of saline water intrusion has been noticed in the deeper aquifer, at least in the area north of Mogdishu. This fact was proved by using water density values, chemical analysis and geoelectric monitoring (Dal Pra et al., 1986). Parsons (1970), who drilled 19 wells north of the capital (Mogdishu), located about 7 km from the shoreline, along the road between Mogdishu and Balad, reported that the production of these wells could be increased up to 24000 m³/day and sustain long-term production without any interference of saltwater. The total production of these wells was about 21000 m³/day at the beginning. This shows that there is no influence from sea water on the freshwater in the aquifer.

In the west of Mogdishu, attempts of such study have not been made, but wells located about 15 to 20 km from the shoreline, which supply the capital, have no indication of saline water intrusion. Chemical analysis indicated no major chemical difference between the waters coming from north or west of the capital mogdishu.


A recharge relationship study between Shabelle river and Merca aquifer was performed by several companies (Parsons, 1970, FAO, 1960 and GKW, 1977) and other personnel.
Parsons (1970) studied water flow direction between Shabelle river and Merca aquifer in a system of wells drilled along a parallel line at distance of 1 km away from the Shabelle river, near Afgoye, 30 km west of Mogdishu. Parsons reported that each of these wells can produce an average safe yield of 0.05 m$^3$/sec. without recharge attribution from the river.

German Technical Institute for Geoscience and Water Resources (GKW) conducted a similar study in 1977 on a system of wells drilled for augmentation of Mogdishu water supply. These wells are located at about 14 to 16 km west of Mogdishu and about 16 km east of Shabelle river. The result of the study has not shown any relationship in terms of recharge between Shabelle river and Merca aquifer.

In Balad area, where Shabelle river passes over the aquifer, Merca aquifer and Shabelle river have no relation in terms of recharge, at least locally, because water level of the aquifer lies about 50 m below the surface and the presence of impermeable material covering Merca aquifer prevents infiltration of Shabelle water towards the aquifer (Dal Pra et. al, 1983)

4. Production

Evaluation of the aquifer productivity has been made at various locations by National Water Development Agency of Somalia (WDA), Parsons and German Technical Institute for Geoscience and Water Resources. 19 production wells have been drilled by Parsons in 1977 north of Mogdishu along the road between Mogdishu and Balad. The total production rate of these wells was
estimated to be about 0.3 m³/sec. (4750 gpm). In 1977, German Technical Institute for Geoscience and Water Resources (GKW) drilled 18 production wells in the west of Mogdishu town for augmentation of water supply. The total production of these wells was estimated to be about 0.5 m³/sec. (7920 gpm) The average production rate of each of several wells scattered around Afgoye, 30 km west of Mogdishu, was estimated at 0.05 m³/sec. (792 gpm) (GKW, 1977).

In Balad area, 30 km north of Mogdishu, several production wells were drilled to supply water to Balad town and some farms. The total production of these wells was estimated at 0.16 m³/sec. (2535 gpm) (GKW, 1977). German Technical Institute for Geoscience and Water Resources have also reported that the total discharge rate of the wells supplying Jolhar and nearby area was estimated as 0.13 m³/sec. (2060 gpm)

Since 1983 several wells have been drilled by the private sector on the Merca aquifer, especially in the southwestern part. This data, which would be very helpful for the evaluation of the aquifer's production in that area, is not available. However, the productivity of the aquifer is generally good enough to supply large volumes of water over long term periods of time to sustain municipal and agricultural demands in the region.

5. Hydraulic Properties.

The nature of lithology of the formation controls the development of the hydraulic characteristics of the aquifer. The Merca aquifer consists mainly of
porous sandstone intercalated with thin layers of limestone and shale followed by porous limestone interbedded with shale and siltstone. The intercalation of shale increases towards the southern part of the aquifer, although geological descriptions have also indicated its presence in the northern part of the aquifer, near Balad and Johar area (Dal Pra' et. al, 1983). Local intercalations of silt and clay have been observed in some parts of the aquifer. The presence of fine grained sediments decreases the hydraulic characteristics of the aquifer because they decrease permeability. However, the hydraulic properties of the Merca aquifer generally increase from the northern part of the aquifer, in Johar area, towards southern part of the aquifer. This increase was observed from the increase in transmissivity of the aquifer. Local variations were also evident due to local changes in the porosity of the aquifer material.

6. Pumping Tests

Pumping tests were performed for the Merca aquifer at various locations using production wells and corresponding observation wells for water level monitoring. The objective of the tests was to determine the transmissivity and, wherever possible, storage coefficient. These parameters are important for the evaluation of the productivity and nature of the aquifer. The results are presented in Table 3.6. Well locations are also shown in Figure 3.36.

7. Analysis of Pumping Test Results

The transmissivity values show an increasing pattern from the northern part to southern part of the aquifer, although slight fluctuations exist locally. The
Table 3.6: Pumping Test data and results for the Merca aquifer.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Location</th>
<th>Test duration (hrs)</th>
<th>Average discharge (l/s)</th>
<th>Calculated transmissivity (m²/sec)</th>
<th>Storage coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Johar</td>
<td>20</td>
<td>14</td>
<td>$1.51 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Balad</td>
<td>25</td>
<td>20</td>
<td>$2.82 \times 10^{2}$</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Balad</td>
<td>16.67</td>
<td>12</td>
<td>$4.1 \times 10^{2}$</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>N. Mog.</td>
<td>33.33</td>
<td>56</td>
<td>$5.1 \times 10^{2}$</td>
<td>$4.82 \times 10^{4}$</td>
</tr>
<tr>
<td>4</td>
<td>N. Mog.</td>
<td>33.33</td>
<td>55</td>
<td>$6.30 \times 10^{2}$</td>
<td>$9.28 \times 10^{-5}$</td>
</tr>
<tr>
<td>16</td>
<td>N. Mog.</td>
<td>33.33</td>
<td>55</td>
<td>$3.5 \times 10^{1}$</td>
<td>$5.73 \times 10^{4}$</td>
</tr>
<tr>
<td>14</td>
<td>W. Mog.</td>
<td>24</td>
<td>50</td>
<td>$8.32 \times 10^{2}$</td>
<td>$1.20 \times 10^{4}$</td>
</tr>
<tr>
<td>3</td>
<td>W. Mog.</td>
<td>24</td>
<td>56</td>
<td>$1.14 \times 10^{4}$</td>
<td>$2.22 \times 10^{4}$</td>
</tr>
<tr>
<td>6</td>
<td>Afgoye</td>
<td>24</td>
<td>50</td>
<td>$2.93 \times 10^{2}$</td>
<td>$3.2 \times 10^{4}$</td>
</tr>
<tr>
<td>12</td>
<td>Qorioley</td>
<td>24</td>
<td>40</td>
<td>$3.3 \times 10^{2}$</td>
<td>$5.6 \times 10^{4}$</td>
</tr>
</tbody>
</table>
Fig. 3.36. Well Location in the Merca Aquifer.
local fluctuations are due to variations in the lithologic characteristics of the aquifer. In Johar area, the transmissivity is low and increases towards south. In most of the Johar area wells, the drawdown increases with time (Fig.3.37). This indicates the presence of low permeability material in the aquifer in this area. The increase in drawdown decrease the specific capacity of the well.

