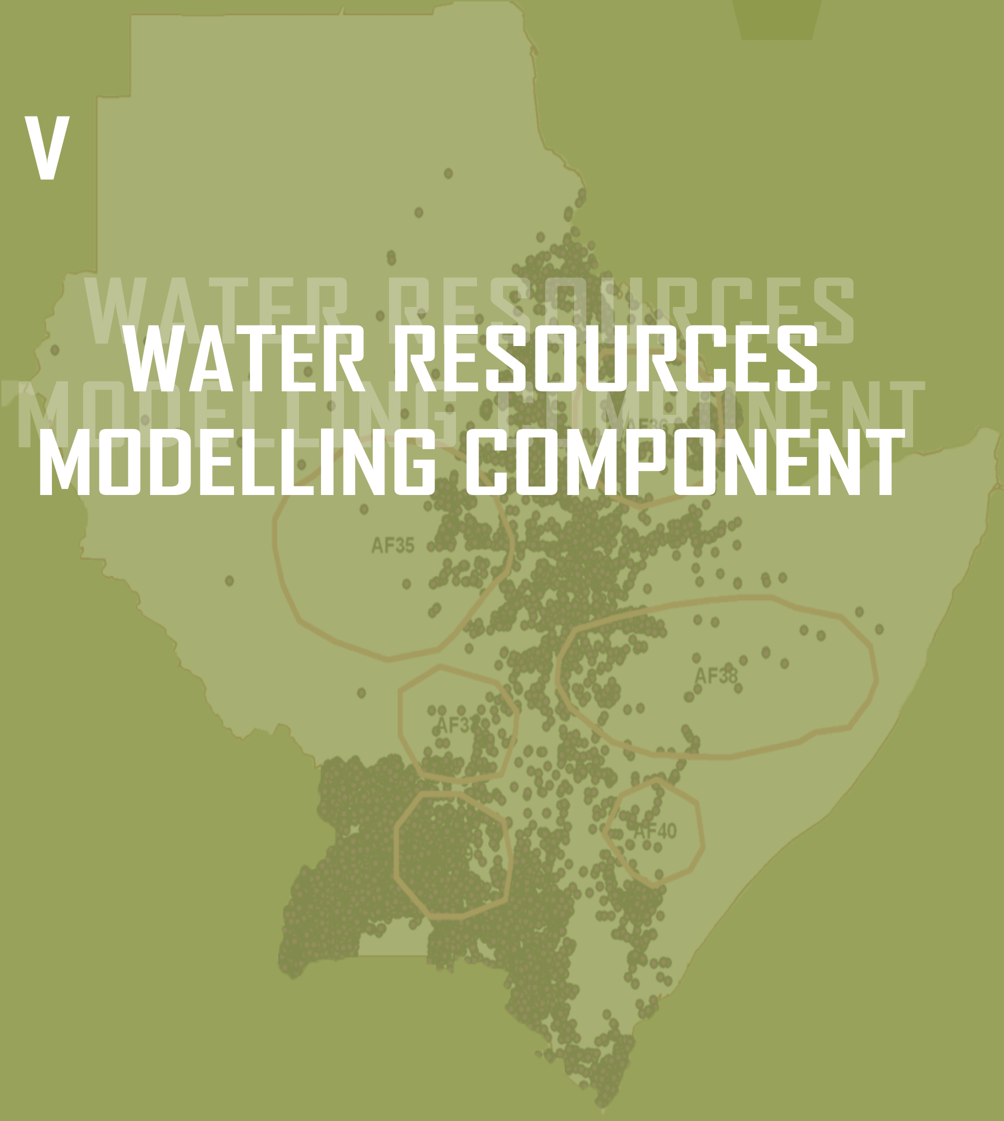
Mapping, Assessment & Management of
Transboundary Water Resources in the
IGAD Sub-Region Project

Volume V



WATER RESOURCES MODELLING COMPONENT

INTERGOVERNMENTAL AUTHORITY
ON DEVELOPMENT

AFRICAN WATER FACILITY

SAHARA AND SAHEL OBSERVATORY

Mapping, Assessment & Management of Transboundary
Water Resources in the IGAD Sub-Region Project

Volume V

WATER RESOURCES MODELLING/ HYDROLOGY COMPONENT

Transboundary water resources assessment in the IGAD sub-region

December 2011

Study conducted with the support of:
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ISBN: 978-9973-856-62-3

PREFACE

The IGAD sub-region represents one of the marginal regions of the world in terms of rainfall available for natural vegetation growth and crop production. About 80% of the IGAD sub-region is arid and semi arid with low level of water use. It has a population estimated at **206 million in 2010** and projected to reach **462 million in 2050** in an area of **5.2 million km^2**.

The most obvious manifestation has been periodic droughts and desertification that have consigned millions to perpetual poverty and deaths. The populations derive their livelihoods from water and land based primary production activities such as nomadic pastoralism and subsistence agriculture in a region where rainfall variability is high. The sub-region is the home of the greatest numbers of pastoral communities estimated to be about **17 million**. Dependable water availability is therefore vital to the development of the region.

The mounting concerns over water scarcity in the IGAD sub-region have focused attention to several socioeconomic challenges of water resource management.

Firstly, as the sub-region expects to advance economically and socially, the demand for water will increase as a result of population growth, rising incomes, changing dietary patterns, urbanization and industrial development. While demand will increase in all sectors, agriculture will account for the bulk of the water and will therefore be the focal point for adjustment of demand pressure.

Secondly, there are concerns as to whether the IGAD sub-region will have enough water to meet the food security needs of a rapidly growing population. Along with food security, water security has also become a fundamental issue for human development in the sub-region

While it is a fact that water occupies pivotal position in development in the IGAD sub-region, none of the **member countries has adequate information** to manage their water resources for the attainment of economic efficiency and equity in water allocation for different uses. Yet, four IGAD countries namely **Eritrea, Kenya, Djibouti and Somalia** are in the category of those experiencing water scarcity i.e. with **less than 1000 m^3 per person per year** or less.

Indeed by the year 2025 even Ethiopia and Uganda which are presently with adequate water will be water stressed (1000-2000 m^3/person/year) while Djibouti, Eritrea, Kenya, Somalia and Sudan will be in water barrier situation «500 m3/person/year » and therefore water will be limiting any sustainable development.

None of the IGAD Member States has at the present time water per capita necessary for industrial development (2400 m^3/day). This lack of water will severely constrain food production, ecosystem maintenance and economic development among other needs and uses.