In the western part of Mogdishu area, the transmissivity values of the aquifer show local variation. the transmissivity increases abruptly towards Afgoye at west, to the south at Qorioley area. The increase in transmissivity is a result of increase of hydraulic characteristics and increase in the thickness of the aquifer. However, The average transmissivity of the Merca aquifer is about $8.5 \times 10^2 \text{ m}^2/\text{sec}$. The results obtained from the various locations indicate that the Merca aquifer is highly transmissive and confined. The results also show that the Merca aquifer is of economical potential and its productivity increases generally towards southern part of the aquifer.

8. Spatial Water Level Distribution and Behavior.

The Merca aquifer increases in depth from north to south. As a result, the water level in aquifer deepens towards southern part of the aquifer. Figure 3.38 shows a spatial distribution of water level in the Merca aquifer. In the northern part of the aquifer, near Johar area, the regional water table lies about 40 meters below the surface and becomes deeper towards south and southwest, where it reaches about 120 meters below the surface.
\[ Q = 1.40 \times 10^{-2} \, \text{m}^3/\text{sec} \]

\[ T = \frac{0.103}{\Delta s} \left( \frac{\text{m}^3}{\text{sec} \cdot \text{m}} \right) \]

\[ T = 0.103 \times \frac{1.40 \times 10^{-2}}{1.70} \]

\[ T = 1.50 \times 10^{-3} \, \text{m}^3/\text{sec} \]

**Fig. 3.37.** Pumping Test At Johar Area, Well No. 10
Fig. 3.38. Contour Map Showing Water Level Distribution in the Merca Aquifer Below surface.
In the northern part of the aquifer, near Johar area, the regional potentiometric surface declines about 15 to 20 meters. This decline of water level decreases towards south and southwest of the aquifer becoming about 8 meters near Merca, Qorioley and Kismania area. The decline is due to overpumping. Development of small local cones of depressions has been met in the northern part of the aquifer. This reflects the overall extent of transmissivity of the aquifer in the vicinity of each pumping center. Transmissivity of the aquifer is low and the thickness of the aquifer is small in the northern part of the aquifer. Down to the south, the water level decline is smaller because both the transmissivity and thickness of the aquifer increase, although local variations in transmissivity caused by lithological changes exist as interpreted from the results obtained from the pumping tests (Table 3.6).

The regional water level decline in the aquifer increases during dry seasons, especially in the northern part of the aquifer, and is mainly related to increased pumpage. However, the steady downward trend of water level in the aquifer in the summer reflects the continued increase in pumping over time.

Local changes in flow direction have been observed in the vicinity of the pumping centers, especially in the northern part of the aquifer near Johar and Balad areas, where transmissivity is low, but the regional trend of the groundwater flow in the aquifer is towards south to southeast direction of the aquifer.


Average thickness (pumping thickness) of 250 meters below the surface was
utilized in order to calculated the total usable amount of water in storage in the Merca aquifer under two conditions (Fig. 3.39).

A. Under confined condition.

The amount of water in storage in this section was calculated applying equation 4B. Inserting the value of the area \(39744 \times 10^6 \text{ m}^2\), average storage coefficient \(3.1 \times 10^{-4}\) and water level drop (70 m) in the aquifer, the volume is

\[ V_1 = 39744 \times 10^6 \times 3.1 \times 10^{-4} \times 70 = 0.862 \times 10^9 \text{ m}^3 \]

B. Under unconfined condition.

The volume of water that can be pumped in this section of the aquifer was estimated using same area, saturated thickness (90 m) and average specific yield (0.03) of aquifer material. Hence, the volume of water stored in this section was found applying equation 4B.

\[ V_2 = 39744 \times 10^6 \times 0.03 \times 90 = 107.30 \times 10^9 \text{ m}^3 \]

Therefore, the total usable storage in the Merca aquifer is

\[ V_t = V_1 + V_2 = 0.862 \times 10^9 \text{ m}^3 + 107.3 \times 10^9 \text{ m}^3 = 108.20 \times 10^9 \text{ m}^3 \]
Fig. 3.39 Schematic illustration of confined part of the Merca aquifer
IV. WATER RESOURCES AVAILABILITY VERSUS DEMAND.

4.1. Available Water Resources.

A subjective assessment of the available reserves water resources of the country has been made by using data based on characteristics of water bearing formations. The mean annual rainfall over the country amounts to about 191.4 \( \times 10^9 \) m\(^3\) and large volume of it is lost to evaporation due to arid climatic conditions prevailing in the region. It is estimated that the mean annual surface water in the two rivers, Jubba and Shabelle, is about 7.8 \( \times 10^9 \) m\(^3\). This constitutes 1.31 % of the present water resources potential in the country. In addition, the amount of groundwater stored in the alluvial aquifers is estimated at about 33.6 \( \times 10^9 \) m\(^3\) with annual replenishment of about 288 \( \times 10^6 \) m\(^3\). The volume of groundwater stored in these aquifers is equivalent to about 5.7 % of total groundwater reserve in the country. Moreover, the potential volume of groundwater in the principal confined aquifers amounts to about 560.6 \( \times 10^9 \) m\(^3\) and their corresponding recharge volume over the outcrop area is 962 \( \times 10^6 \) m\(^3\) per year. The volume of groundwater reserve in the principal aquifers constitutes 94.3 % of the total volume of groundwater potential estimated in both confined and unconfined aquifers. Thus, from these estimates, one can arrive at 7.8 \( \times 10^9 \) m\(^3\)/year of surface water from the rivers and proven reserve potential of 594.60 \( \times 10^9 \) m\(^3\) from the confined and unconfined aquifers which can be replen-
ished by normal rainfall, whose volume is \(1250 \times 10^6\) m\(^3\) per year. Table 4.1 shows a summary of available water resources in the country and their corresponding source. The results of these calculations show the presence of large amount of water in the country in spite of difficulties of water shortage in some parts. These shortages are due to lack of development of the aquifers and of a proper plan of water distribution. The volume of water available in the country is enough to meet the demand for water and can be used to convert the suffering nomadic people to settled agricultural society and to reduce the chances of famine in the country.