Water resources link the IGAD Member states internally and externally with adjacent regions. Six transboundary river basins and six transboundary aquifer systems have been identified in this stage of the IGAD sub-region study. **The ratio of water demands to available supply averages which is 9% in 2011 will increase to 15% in 2031** as projected by this study which is known as "*Mapping, Assessment and Management of Transboundary Water Resources in the IGAD Sub-region Project*". However, there are specific problems that call the need for adequate knowledge of surface and ground water resources.

This Study (the first sub-regional study) has provided a platform for refocusing efforts within the sub-region towards better quantification and understanding of the extent of water scarcity and other water related factors that impact socioeconomic development in the sub-region. The most significant of the drivers of water demand in all sectors is population, which in the sub-region is projected to increase by 165% between 2010 and 2030, and by 136% between 2030 and 2050. This study demonstrates that these increases will create significant increases in water withdrawals for domestic supply and for industry.

The other significant sector is agriculture, which combines irrigation and livestock. Again here population is the most important parameter of change, driving the demand for food and hence the need to raise agricultural productivity through irrigation development.

The regional process has highlighted the **low level of water use** and hence of water security currently estimated as about 3% of the annually renewable water resources as a basic indicator of the overall lack of water infrastructure development to ensure water security for the social and economy and environmental use. The IGAD sub-region is one of the most vulnerable areas to climate variability and recurrent droughts.

Hence, there is need to further understand in depth the environmental situation and consolidate IGAD capacities to monitor the linkages between climate and the water system along with identification and mapping of the water resources and the major risks associated with degradation, pollution and water quality deterioration. Policies, strategies, and objectives of cooperation and how to achieve them should be set out in a second stage of the IGAD project study.

It is important to note that the IGAD project was implemented at national and sub-regional levels with active participation of the focal national institutions by employing national and regional consultants. The project coordination is done by OSS with the establishment of national coordination units in the focal national water institutions of the IGAD Member States. Steering Committee of the project was in place and the regional coordination and facilitation was done by IGAD.

We would like to thank everyone who contributed to the success of this project: the Ministries in charge of Water and national institutions, the IGAD and OSS cooperation partners (particularly the African Water Facility), the national teams, national and international consultants, the project team within the Executive Secretariat of OSS and The IGAD Secretariat.

Our satisfaction was to pass the ownership of all project results by national teams and the establishment within the Executive Secretary of IGAD powerful tools to ensure the continuity of the project.

This final project report is made up of 7 individual documents namely

- Introduction, Overview and General Recommendations
- Volume 1: Institutional Framework Component Report
- Volume 2: Socioeconomic Component Report
- Volume 3: Environment Component Report
- Volume 4: GIS/Database Component Report
- Volume 5: Water Resources Modelling/Hydrology Component Report
- Volume 6: IWRM Component Report

We also thank SEREFACO Consultants Limited and its team for the excellent work carried out despite all the difficulties encountered particularly the lack of reliable data.

The Executive Secretary of OSS Dr. Ing. Chedli FEZZANI	The Executive Secretary of IGAD Eng. Mahboub Mohamed MAALIM

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LIST OF ACRONYMS

95PPU	95% Prediction Uncertainty
ADCP	Acoustic Doppler Current Profiler
AET	Actual Evapotranspiration
ASAL	Arid and semi-arid land
AQUASTAT	Global Information System on Water and Agriculture of FAO
BCM	Billion cubic metres
CIESIN	Centre for International Earth Science Information Network
CN2	Curve Number
CRU	Climate Research Unit
DB	Database
DEM	Digital Elevation Model
DWRM	Directorate of Water Resources Management
FAO	Food and Agricultural Organisation
GIS	Geographical Information System
GLC	Global Land Cover
GLCC	Global Land Use Land Cover Characterization
HRUs	Hydrologic Response Units
IGAD	Inter-government Authority on Development
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
LH-OAT	Latin Hypercube-One-at-A-Time
MoWR	Ministry of Water Resource and Hydrology
NBI	Nile Basin Initiative
NELSAP	Nile Equatorial Lakes Subsidiary Action Programme
NMSA	National Meteorological Services Agency
PET	Potential Evapotranspiration
SM	Soil Moisture
SRTM	Shuttle Radar Topography Mission
SSO	Sahara and Sahel Observatory
SUFI	Sequential Uncertainty Fitting
SWAT	Soil Water and Assessment Tool
TECCONILE	Technical Cooperation Committee for the Promotion of the Development and Environmental Protection of the Nile Basin
ToR	Terms of Reference

UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Surveys
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

The work involved data collection, hydrological model set-up, identification of the most sensitive model parameter, model calibration and sensitivity analysis for the IGAD transboundary basins. The main output of the strategy was a clearer understanding of the hydrological response of several IGAD catchments and the potential use in terms of solving controversies surrounding fluctuating stream flows and Lake water levels, sustainable agriculture, rural development, hydropower generation and environmental stewardship.

The Water Resources Modelling section conceptualized and developed of a hydrologic model for water resources assessment of the identified transboundary basins in the IGAD region. This involved close collaboration with the GIS/Database expert for effective preparation, presentation and archiving of water resources and hydrologic data in the agreed format. Substantial knowledge of GIS was required by the potential participant of the water resources modelling modules. In terms of software requirements, ArcGIS was also required for hydrological models setup/simulation of the water resources modelling component. Several meteorological datasets were acquired for effective modelling; however, the continued lack of daily stream flows still limited the effective calibration of the delineated hydrological IGAD basins. Several attempts were carried out to ensure effective estimation of the Water resources for the IGAD basins.

A basin-wide summary of the simulated water resources components was presented to give a general insight into the water resources components for IGAD transboundary basins. Additional data especially daily stream flows at several locations in the basin, are required to improve the water resources simulation. The available hydrological and climatological data from the IGAD databases revealed large deficiencies, especially regarding daily observations - a number of observations are missing. Furthermore the available data from other sources were sparse and not free of errors. The climate in the IGAD basin is rather complex and for accurate use of hydrological models, representative precipitation sequences may be required. For the IGAD hydrological basins, evaluation of the hydrological performance of the SWAT model on a daily/monthly time resolution should reveal the hydrological patterns and the sensitivity of hydrological variables to input rainfall datasets and parameter estimates. A simple sensitivity study helped reduce the dimensionality of the calibration challenge.

The results of the Water Resources Modelling/Hydrology component of this study represent a first attempt to comprehensively model the water resources of the 6 transboundary river basins in the IGAD Sub-region. For most of the basins, the estimated available annual water resources were in good agreement with results from other studies (for example those by the FAO Water Resources Project). This was the case for Danakil, Gash-Baraka, Turkana-Omo and Ayesha. The estimates for Juba-Shebelle and Ogaden exhibited wider discrepancies with the FAO estimates. However, the estimates were based on data available to the consultant at the time of the study. As noted in the report and elsewhere, the datasets were limited in both temporal and spatial terms. In particular, model calibration requires the availability of reliable flow data for major rivers within the basins. These data were not available for the current study. As such the estimates for all basins need further investigations before they can be used as a basis for comprehensive decisions about the basins. There is need for collection of additional data from the member countries as soon as a mechanism for data sharing can be implemented. The absence of an IGAD level data sharing protocol may be one of the reasons why some countries could not avail their data to the consultant.

There is also a need for installation of new data collection stations in the transboundary basins. At present, the IGAD basins have limited capacity in terms of gauge network for hydrolometeorological monitoring and operations and each country should have additional capacity for effective operation of the designed hydrometeorological networks. Once the networks are setup, it should be ensured that all stations have complete installation of equipment to guarantee effective monitoring of hydrological events. New equipment for measuring both climatic and hydrologic variables is needed to complement the limited data available in the countries. The proposed coordination mechanisms for data collection, transmission and storage are documented in the Institution Component report. IGAD should establish a capacity building component especially in fields related to water resource modelling and this should be done in a way that member countries create opportunities for cooperation in water resources assessment at sub-regional levels. To ensure effective data collection for all the IGAD member countries, several programmes that support effective data collection and monitoring should be implemented and these should as well ensure mechanism for data achieving and sharing among IGAD member countries.

Basin	Surface water	Groundwater
Danakil	**1.0**	**0.6**
Gash-Barka	**2.8**	**1.4**
Juba-Shebelle	**64.6**	**43.7**
Ogaden	**14.1**	**6.5**
Turkana-Omo	**28.7**	**19.3**
Ayesha	**0.1**	**-**
Total	**111.3**	**71.5**

Simulated estimates of available water resources (km^3) for the IGAD transboundary basins.

1

INTRODUCTION

1. CONTEXT

The water resources component aimed at assessing and analyzing the water resources for IGAD basins. For this sub-component, several transboundary water resource models were developed for IGAD member countries using the spatial distribution of available natural resources including the land use, soils and water resources' components. The majority of the residents depend on the natural water resources for agricultural, industrial and economic productivity; hence the variability in precipitation patterns influences the several water resources in the IGAD aquifer system which in turn may affect the economic productivity. The development of suitable water resources models was a suitable tool for water resource management, however the availed information/reports for the IGAD countries; i.e. Ethiopia, Kenya, Sudan, Uganda and Djibouti provided limited data for water resource modelling. Other reports provided included the state of the environment reports, water resources reports and social economic situation reports - which did not provide the majority of the required water resource modelling information. However, additional data required for the study areas were obtained through additional consultation and access to international databases. The success of the water resource modelling component highly depended on the availability of the required datasets for climate and hydrology in the IGAD area.

2. OBJECTIVES

The main goal of the MAM-TWR project was to assess and analyze the water resources, socio-economic and environmental condition of the sub region and come-up with a set of strategies, recommendations, and action plans to enable member states to implement and operate an integrated trans-boundary water resources management process. To achieve these objectives, a water resources modelling component was included to assess and analyse available hydrological datasets to estimate the spatial and temporal variability of water potential in the IGAD study areas. This involved the selection of a hydrological/water resources simulation tool for hydrology modelling/simulation, to build additional capacity of the IGAD member countries to continuously and effectively analyze the water resources in the IGAD region, for the present and future varied climate conditions.

To allow the conceptualisation and development of several hydrologic modelling components to assess water resources for transboundary basins in the IGAD region, a number of specific objectives were envisaged, including:

- Identification of available sources of water-related data and information at regional levels, especially for the IGAD regions: This involved evaluation of available data and information;
- Identification of data and information gaps and ways to clarify on means of completing the data-gaps for example; applying earth observation data or employing stochastic infilling procedures;
- Identification of major trans-boundary river basins and aquifer systems based on the available information and study documents at national & regional levels
- Identification of water resources and hydrological models, including Inventory of water resources, rainfall-runoff modelling and modelling of key hydrological cycle components. This eventually led to the development of hands-on-training on selected climate and hydrological modelling tools. The modelling tools include water balance models implemented within a GIS environment and water use scenario assessment.
- Preparation of an archiving system for water resources and hydrologic data in an agreed archive-format - implemented closely with the GIS/Database.
- Propose a key meteorological and hydrological monitoring system for the IGAD Sub-region and also identify the required hydrometeorological equipment..

3. ACTIVITIES

The objective of the water resources modelling component was to conceptualise and develop of a hydrologic model for water resources assessment for selected transboundary basins in the IGAD region. Woking closely with the GIS/Database component, the water resources component intended to achieve several objectives including the preparation, presentation and archiving of water resources and hydrologic data in the agreed format.

A physically-based simulation model (as compared to conceptual models) was desired for the simulation of the water balance in the IGAD region. This required long term time-series of daily hydrological and climatic inputs for calibration and validation. A number of automated calibration and validation routines that exist were applied for this assignment, however, successful application and validation of such water resources model structures requires extensive daily datasets.

A brief description of the anticipated methodologies employed for the water resources component is briefly described below:

1. Review the available datasets & information on water resources submitted by national consultants for the purpose of sub-regional assessment and analysis. This involved the following activities:
   - Identification of sources of water-related data and information at regional levels; Identification of data and information gaps and means of completing data gaps, such as the use of statistical tools to infill data-gaps and remote sensing datasets;
   - Identification of major trans-boundary river basins and aquifer systems based on the available information and study documents at national & regional levels. Master

plan studies of the IGAD member countries can be useful sources of data and information; this can be achieved using GIS tools, such as ARCHYDRO, SWAT, etc and Transboundary basin selected and verified by exiting maps and reports;

- Preparation of a note on status and format of the national data and information based on the outputs of the national studies in order to identify gaps in data collection points at the sub-regional level. This involved a review and assessment of the national reports, consultation with local consultants (IGAD) and data collection agencies;
- Validation of the findings and acquisition of supplementary data and information - this was done through workshops/dialogues;

2. Identification of key data collection points for sub-regional monitoring. This involved the analysis of existing climatic data, hydrological and hydro-geological data and information - which involved the description of the state of the national database dedicated to the management of water resources of the member countries;
3. Simulation and assessment of trans-boundary water resources of selected major river basins and aquifer systems in the IGAD sub-region: This involved the Identification of (a) appropriate simulation model; the Soil Water and Assessment Tool (SWAT); (b) pre-processing of input datasets; (c) model set-up; (d) attempt on model calibration and validation;
4. Analysis of climatic datasets, hydrological and hydro-geological datasets and information related to the management of water resources of the member countries and organisation in a coherent and homogeneous manner for the IGAD basin (in collaboration with the database expert).
5. Generation of inputs towards the development of a conceptual common database: This involved:
    - generation of a global modelling platform for the water resources (surface and groundwater resources);
    - development of water resources maps/charts;
    - development of a framework for harmonization of water sector strategies between member countries. This involve spatial representation of available water resources using GIS and Database structures at sub regional levels;
    - elaboration of the sub-regional strategies for strengthening sub-regional and national capacities on a medium to long term basis, which will also involve training in the field of Integrated Water Resources Management and
    - development of a roadmap for establishing trans-boundary water resources management organizations - which also involve training in the field of Water Resources Modelling.