4.2. Water Demand.

The demand for water as presented here comprises the demands for domestic and livestock population, and agricultural and industrial purposes. In an attempt to cover the water requirements for purposes other than those already mentioned, the total demand could be increased by the required percent. However, the estimation of water demand is based on the rate of consumption for the various use sectors in accordance with their modified growth and development within the projected period of twenty years.

4.2.1. Domestic and Livestock Water Demand.

About 70% of the Somali population are nomadic and the remaining 30% are inhabitants of the large towns and villages. Water consumption by rural inhabitants depends on the proximity to water sources. Consumption increases markedly if the distances traveled to obtain water is about a couple of
Table 4.1: Summary of Available Water Resources in the Country.

<table>
<thead>
<tr>
<th>Groundwater</th>
<th>Surface Water</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Aquifers</strong></td>
<td><strong>Source</strong></td>
</tr>
<tr>
<td><strong>Annual Recharge</strong> x 10^6 m³</td>
<td><strong>Available Reserve</strong> x 10^9 m³</td>
</tr>
<tr>
<td>Baidoa 115.5</td>
<td>Shabelle R.</td>
</tr>
<tr>
<td>Jesomma 258</td>
<td>Jubba R.</td>
</tr>
<tr>
<td>Aurado 445.6</td>
<td></td>
</tr>
<tr>
<td>Taleh 142.8</td>
<td></td>
</tr>
<tr>
<td>Merca</td>
<td></td>
</tr>
<tr>
<td>Alluvial Aquifers 288</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong> 1250</td>
<td><strong>Total Available Water Reserve</strong> = 602.20 x 10^9 m³</td>
</tr>
</tbody>
</table>
kilometers, otherwise consumption is normally less than 15 liters per capita per day. This has been shown to be true in water studies throughout the world and has been confirmed by the limited studies in Somalia. On the other hand, water consumption of the inhabitants of the towns and villages depends on their income per capita and standard of living. However, the total consumption requirement is obtained by multiplying the domestic and livestock population figures by a potential improved rate of 30 liters per day per capita for rural population, 70 liters per day per capita for inhabitants of towns and villages (domestic and 20 liters per day per capita for livestock, considering a growth of 2.5\% per year for domestic population and 12\% for livestock population within the projected period (LBI, 1985; GMBH-Lingen, 1989; Lahmeyer, 1987). The expected future water requirement for both domestic and livestock during this projected period is shown in Table 4.2. Besides, the approximate total volume necessary to fulfill the needs for both domestic and livestock in the year 2010 will be about 13 × 10^9 m^3, about 64\% of the total demand of the country in the year 2010.

4.2.2. Agricultural Water Demand.

The requirement of water per unit of agricultural production depends on the climate, type of crops, method of irrigation practiced, adequate water supply and level of irrigation management. At present, the irrigated land in the country is about 80,000 hectare which occupies about 7.3\% of the cultivated land (Table 1.1). The major crops which are produced from this 7.3\% of the cultivated land
are classified into two groups: perennial and seasonal. 30% of this land is used to produce perennial crops (banana, sugar cane and citrus) while the remaining 70% is used to produce maize, sesame, rice and vegetables of various types. Under the present conditions, the average water requirement of the perennial crops is estimated as $13 \times 10^3$ m$^3$/ha per year (Lahmeyer, 1987). Thus, the total amount of water required by the perennial crops produced from the 30% of the irrigated land is estimated as $312 \times 10^6$ m$^3$/year. The seasonal crops occupy about 70% of the total irrigated land and are harvested two times per year (if all involved conditions remain normal). The average water consumption per hectare of these seasonal crops is about $8 \times 10^6$ m$^3$ per season (Lahmeyer, 1987). Therefore, the total volume of water required per year for these seasonal crops is estimated as $896 \times 10^6$ m$^3$. At present, the total water demand per year for the irrigated land amounts to $1201 \times 10^6$ m$^3$.

About 92.7% of the cultivated land is of rain-fed type producing sorghum and other crops which are extensively dependent on rain water. The development of groundwater for irrigation in those areas is practically negligible and the rivers are too far away to get water from. Therefore, the efficiency of production is very low. However, if the irrigated land is increased by 10% per year during the projected period and all involved conditions remain normal, the total requirement of water for irrigation will be about $8.14 \times 10^9$ m$^3$ in the year 2010 (Table 4.2). In addition, the total volume of water estimated for the irrigated land is not under consumption throughout the year, but it is used as a supplement when wet conditions decrease during the dry season. Presently, irrigated
Table 4.2: National Water Demand.

<table>
<thead>
<tr>
<th>Year</th>
<th>Domestic $\times 10^9$ m$^3$</th>
<th>Livestock $\times 10^9$ m$^3$</th>
<th>Agricultural $\times 10^9$ m$^3$</th>
<th>Total $\times 10^9$ m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>0.126</td>
<td>0.340</td>
<td>0.121</td>
<td>1.676</td>
</tr>
<tr>
<td>1995</td>
<td>0.7044</td>
<td>2.710</td>
<td>1.950</td>
<td>5.3644</td>
</tr>
<tr>
<td>2000</td>
<td>0.800</td>
<td>4.330</td>
<td>3.140</td>
<td>8.27</td>
</tr>
<tr>
<td>2005</td>
<td>0.90</td>
<td>6.93</td>
<td>5.16</td>
<td>12.99</td>
</tr>
<tr>
<td>2010</td>
<td>1.10</td>
<td>11.9</td>
<td>8.14</td>
<td>20.33</td>
</tr>
</tbody>
</table>
land exists along the Jubba and Shabelle rivers and is irrigated by using river water. Only marginal areas of agricultural lands are irrigated by supplemental groundwater, especially during low river flow conditions. Therefore, the use of groundwater for irrigation remains negligible until better economic standards are achieved.

4.2.3. Industrial Water Demand.

The development of the industrial sector in Somalia is considered minimal because only a small number of factories are operating in the country and their consumption of water is marginal. Even if the industrial water demand grows considerably within the coming years, the quantity of water required will always remain negligible when compared to the other sectors of water consumption. Therefore, it is assumed that future industrial water demands will be met without any loss to other sectors demands.

4.3. Calculation of Water Resources Demand.

4.3.1. Water demand for domestic and livestock.

A weighted average of consumption figure of 30 l/d per capita for rural population, 70 l/d per capita for inhabitants of towns and village (domestic consumption) and 20 l/d per capita for livestock population is used for assessment of water demand in a projected period of twenty years (1990-2010). These conservative numbers are referenced from the previous studies conducted by Louis Berger International, Co. (1985) and Lahmeyer (1987) in some parts of the country.
A. Domestic Demand for Water.

In 1990, the total population of Somalia was 8.2 million. Assuming a modified growth of 2.5% per year, the demand for water is calculated and presented in Table 4.3.

*Table 4.3. Domestic water demand.*

<table>
<thead>
<tr>
<th>Year</th>
<th>Population</th>
<th>Water Demand (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>8,200,000</td>
<td>$125.71 \times 10^6$</td>
</tr>
<tr>
<td>1995</td>
<td>9,277547</td>
<td>$704.4 \times 10^6$</td>
</tr>
<tr>
<td>2000</td>
<td>10,437,240</td>
<td>$800 \times 10^6$</td>
</tr>
<tr>
<td>2005</td>
<td>11,741896</td>
<td>$900 \times 10^6$</td>
</tr>
<tr>
<td>2010</td>
<td>13,812,500</td>
<td>$1011 \times 10^6$</td>
</tr>
</tbody>
</table>

B. Livestock Water Demand.

The total livestock population in Somalia was 46,344,132 in the year 1990. The average growth of livestock population is about 12% per year (Study on water points in Gedo and Bakool, Somalia, 1989). The demand for water is calculated and presented in Table 4.4.
Table 4.4. Livestock water demand.

<table>
<thead>
<tr>
<th>Year</th>
<th>Population</th>
<th>Water Demand (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>46,344,132</td>
<td>340 × 10⁶</td>
</tr>
<tr>
<td>1995</td>
<td>74,149,012</td>
<td>2710 × 10⁶</td>
</tr>
<tr>
<td>2000</td>
<td>118,638,420</td>
<td>4330 × 10⁶</td>
</tr>
<tr>
<td>2005</td>
<td>189,821,472</td>
<td>6930 × 10⁶</td>
</tr>
<tr>
<td>2010</td>
<td>303,714,355</td>
<td>11090 × 10⁶</td>
</tr>
</tbody>
</table>

4.3.2. Agricultural Water Demand.

The present irrigated land is about 80,000 ha. 30% of these land is used to produce perennial crops while the remaining 70% produces seasonal crops. The future water demand of this irrigated land is as follows.

I. 30% of the irrigated land is about 24,000 ha. An average per hectar demand of water for perennial crops is about $13 \times 10^3$ m³/year. Thus, the total demand per year is about $312 \times 10^6$ m³/year.

II. 70% of the irrigated land is about 56,000 ha. An average per hectar demand of water for seasonal crops is about $8 \times 10^3$ m³/season. Hence, the total
demand per year is about $896 \times 10^6 \text{ m/year}$. If the irrigated land is increased by 10% per year (beautiful Somalia, 1980) and all involved conditions remain normal, the growth of water demand for irrigation will be as shown in Table 4.5.

Table 4.5. Agriculture water demand.

<table>
<thead>
<tr>
<th>Year</th>
<th>Irriga. Land (ha)</th>
<th>Water Demand ($m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>80,000</td>
<td>$121 \times 10^6$</td>
</tr>
<tr>
<td>1995</td>
<td>128,840.8</td>
<td>$1950 \times 10^6$</td>
</tr>
<tr>
<td>2000</td>
<td>207,499.4</td>
<td>$3140 \times 10^6$</td>
</tr>
<tr>
<td>2005</td>
<td>311,249.1</td>
<td>$5160 \times 10^6$</td>
</tr>
<tr>
<td>2010</td>
<td>538,199.96</td>
<td>$8140 \times 10^6$</td>
</tr>
</tbody>
</table>

4.4. Comparison Between Available Water Resources and Demand for Water

Comprehensive analysis of the available water resources and demand for water is made and, as estimated in the previous sections, it is clear that the present available potential reserves exceeds the consumption of water and satisfy the demand during the projected period. Tables 4.1 and 4.2 show the results of projected water demand according to the consumption of various sectors and readily available water resources. It is evident that both surface water from the
rivers and groundwater from the aquifers are adequate to meet the projected demand, but will not be sufficient beyond the year 2042 if the growth of water demand continues to increase with same ratios. The available groundwater resources are limited and will not be sufficient to satisfy the growing demand, if the country is to depend solely on groundwater, unless new measures of groundwater strategies are established and implemented in the near future. This is because the long term future prediction (after 2010) shows early depletion of groundwater, despite expected future annual recharge (to the aquifers) and surface water being included in the reserve during the prediction. This future prediction is based on the assumption that the net withdrawals are equal to the future demand of the country at the beginning of the prediction (year 2010). The demand will increase at about 3.42 % per year of the available groundwater in the country after the beginning of prediction. The resultant rate of mining of groundwater is shown in Figure 4.1. This figure shows that the groundwater reserve will be exhausted and ultimate depletion of the aquifers will occur before the year 2043. Therefore, efficient planning and management of groundwater reserves and development of new resources are needed in order to balance the optimal demand and decrease the economic and environmental consequences related to the shortage of groundwater resources. This can be achieved by considering other alternatives like developing new resources, conserving them, imposing new regulations and legislations, and practicing measures of monitoring and minimizing consumption.


The available water resources satisfy the demand for water. However,
Fig. 4.1. Rate of Mining of Groundwater Reserve.
while this indicates that availability of water is greater than the demand, it does
not mean that it is developed and distributed evenly, nor does it mean that it is
distributed at the specific locations where it is most needed. Severe hardship
have been observed for many Somalis, to the extent that many animals died as a
result of traveling long distances to obtain water. The development of existing
aquifers is minimal because wells are scattered and the distance between a group
of wells to another group of wells in the same aquifer could be in an order of 60
to 70 kms, especially in the northern and central regions where aquifers are
deep. In order to overcome this problem, a scheme of distribution of surface
water from the rivers which pass through the southern part of the country and
dump large volumes of water to the Indian Ocean is required. This scheme
should be achieved either by means of pipelines or diverting the flow towards
the grazing land. Of course, both alternatives are not feasible at the present eco-
nomic standard of the country. Further efforts should be put into exploration
and development of groundwater from the suspected deeper hydrogeological
basins. Also more wells needed to be drilled and properly located on the exist-
ing aquifers to augment the water supply which is essential in order to accom-
plish the required demand for water in the various parts of the country. In
addition, more effort and investment should be put into the implementing a sys-
tem of series of small dams and embankments which could store rain water in
areas where water is scarce. This can sustain the need for water in remote
nomadic areas of the country, where some basic agricultural activity could be
started, and nomadic life could yield to a more sustaining agricultural settle-
ments.