2

INTRODUCTION TO THE IGAD HYDROLOGICAL BASINS

1. GENERAL DESCRIPTION OF THE IGAD HYDROLOGICAL BASIN

The IGAD hydrological basins lie towards the east of the Nile basin (Figure 1). The major transboundary basins defined for this project vary in size and a country-based summary of the basic water balance components are presented in Table 1. The different sub-basins vary in terms of basic hydrology and also include marginal regions such as arid and semi-arid regions, wetlands, and other natural vegetated areas. The major transboundary basins that were considered for water resources modelling are presented in Figure 1. A general summary of the country-based renewable surface water and groundwater supplies, including surface flows of a transboundary nature are summarised in Table 1.

Country	Area (**km^2**)	Average Precipitation (1961-1990) (km^3/yr)	Internal water resources (Total) (km^3/yr)	External water resources (km^3/yr)	Total water resources (km^3/yr)	Dependency ratio (**%**)	IRWR (per capita) m^3/yr inhab.	TRWR (actual) (per capita) m^3/yr inhab.
Djibouti	**23,200**	**5.1**	**0.3**	**0.0**	**0.3**	**0.0**	**475**	**475**
Eritrea	**117,600**	**45.1**	**2.8**	**3.5**	**6.3**	**55.6**	**765**	**1,722**
Ethiopia	**1,104,300**	**936.0**	**110.0**	**0.0**	**110.0**	**0.0**	**1,749**	**1,749**
Kenya	**580,370**	**401.9**	**20.2**	**10.0**	**30.2**	**33.1**	**659**	**985**
Somalia	**637,660**	**180.1**	**6.0**	**7.5**	**13.5**	**55.6**	**684**	**1,538**
Sudan	**2,505,810**	**1043.7**	**30.0**	**119**	**64.5**	**76.9**	**965**	**2074**
Uganda	**241,040**	**284.5**	**39.0**	**27.0**	**66.0**	**40.9**	**1,674**	**2,833**

TABLE 1. Country based water resources budget for IGAD countries

Extracted from FAO (2003), review of world water resources by country

The quantities represent average freshwater resources in IGAD countries and the total water resource is also referred to as the total natural renewable water resources. Generally, the higher the external water resources, the more fragile the country may be in terms of transboundary water resources management.

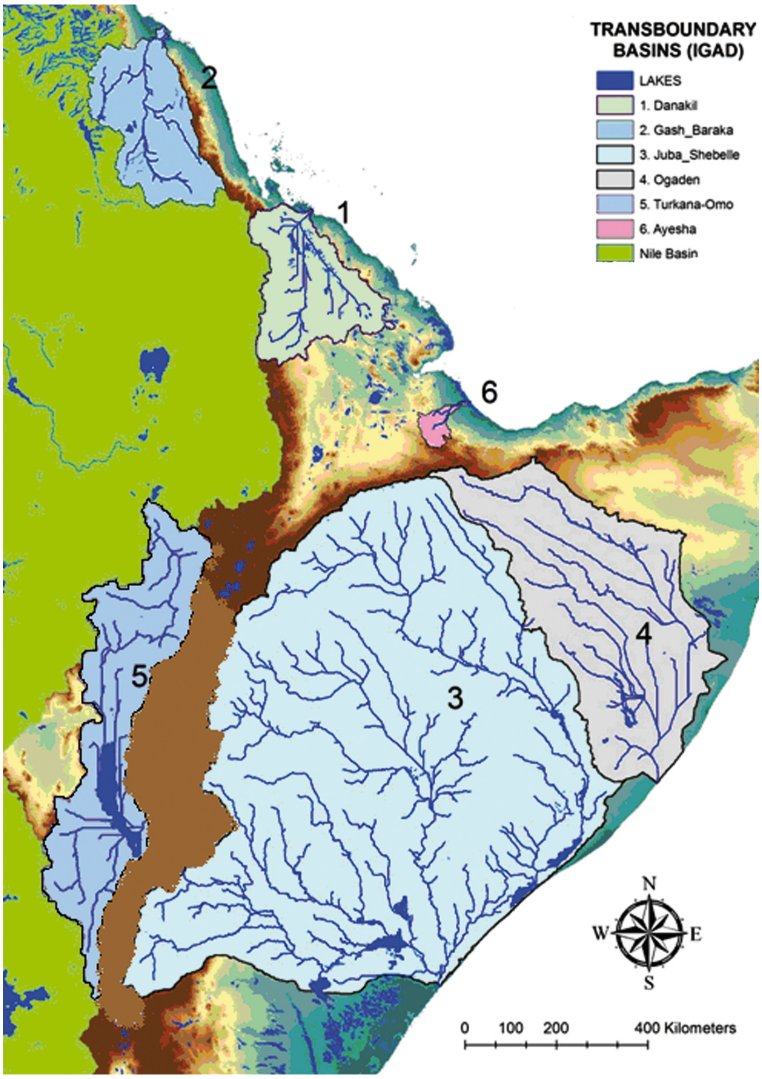

Figure 1: Transboundary basins for IGAD countries and the major Trans-boundary Lake/River system

2. AVAILABLE DATASETS FOR IGAD BASINS

2.1. Situational Analysis

For effective modelling of water resources for the IGAD sub-basins, a set of datasets were required, including water abstraction datasets, geophysical datasets, meteorological and hydrological datasets. The meteorological and hydrological datasets were required on a daily scale, while the other geophysical datasets were required for the recent periods (about 5 - 10 years). However, the available reports received from the IGAD secretariat only provided a general overview of the water resources in the IGAD countries. Quantitative information given was mainly available at large scales (in time/space). Hydrological data sets were mainly available as monthly and annual summaries. For hydrological modelling, less can be achieved by use of monthly and annual summaries. Therefore, access to daily datasets was necessary for successful water resources modelling.

For the water resources assignment, the datasets required for effective modelling vary and most of the crucial datasets should be made available for effective modelling of water resources.

The following list gives the details of the datasets that were required for water resources modelling:

- Climate datasets: For most countries, climate data sets were most likely stored at national meteorological or hydrological monitoring data centres. These datasets were required at daily time-scales for water resources modelling. The Climate Research Unit (CRU) dataset of climate data was used. The data is available at (http://www.cru.uea.ac.uk/cru/data/availability/).
- Hydrological datasets: This type of data are available at several sources including the hydrological monitoring data centres, large-scale water users such as municipal water abstraction centres, industrial abstraction centres, water supply schemes, and hydropower generation companies. The digital stream network was required and obtainable from the USGS' HYDRO1k stream network database or derived from the flow accumulation layer for areas with an upstream drainage area greater than 1,000 km^2.
- Spatial Datasets:
    - Land use (spatial) datasets: This dataset was available from several national spatial databases. Some of the sources include the FAO archives (http://www.africover.org/system/africover_data.php); and the USGS Global Land Cover Characterization (GLCC) database (http://edcsns17.cr.usgs.gov/glcc/glcc.html). The spatial distributions of land cover (shown in Figure 2 - Figure 3) reveal that the basins are mainly overlain by grasslands.
    - Land cover / Land use and Soil data: This information can be acquired from FAO archives, mainly available as national Multipurpose Africover Databases on Environmental Resources (MADE). This may be available from several sources including http://www.africover.org/system/africover_data.php. The spatial distribution is shown in Figure 4.
    - Soil datasets (spatial datasets): This dataset can be acquired from FAO archives, mainly available as national spatial datasets. The Food and Agriculture Organization of the United Nations (FAO, 1995) provides almost 5,000 soil types at a spatial resolution of 10 km with soil properties for two layers (0 - 30 cm and 30 - 100 cm depth). Further soil properties (e.g. particle-size distribution, bulk density, organic carbon content, available water capacity, and saturated hydraulic conductivity) can be obtained from Reynolds et al. (1999) or by using pedotransfer functions implemented in the model Rosetta (http://www.ars.usda.gov/Services/docs.htm?docid=8953). The spatial distributions of soil-types is shown in Figure 3 and the IGAD basins are mainly underlain by Be9-3c#24, Yk15-2a#361, and Rc23-1/2a#215 soil systems.
    - Digital Elevation Model (DEM). This can be acquired from several public domains including http://www2.jpl.nasa.gov. The other source for a DEM is the Geological Survey's (USGS) public domain geographic database HYDRO1k (http://edc.usgs.gov/

products/elevation/gtopo30/hydro/index.html), which is derived from a 30 arc-second digital elevation model of the world GTOPO30. The preferred scale of the DEM should be higher than "90m". The spatial distribution is shown in Figure 5.

- Spatial distribution of major water abstraction points: Time-series of the several water users (abstractions) were required. This included, water abstraction for hydropower generation, water supply, irrigation, etc.
- Spatial distribution of lakes/wetlands and associated water levels
- Climatological time-series of Precipitation, Temperature, Hydrological flows and other climate and hydrological variables. This data is most likely archived at the national meteorological and hydrological institutes.
- Time-series of reservoir operation.

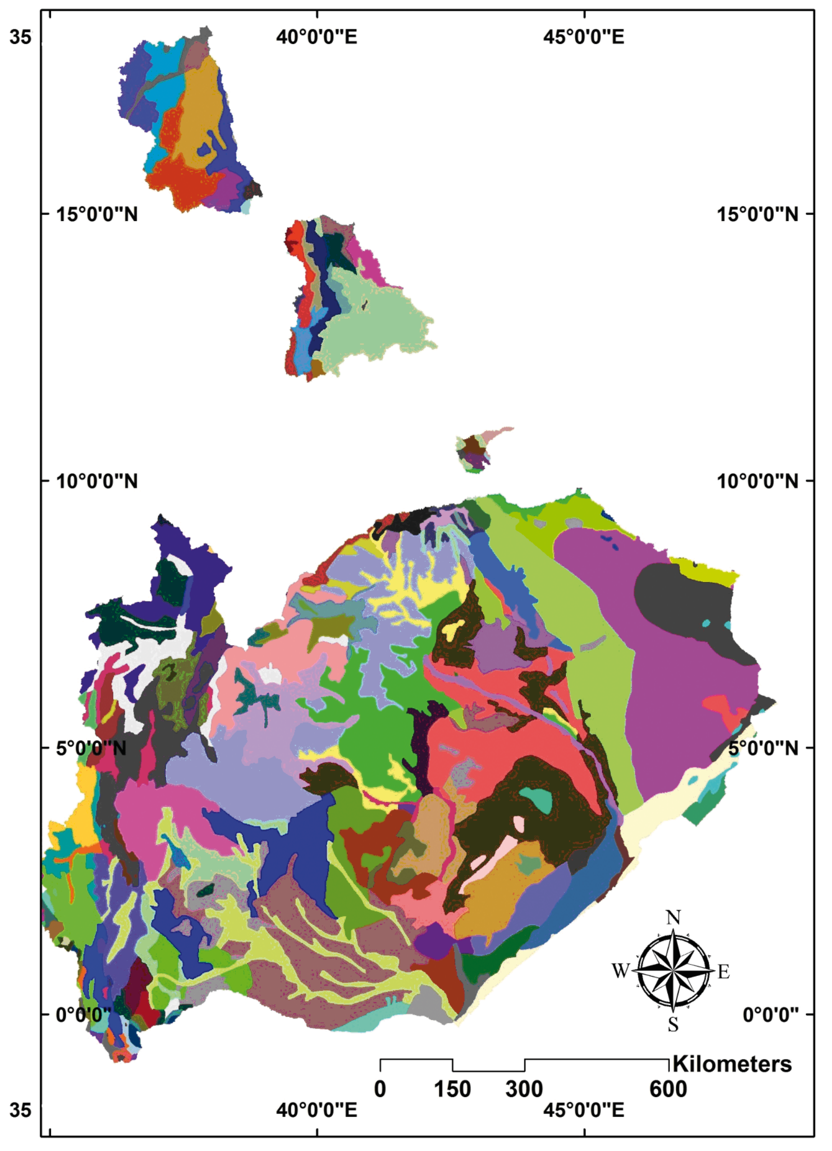

Figure 2: The distribution of soil types for IGAD basins; The Soil Legend is shown in Figure 4.