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V. WATER QUALITY.

5.1. Introduction.

The chemical composition of groundwater is related to the soluble products of rock weathering, composition of the aquifer rocks and geochemical processes taking place in the aquifer system. Geochemical studies provide complete knowledge and information about water resources depending on the nature and correctness of the samples collected. The assessment of water quality in Somalia, especially in the aquifers under consideration is based on the results published by Louis Berger International (1985), National Water Development Agency (1975), Popov and Kidawi (1973), Parsons (1970) and other agencies. Chemical analysis and electrical conductivity of the waters from the aquifers are employed in this section for water quality evaluation. In addition, the relationship between total dissolved solids and electrical conductivity has been utilized to evaluate the type of water in the aquifer. The available water quality data are referred to international standards in order to categorize the use of water from each aquifer and its suitability for the various demanding sectors.

5.2. Baidoa Aquifer.

5.2.1. Chemical quality pattern.

The pattern of water quality in the Baidoa aquifer is based on the variation of total dissolved solids (TDS) and concentrations of major ions in the water. The spatial distribution of the total dissolved solids in the Baidoa aquifer is shown in Figure 5.1. The results of chemical analysis of the samples collected
from the various parts of the aquifer are presented in Table A.1. (Appendix A).

Figure 5.1 shows an increase in total dissolved solids from the northeastern part, near the recharge area, towards the western and southwestern part of the aquifer. The concentration of chloride, sulfate and sodium ions increase towards the south and west of the aquifer as water moves slowly and leach minerals while in contact with aquifer formation. The degree of increase of these ions in this direction is higher for chloride ion and lower for sodium ion. Bicarbonate ions decrease towards the south. This fact can be correlated with the hypothesis of Chebotarev (1955) which explains that the longer the time water remains underground, and farther it travels, the more it resembles sea water. In this regard, Domenico (1972) has noted that the chemistry of groundwater changes with depth in the aquifers as follows (Driscoll, 1987).

Higher zone (recharge area): water is low in dissolved solids and high in bicarbonate ($\text{HCO}_3^-$).

Middle zone: water moves more slowly and gains in dissolved solids; sulfate ion ($\text{SO}_4^{2-}$) becomes dominant.

Deep zone: the movement of water becomes slow and mineral leaching is extremely active, producing high content of dissolved solids and relative increase of chloride ion ($\text{Cl}^-$).

In Sarmaan Dheere area, northwest of Baidoa town, the most productive area of the aquifer, a relative increase of total dissolved solids and chloride ion concentrations is observed. The increase is a result of deeper percolation of groundwater, which coincides with the direction of groundwater flow. The high
concentration of chloride and sulfate ions, especially chloride, in the water increases, generally, the total dissolved solids which in turn increase the electrical conductivity of the water. Wells in Awshinile, Hareero Jeefo, Durci Ali Galle, and Bulo Fur, which are located in the southern part of the aquifer, are characterized by relatively high chloride ions (Table A.1; Appendix A). The composition of the Baidoa water is not homogeneous because of lateral variation of the formation and residence time of water in the aquifer. This can be observed from the total dissolved solids, which range between 756 mg/L in the northern part to 1816 mg/L in the southern part of the aquifer. Local variation of total dissolved solids is common in the central part of the aquifer.

5.2.2. Water Type.

The relationship between the total dissolved solids (TDS) and electric conductivity (EC), which both increase with the concentration of ions, has been expressed by Hem (1970) as:

\[ \text{TDS} = A \times \text{EC}. \]

where TDS is in mg/L,

EC is in micromhos/cm and

A is a conversion Factor.

Hem (1970) reported a wide range of A as 0.55 to 0.75. This range represents nearly all types of natural waters. The range between 0.5 to 0.65 includes NaCl water type only while the range between 0.65 to 0.75 is a mixture of water types represented by NaCl, CaSO₄ and NaSO₄ (Sen, 1985). Figure 5.2 shows
the relationship between electric conductivity and total dissolved solids from the Baidoa aquifer. The existence of a good relationship is evident from the correlation coefficient ($R^2 = 0.89$). The conversion factor (0.75) falls in the upper of the range designated for mixed water by Hem (1970). In other words, the water in the Baidoa aquifer is a mixture of $\text{NaCl}$, $\text{CaSO}_4$ and $\text{NaSO}_4$. The presence of these ions reflects the response of chemical processes operating within the lithology of the aquifer and also the pattern of groundwater flow and is a diagnostic tool to distinguish water masses originating from different rock types over different time scales in the same aquifer and along the lines of evolution of flow paths.

5.2.3. Water Use.

Water quality should satisfy the standards set for specific uses: domestic, livestock, agricultural and industrial purposes. The World Health Organization has set a limit for various purposes of water use. The total dissolved solids in the Baidoa aquifer are slightly higher than the limit (1000 - 1500 mg/L) set by the World Health Organization for potable water although it is still acceptable and suitable for all purposes because the maximum tolerable limit of salinity for drinking water is about 2000 mg/L. In addition, the mineral content of drinking water, according to the provisional standards adopted by the National Water Development Agency, should not exceed an electric conductivity of 3500 micromhos/cm. This corresponds to total dissolved solids of about 2500 mg/L (Fig. 5.2). The Baidoa water has total dissolved solids lower than the local limit set by the National Water Development Agency. The water in the Baidoa
aquifer has been used and is still supplying towns, villages, rural areas and small agricultural sectors.

The Sodium Adsorption Ratio as calculated in Table A.1 for the Baidoa aquifer shows a low sodium hazard as values obtained fall far below the maximum limit (SAR = 11). In view of the how SAR values and how TDS, the Baidoa aquifer waters can be classified as suitable for all irrigation purposes.

5.3. Jesomma Aquifer.

5.3.1. Chemical quality pattern.

The assessment of chemical quality of the water in the Jesomma aquifer is based on the distribution of the total dissolved solids and electrical conductivity. The total dissolved solids concentration and its corresponding electrical conductivity are shown in Table A.2. (Appendix A). The pattern of total dissolved solids is in conformity with the regional direction of groundwater flow in the aquifer. The total dissolved solids concentration increases from west to east, near the border between Ethiopia and Somalia (in Togwajale, Balanbal, and Abudwakh) and towards the south and southeastern part of the aquifer around Aden Ival and Gulane (see Fig. 5.3). The increase of sulfate and chloride ions concentrations coincides with the regional direction of groundwater flow. These ions rarely exceed 500 mg/L in the deeper parts of the aquifer, especially in the south and southeastern part (LBI, 1985).
5.3.2. Water Type.