The availability of most of these datasets was considered critical for successful implementation of water resources modelling exercise. Although the consultant provided literature mainly in form of national reports, most of the available documents (including national reports) provided qualitative information with very limited quantitative data necessary for the water resources modelling required. Additional efforts are still underway to have the detailed data available for the effective setup and modelling of the IGAD basins.

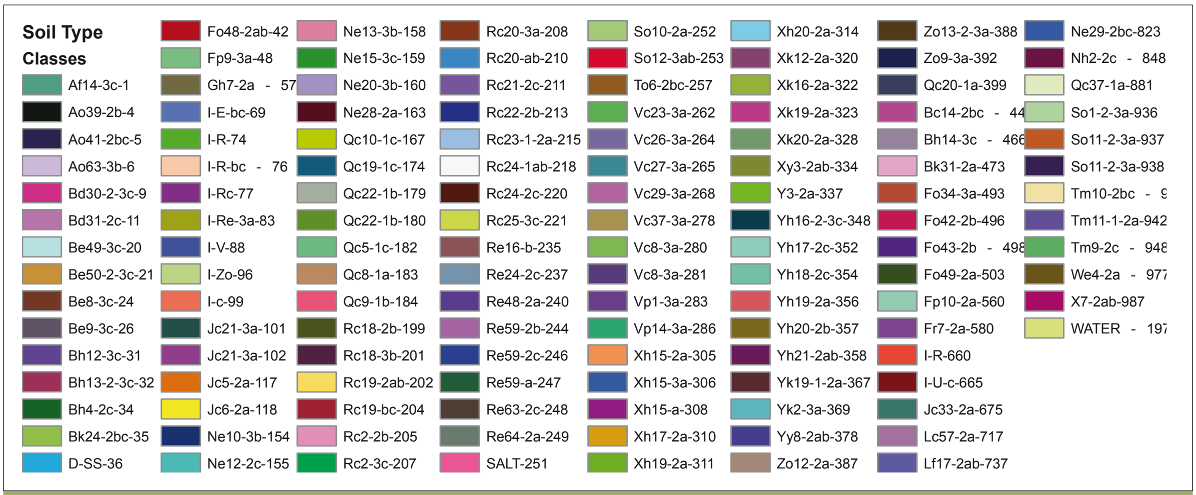

FIGURE 3: Key to the FAO Soil Types in Figure 2.
The description of the soil system is described in detail in the Rosetta system (available: http://www.ars.usda.gov/Services/docs.htm?docid=8953).

A country-based assessment of the required data for the planned water resources modelling in terms of the main water resources modelling data requirements - which includes: Digital Elevation Model (DEM); Land cover / Land use and Soil data; Soil data; Spatial distribution of major water abstraction points; Spatial distribution of Lakes/wetlands and associated; Time series of precipitation, temperature, hydrological flows, reservoir operation and other climate and hydrological variables are summarised in the following sections.

The availed national information, in terms of suitability/adequacy for water resources modelling was done to verify the suitability of the availed datasets in addressing the objective of the water resources modelling assignment. The findings are briefly discussed by country in the following section:

2.2. Republic of Djibouti

The available water resources report described some monthly attributes to the hydrological streams, mainly giving summaries of the major drainage basin characteristics. Little is mentioned about the data collection agencies, previous studies that facilitated climate/hydrological data collection and any other likely sources of data. This is particularly observed for Djibouti compared to other countries. To successfully accomplish the water resources modelling tasks, additional (daily) time series datasets (climate and hydrological datasets) were required.

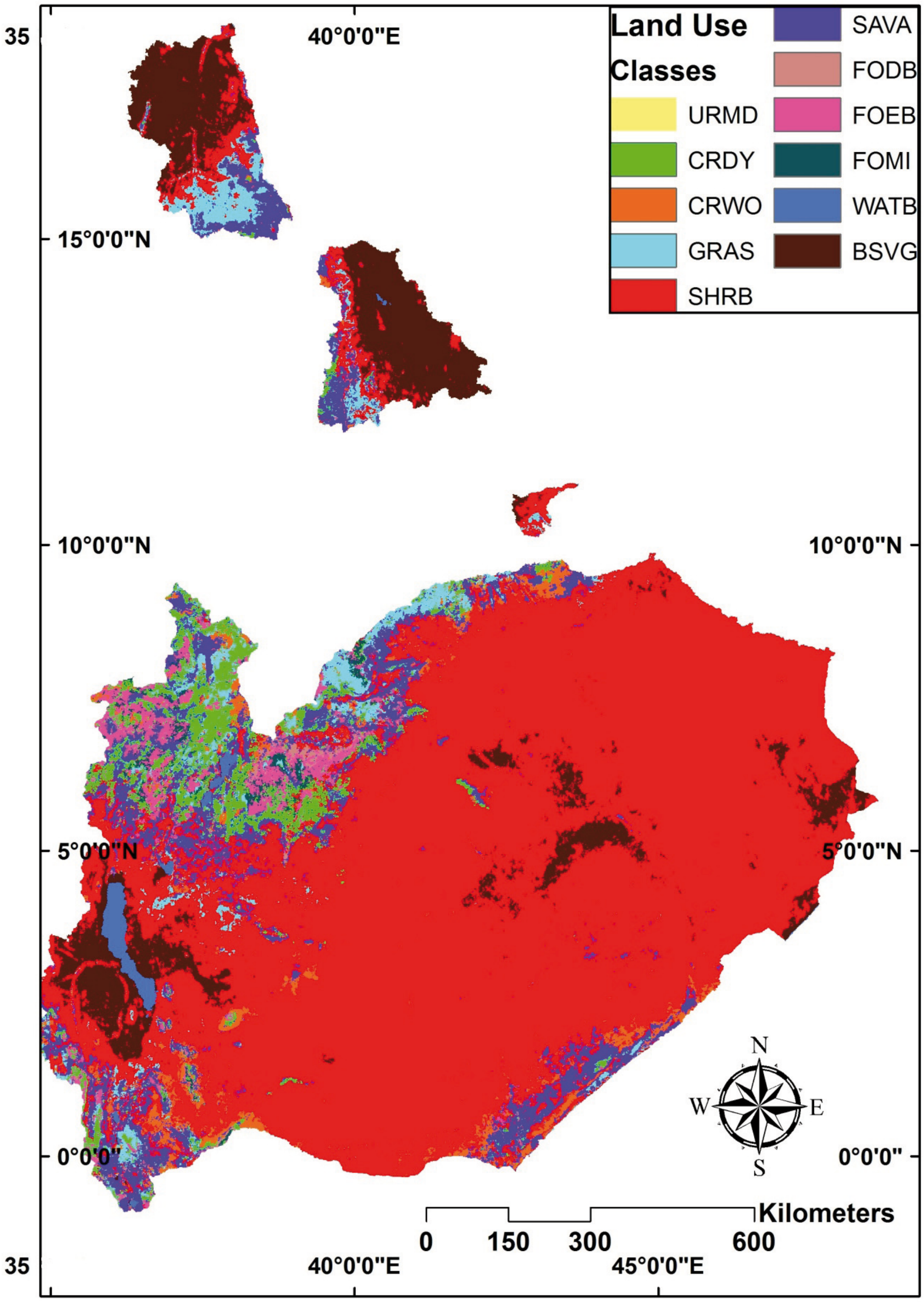

Figure 4: The spatial distribution of Land-use types for IGAD basins.