The relationship between total dissolved solids and electrical conductivity is employed in order to compute the conversion factor, which provide a field evaluation of total dissolved solids and water type in the aquifer at that particular location. Figure 5.4 shows the EC-TDS relationship and the very good correlation (R² = 0.998) between them for the Jesomma aquifer. The conversion factor (A = 0.71) calculated for the Jesomma aquifer falls in the range of mixed water type (NaCl, NaSO₄ and CaSO₄) in which this aquifer belongs.

5.3.3. Water Use.

The averages of the TDS and EC of waters of the Jesomma aquifer are 1284 mg/L and 1805 micromhos/cm, respectively. The range of TDS in the aquifer varies from 1025 to 1607 mg/L while EC varies from 1300 to 2500 micromhos/cm. These values (TDS) are around the maximum tolerable limit (1500 mg/L) adopted for drinking water by the World Health Organization. Since water containing less than 2000 mg/L of total dissolved solids is still suitable for drinking purpose (Freeze and Cherry, 1979), the water in the Jesomma aquifer is suitable, in general, for all purposes and can be considered fresh water. The Jesomma water has been used and still using for domestic and rural supply.
5.4. Aurado Aquifer.

5.4.1. Chemical quality pattern.

Chemical quality of the Aurado aquifer is slightly influenced by the presence of anhydrite and gypsum layers in the recharge area. The total dissolved solids and corresponding electrical conductivity values obtained from the various parts of the aquifer are shown in Table A.3. (Appendix A). In the central part of the aquifer, the distribution of total dissolved solids is uniformly distributed with a value of about 1800 mg/L except in the Galdogob area, located near the border between Somalia and Ethiopia, in which the TDS are about 3000 mg/L (Fig. 5.5). The chloride and sulfate ions in this locality are 809 and 530 mg/L respectively. Dissolution of anhydrite and gypsum lithology in the recharge area, near Galdogob, has caused the increase of chloride and sulfate ions in this locality. The chloride and sulfate levels are below 300 mg/L in the rest of the aquifer and their amounts increase towards the deeper parts of the aquifer. In the western part of the aquifer, near the border, the water is dominated by calcium and bicarbonate except in the contact between the Aurado and Taleh formation in the recharge area, where anhydrite lithology dominate in the upper part of the Taleh formation (GTZ, 1979). Lack of data makes impossible to reach a complete evaluation of TDS concentration in the eastern part of the aquifer (Fig. 5.5) because the depth of the aquifer lies beyond 600 meters and no wells are tapping. However, Agip drilled several wells in the area for oil exploration purpose and reported the presence of low mineralized water at depth of 740 meters in the porous Aurado limestone (GTZ, 1979). In the northern part of the aqui-
fer, there is a general pattern of increasing TDS along the flow direction of the groundwater from north to south. In addition, TDS is low in the northern part of the aquifer.

5.4.2. Water Type.

Figure 5.6 shows the relationship between TDS and EC with a conversion factor of 0.71 and an excellent correlation between TDS and EC. The conversion factor falls in the range of mixed waters. Therefore, the Aurado aquifer belongs to the mixed type of water: NaCl, CaSO₄ and NaSO₄.

5.4.3. Water Use.

The Aurado water has been used for domestic and livestock watering purposes in the past. The salinity level in the Aurado aquifer ranges between 714 and 2300 mg/L (except Galdogob well - 3000 mg/L - maximum). The average total available dissolved solids and electric conductivity data are 1940 mg/L and 2710 micromhos/cm, respectively. These values indicate that the Aurado aquifer is suitable, in general, for all purposes except it tends to be marginal for drinking purposes, especially near the border in the Galdogob area.
5.5. Taleh Aquifer.

5.5.1. Chemical Quality Pattern.

Chemical quality of the water in the Taleh aquifer is influenced by the nature of the lithology of the formation. The total dissolved solids are not homogeneous throughout the extension of the aquifer. In the Northern part of the aquifer near Aragabo, the total dissolved solids in wells supplying the town, range between 580 to 715 mg/L with an average conductivity of about 1000 micromhos/cm. In the south, Las Anno, Garoowe and Bali Busle (see Fig. 5.7), the total dissolved solids concentration increases to about 1400 mg/L with lower levels of sulfate, chloride and sodium concentrations (Pozzi, 1983; LBI, 1985). In the area between Galcaio and Obbia, the total dissolved solids concentration varies from 2145 mg/L, near Galcaio, to 4500 mg/L, near Obbia, with an increase of chloride, sulfate and sodium concentrations. In the southeastern part of the aquifer at Olgula, Afguduudle and Yamaarugle, wells contain low quality water with high concentration of chloride and sulfate ions. The dominant ion in this area is sulfate, which reaches about 1000 mg/L in some wells. In the northeastern part of the aquifer at Las Gidet near Bender Baila, the total dissolved solids concentration is in the range of 1500 mg/L with slight increase of sulfate ions in this direction. The electric conductivity measured in wells tapping the aquifer varies, generally, from 800 micromhos/cm in the northern part to 6000 micromhos/cm in the southern and southeastern part of the aquifer (LBI, 1985; Pozzi, 1983; GTZ, 1979).
The variation in total dissolved solids concentration in the aquifer is a result of lateral change in the lithology of the formation. The Taleh formation changes, in the upper part, from anhydrite in the southern and southeastern part of the aquifer to completely dolomite and limestone with an intercalation of marls and clay in the northern and northeastern part of the aquifer. The controlling factor in water quality for this aquifer appears to be the presence or absence of soluble anhydrite deposits. Therefore, the high salinity levels in some parts of the aquifer are the result of dissolution of soluble anhydrites.

5.5.2. Water Use.

The total dissolved solids concentration of the aquifer is high and this renders water quality poor. In the southern and southeastern part of the aquifer, because of the higher salinity of the aquifer, the water is not considered potable. Therefore, wells in this area are mostly used to supply livestock, which can generally tolerate a salinity of about 7000 mg/L. Wells in the northern part of the aquifer are suitable for domestic supply and agricultural purposes because the salinity (TDS = 1200 mg/L - average) is lower than the maximum tolerable limits for potable water. Wells in Aragabo town (northern part of the aquifer) are used for the irrigation of small plots with fruits and vegetables, besides domestic supply.
5.6. Merca Aquifer.