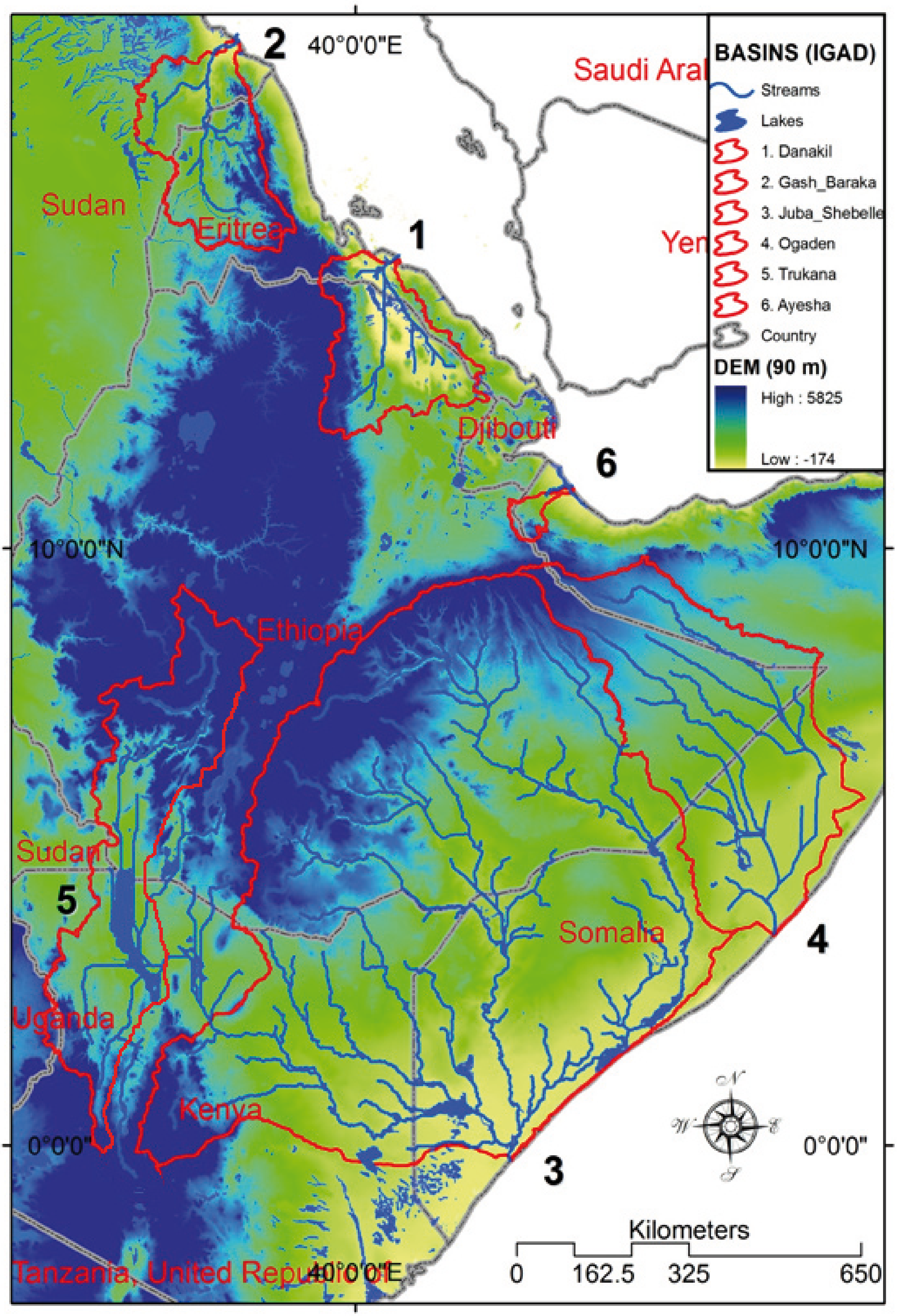

FIGURE 5: The Digital Elevation Model (DEM for IGAD basins).

2.3. Republic of Ethiopia

The available water resources report described monthly summaries of the major drainage basin characteristics with little mention of the availability and possible location of the observed data (such as rainfall, and river flows). Precipitation data was mainly available as basin-wide monthly averages, which is inadequate for hydrological modelling. Additional datasets were required and climatological datasets were anticipated from several sources including: (a) NMSA (National Meteorological Services Agency) datasets, although these were mentioned to contain monthly values taken from complete or partial series of daily data and (b) FAO through CLIMWAT databases, which also contained average monthly values, with indication of the number of years used, but not the period (start and end year). For effective water resources modelling, additional (daily) time series of climatological and hydrological data sets were required

2.4. Republic of Kenya

The report described several drainage basin characteristics with little mention of the availability and possible location of the observed data (such as rainfall, and river flows). Little was available about the actual climatological and hydrological datasets that was expected to be compiled in a harmonised database for water resources modelling. The available water resources report described several types of surface water resources in Kenya, namely, rainfall, stream flows, lakes and wetland, ice and glaciers and oceans. Additionally, it was mentioned that the data required for hydrological modelling for Kenya is collected by several agencies including the Ministry of Environment and Natural Resources and the Department of Resource Surveys and Remote Sensing (DRSRS). However, the data required for hydrological modelling was missing. Similar to other places in the region, the meteorological stations have also suffered a major decline since the early 90's, although with the World Meteorological Organization (WMO), improvements are underway. To successfully accomplish the water resources modelling tasks, additional (daily) time series data sets will be required.

2.5. Republic of Sudan

The hydrological water resources in Sudan are mainly comprised of seasonal streams, mainly on the Nile system. The available water resources report was mainly descriptive of Sudan's shares of the Nile system. It was anticipated that more data could be obtained from the Meteorological and hydrological departments of Sudan and any other department responsible for archiving the historical meteorological and hydrological data. Compared to other country reports, the Sudan report had little mention of the possible sources of climate and hydrological data. To successfully accomplish the water resources modelling tasks, additional datasets were and other likely sources of climate and hydrological data for water resources modelling. Potential sources could include national archives of the HYDROMET Project, TECCONILE, and the NBI projects.