5.6.1. Chemical Quality Pattern.

The evaluation of chemical quality of the water in the Merca aquifer is based on the distribution of the total dissolved solids and electric conductivity in the aquifer. Table A.4 (Appendix A) shows the distribution of total dissolved solids concentrations obtained from the analyzed samples and their corresponding electric conductivity measured from the sampled wells of the aquifer. The distribution of total dissolved solids in the aquifer increases, generally, from the shallower part of the aquifer (north) towards the deeper part (south) of the aquifer (Fig. 5.8), although local variations have been observed in some parts of the aquifer, especially in the area between Mogdishu and Qorioley. The levels of chloride and sulfate ions in the aquifer are generally below 250 mg/L and increase slightly towards the south. This trend correlates with the direction of groundwater flow and thus with the general groundwater chemical evolution pattern. The concentration of sodium increases towards the deeper part of the aquifer but its concentration is low compared to other ions.

5.6.2. Water Type.

The relationship between the total dissolved solids (TDS) and specific conductivity (EC) shows good correlation (R) with a conversion factor of 0.71 (Fig. 5.9). The conversion factor indicates the presence of mixed type of water in the aquifer because it lies in the range designated for mixed water (NaCl, NaSO₄ and CaSO₄) by Hem (1970).
5.6.3. Water Use.

The Merca water is suitable for all purposes because its total dissolved solids contents and electric conductivity fall under the maximum limit for potable water. The range of total dissolved solids varies from 630 mg/L in the northern part to about 1900 mg/L in the southern part of the aquifer. The average total dissolved solids in the samples analyzed is about 1200 mg/L with corresponding electrical conductivity of about 1670 micromhos/cm. The Merca water has been used for domestic and agricultural purposes for a long time.
Fig. 5.2. Electric conductivity Versus Total Dissolved Solids for Baldoa aquifer.

\[ A = \text{TDS/EC} \]
\[ A = \text{Conversion Factor} \]
\[ A = 0.75 \]

\[ R = \text{Correlation Factor} \]
\[ R^2 = 0.89 \]
Fig. 5.3. Distribution of Total Dissolved Solids in the Jesoma aquifer.
Fig. 5.5. Map showing the distribution of total dissolved solids in the Aurado aquifer
Fig. 6.6. Electric conductivity versus total dissolved solids for Auredo Aquifer.

A = TDS / EC
A = Correlation Factor
A = 0.71
R = Correlation Factor
R^2 = 0.999

EC (micromhos/cm)

0 400 800 1200 1600 2000 2400 2800 3200 3600 4000

TDS (ppm)
Fig. 5.8. Contour map showing the distribution of TDS in the Merca aquifer.
VI. CONCLUSIONS AND RECOMMENDATIONS.

6.1. Conclusions

Somalia is characterized by an arid to semi-arid climate and is increasingly becoming dependent on water resources. Availability of water resources in Somalia varies from insignificant to reasonably productive areas in different regions. A comprehensive assessment and evaluation of groundwater in the Baidoa, Jesomma, Aurado, Taleh and Merca aquifers and surface water in the two perennial rivers, Jubba and Shabelle, have been made in order to compare them with the future demand of the country.

Transmissivity of the Baidoa aquifer changes rapidly from one place to another due to lack of homogeneity of hydraulic properties of the aquifer. The Sarmaan Dheere area, which is located northwest of Baidoa Town, is the most productive area in the aquifer with transmissivity of $2.52 \times 10^{-2}$ m$^2$/sec. In the southern and southwestern part of the aquifer, the transmissivity is low due to lithological changes. In the northern part of the aquifer, at Marti Moog, Maleel, Isgeed and Mintaan area, the productivity of the aquifer is higher than in the southern part because of higher transmissivity. The Baidoa aquifer has a high potential and can sustain long-term withdrawals because large volumes of water are being replenished annually. The Baidoa aquifer has not been developed to its greater extent and the present annual groundwater abstraction from the aquifer is far lower than its storage capacity. Water level behavior is influenced
by the transmissivity distribution, amount of withdrawals from the aquifer and recharge received over outcrop areas. Water level declines are generally higher in the southern and northern parts of the aquifer, where transmissivity is relatively lower. The declines are low in the western and central parts of the aquifer due to relatively higher transmissivity. From the data available, the average water level fluctuation in the aquifer reaches about 10 meters.

The Jesomma aquifer is one of the major productive aquifers in the country. The transmissivity of this aquifer is relatively higher in the southern and southeastern part of the aquifer indicating the change in textural properties and enhancement of permeability of the formation. In the northwestern part of the aquifer at Togwajale, the transmissivity \(1.5 \times 10^2 \text{ m}^2/\text{sec.}\) is relatively low and increases towards the southeast at Buroa \(4.27 \times 10^2 \text{ m}^2/\text{sec.}\). The productivity of the Jesomma aquifer increases from the north and northwest near the border between Somalia and Ethiopia to south and southeastern part of the aquifer near Mataabaan, Aden Ival and Gulane because of higher transmissivity of the aquifer in these areas. Large volume of water can, in general, be withdrawn from the Jesomma aquifer particularly in the southern part, where transmissivity of the aquifer is high. The water level of the Jesomma aquifer has been influenced in the past years by the drought coupled with heavy pumping which caused the decline of water level in some areas of lower transmissivity, like Togwajale (northwest) and Jesomma (southwest of the aquifer). The wetter climatic conditions that followed the drought period reversed the decline of water level. Generally the decline varies from 10 to 15 meters in the western part of the
aquifer along the border between Somalia and Ethiopia where the transmissivity of the aquifer is low.

The Aurado aquifer is the most productive aquifer in the country. The transmissivity of the aquifer increases from the border (western part of the aquifer) near Galdogob towards the southeastern part of the aquifer near El-Bur and Hersi Garablo area. From the border between Somalia and Ethiopia (western part of the aquifer) towards the eastern part of the aquifer near Bur-Hisso, Gardo and Aragabo area, the transmissivity is also high and is increasing towards this direction. These two trends indicate the increase and improvement of hydraulic properties of the aquifer. The Aurado aquifer is of high potential due to its high transmissivity, especially near El-bur and Hersi Garablo area, and can sustain to supply large agricultural schemes, besides domestic supply. The water level decline is relatively high in the areas near the border between Somalia and Ethiopia, especially Galdogob and Bur-Hisso. The net regional water level decline is not available due to lack of enough data, but in the drought period it reached about 15 meters in areas of low transmissivity.

The transmissivity of the Taleh aquifer increases, generally, from Kalla Bair (southwest of the aquifer) towards Las Gidet (northeastern part of the aquifer) and decreases towards southeastern part of the aquifer (Obbia). Local variation of transmissivity exists in both trends. The change in transmissivity values is due to changes in the lithology of the formation. Water levels have declined more in the southern part of the aquifer, where transmissivity is relatively low.
The productivity of the Merca aquifer generally increases from the northern part (Johar) towards the southern part of the aquifer (Qorioley). Local fluctuations exist in the area between Mogdishu and Qorioley. Local changes of flow direction of the groundwater have been observed in the areas of low transmissivity during the dry season, particularly in the northern part of the aquifer. The decline of water level is greater in the northern part of the aquifer due to excessive pumping and lower transmissivity. The decline is less towards the south due to high transmissivity and less pumping.

The extent of availability of surface water in the country throughout the year is limited in the two perennial rivers, Jubba and Shabelle, which hold a large quantity of water. These two rivers pass in the southern part of the country. In spite of severe water shortages in some parts of the country, significant amount of water is lost to evaporation or discharged into the oceans through wadis during rain period, making the availability of surface water non-existent.

Statistical calculations were made to evaluate the available amount of water resources and the total water demand throughout the country. The results obtained show that the present available water resources in Somalia exceed the total consumption of water in the country and satisfies the future projected demands for the period of twenty years (1990 - 2010). The available groundwater alone will not be enough to supply the country's growing demand in the near future if the present climatic conditions change and the amount of available surface water decreases. The groundwater alone will not satisfy supplying the agricultural activity and shortages will become very acute. However, topographic
conditions are favourable for developing surface embankments and reservoirs throughout the country in order to collect surface water and distribute the stored water to balance the growing demand.

The chemical quality of groundwater in the aquifers is generally suitable for all purposes except in the Taleh aquifer, where the water in the southeastern part of the aquifer is characterized by having relatively high total dissolved solids and poor quality. The total dissolved solids of waters in all the aquifers increase generally along the direction of the groundwater flow.

6.2. Recommendations.

The development of the major aquifers in Somalia is very low due to the small number of wells tapping them. Therefore, Somalia needs a continuous effort to develop water resources, especially groundwater, to their optimum potential. More exploratory work must be conducted in order to delineate the boundaries of the aquifers and to look for new ones. A better knowledge of recharge, underflow, discharge and drilling of exploration and production wells is essential. More drilling should be conducted on the Aurado, Jesomma, Merca and Baidoa aquifers. In the eastern part of the Aurado aquifer, where the depth of the aquifer lies beyond 600 meters, some future development may be feasible to supply water of better quality to rural and urban population. In central Somalia, where wells tapping the Aurado aquifer are only available in villages and towns, new wells should be drilled in the grazing areas and developed properly in order to avoid long travel for water. The development of the Aurado aquifer in the central and northeastern parts of Somalia can satisfy the demand

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in these areas, but planned distribution and comprehensive drilling of production wells are essential. In the western part of the northern region, where the land is mostly used for grazing, the Jesomma aquifer should be developed and wells should be drilled in order to augment the supply of water for rural people who depend mainly on livestock herding. In the southwest of Somalia, the distribution of the wells in the Baidoa aquifer should be increased, especially in the rural areas in the west and northwest of the region, where livestock and people travel long distance for water.

In spite of the presence of sharp water shortage in some parts of Somalia, especially in the rural areas, the available water resources, both surface and groundwater, exceed the total demand of the country. Therefore, a comprehensive program of planning and development is recommended so as to improve the availability of water to rural inhabitants. The only way to accomplish these goals is to place wells in the grazing and populated areas. In addition, large surface reservoirs should be designed to collect and store rain water where no groundwater is available. A proper means of exploitation of the waters in the rivers, which requires a large investment, is another means of reducing the hardship of water shortage in the country. The availability of surface water from the two rivers should be studied more thoroughly in order to estimate the net available amounts of water under extreme conditions. This will allow planners to lay down the proper schemes for exploiting these waters and to evaluate the extent of availability of these resources for future planning.

Further exploration and investigation of potential hydrogeological basins in
northern Somalia, especially in the Adigrat sandstone and Hamanley limestone, and deeper basins in central and southern Somalia, should be conducted in order to establish and develop new additional resources. In addition, more thorough and detailed investigations of the aquifers, based on additional data collection, is required in order to better estimate the thickness and hydrologic parameters of each aquifer and to evaluate the quantities of groundwater available in each aquifer.

It is very essential to develop a comprehensive plan to develop each aquifer to satisfy each area or sector of population within the basin of the aquifer in a manner to overcome the shortage that are causing droughts and famines in the country. Also implementation of a nation-wide program for rehabilitation of existing deep and shallow wells in the various aquifers is important for the continuity of production of groundwater to satisfy the growing needs of the population.

A water resources development master plan for the whole country is required; efforts should be made to obtain financial aid from international organizations and donor agencies for this purpose.

Chemical quality of groundwater in the various aquifers should be investigated thoroughly in order to better understand and avoid degradation of water quality and supply water of better quality to the people.

As people are little aware of the dangers of water-related diseases, a strong health program is required for improvement of sanitary conditions of surface reservoirs and shallow hand dug wells.
Increase of public participation through incentives towards diversification in the economy and to shift to a permanent agrarian system to replace the nomadic mobile life is necessary for Somalia.

Investment by the government and world organisations in creating agricultural settlements as models to settle the nomadic population and to create a base for an agricultural system is recommended.

Wells can be drilled in areas rich with agricultural soils to create such agrarian settlements and settlement loans should be given to families that are willing to settle and maintain agricultural plots distributed to them.
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APPENDIX A.
Table A.1. Chemical analysis of the Baidoa aquifer.

<table>
<thead>
<tr>
<th>Well No</th>
<th>Location</th>
<th>Unit concentration</th>
<th>Ca^{++}</th>
<th>Mg^{++}</th>
<th>Na^+</th>
<th>K^+</th>
<th>SO_4^-</th>
<th>CL^-</th>
<th>HCO_3^-</th>
<th>TDS</th>
<th>SAR</th>
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<tr>
<td></td>
<td></td>
<td>ppm</td>
<td>272</td>
<td>89</td>
<td>100</td>
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<td></td>
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<td>7.3</td>
<td>4.4</td>
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<td>7.9</td>
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<td>71</td>
<td>77</td>
<td>6</td>
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<td>Meq/l</td>
<td>8.5</td>
<td>6.1</td>
<td>3.4</td>
<td>0.15</td>
<td>2.2</td>
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Table A.2: TDS and corresponding specific conductivity in the Jesomma aquifer

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Table A.3: TDS and corresponding specific conductivity in the Aurado aquifer

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Table A.4: TDS and corresponding specific conductivity in the Merca aquifer

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