2.6. Republic of Uganda

Reports briefly covered (qualitatively) the status of the existing water resources. Little was available about the actual data (time series) that was expected to be compiled in a harmonised database for water resources modelling. Additional data was expected to be collected in order to model the surface water resources of the major catchments. It was mentioned that only 75 out of 566 (13%) of the rainfall stations are functional. To successfully accomplish the water resources modelling tasks, additional (daily) time series data sets were required. It is anticipated that the data can be obtained from the Meteorological Department of Uganda and the Directorate of Water Resources Management (DWRM); the two departments are reported to be the main agents responsible for archiving the historical data and availing it to the public.

2.7. Additional data sources

For successful implementation of the objectives, several sources of data relevant for the IGAD water resources modelling were required. These included national reports and other sources that are public and cover regions covering IGAD transboundary regions. Some of the datasets that were required for water resources modelling (Training/simulation) are listed as follows:

- **Meteorological datasets:** Meteorological and hydrological datasets for several key stations in IGAD basin were required, mainly on daily time-scales. These include daily time-series for precipitation, temperature, humidity, solar radiation, wind, net radiation, and humidity and others;
- **Stream flow data:** Complete daily stream flow records at several flow stations were required for successful model simulations. The challenges were that most stations' databases were significantly incomplete with gaps ranging over periods of months to years over the historical period. The availability of stream flow data was critical for this assignment given that effective calibration is dependent on long-term flow series. In general, there is a tendency to have limited gauges over the high altitudes.
- **Elevation data:** A digital Elevation Model (DEM) of at least "90 m" resolution was required. This was obtained from the Shuttle Radar Topography Mission (SRTM) archive (www.srtm.csi.cgiar.org/). Most basins envisaged for the IGAD areas were relatively mountainous.
- **Soils, Geology, and Land use coverage:** Soils coverage maps were obtained from the digital soil map of the world, developed by the Food and Agriculture Organization (FAO) (FAO, 1974, 1997). Geological formation data was acquired from FAO. Land cover and land use coverage was obtained from the FAO biomass studies. Soil maps were obtainable for 5,000 soil types comprising two layers (0 – 300 mm and 300 – 1000 mm depths) at a spatial resolution of 10 km.

A number of other web-based sources of data were available for the assignment. A few of these are briefly listed here:

1. IGAD Spatial datasets:
 http://www.igad-data.org/index.php?option=com_docman&task=cat_view&gid=3
2. GIS, Remote Sensing, Spatial and Hydrological data sets
 http://free-gis-data.blogspot.com/2009/04/aster-global-digital-elevation-model.html

3. Digital Elevation Data
http://www.gdem.aster.ersdac.or.jp/register.jsp

4. The Food and Agriculture (FAO) website (Africover)
http://www.africover.org/

5. WHO / UNICEF Joint Monitoring Programme for Water Supply and Sanitation at http://www.wssinfo.org/resources/documents.html.

6. Country specific sites providing water resources information
Djibouti: http://www.afdevinfo.com/htmlreports/org/org_45502.html
Ethiopia: http://www.mowr.gov.et/index.php?pagenum=11&pagehgt=1430px
Kenya: http://www.water.go.ke/index.php?option=com_docman&Itemid=62
Sudan: http://www.moiwr.gov.sd/irrigation/english.php
Uganda: http://www.mwe.go.ug/DWRM/55/Publications-Reports

For IGAD countries, other organisations from which information related to water resources and hydrological modelling may be obtained mainly include: the ministries dealing with quantification and monitoring of water resources, agriculture, natural resources and environment.

3. Infilling of data gaps

For effective hydrological modelling in the IGAD basins (to be described in Chapter 3) additional climatological and hydrological datasets were collected on a daily time step. One possibility of infilling the missing datasets was to use historical climate variables derived from global climatological datasets for the IGAD region, however, this required the derivation of climate variables that can be used to stochastically generate daily climate variables.

4. Hydrological challenges in the IGAD basins

The major transboundary basins defined for this project vary in size and a country-based summary of the basic water balance components has been briefly discussed. The different sub-basins also vary in terms of basic hydrology and also include marginal regions such as arid and semi-arid regions, wetlands, and other natural vegetated areas.

Several Challenges that existed and are likely to worsen in the future include climate change and land use change. For water resources modelling in the IGAD Sub-region, several other challenges exist, including:

- Inadequate infrastructure for water resources and hydro-meteorological management to support effective surface water and groundwater resources monitoring
- Variable and irregular climatological and hydrological data availability: Availability of surface and groundwater resources was limited for most basins being modelled
- Variable rainfall patterns, leading to challenges in rainfall and water resource management
- Influence of climate and land use change: deforestation and land use management

practices have a great influence on the hydrology and water resources hydrological simulation

- Limited information of monitoring and management of water resources systems in the IGAD Sub-region.

The next chapter presents basic concepts of hydrological modelling and then briefly describes the scientific modelling of the hydrological challenges in the IGAD Sub-region.

3

REVIEW OF THE SWAT HYDROLOGICAL MODEL AND PARAMETER ESTIMATION METHODS

1. INTRODUCTION TO HYDROLOGICAL MODELLING

All hydrological models are a simplification of the real world and in most cases all models are to some degree lumped, whereby the mathematical set-up and parametisation is aggregated in space and time. Consequently, model parameters do not often correspond directly to measurable entities, and in general, can only be estimated indirectly, for example through calibration. Catchment models are mainly classified according to process description as empirical, conceptual or physically based. That is to say, physically based models include parameters that may be associated with physical properties of the catchment, and hence are attractive for representing physical changes such as those due to land use and climate changes.

However, physically-based distributed models pose the disadvantages of over-parameterisation and scale issues which complicate the search for a truly physical based description of processes and data requirements. In contrast, conceptual models are generally much simpler and model parameters defined by simple calibration and/or regionalisation, however, several challenges arise due to data and model structure limitations.

Various catchment models contain a mixture of physically based components, conceptual components, and empirical components, hence the best parameter estimation approach was not clear-cut especially when good datasets rarely exist. A common feature of both conceptual and physically-based models is that a clear identification of the model structure has to be specified prior to modelling and a key assumption usually employed is that the pre-selected model structure is adequate.

For the IGAD sub basins, the water resources modelling assignments required the development of rainfall-runoff models to simulate the water resources in the IGAD Sub-region and also provide a future possibility of studying the impact of land use change and climate change on water resources. After a detailed literature review, the chosen hydrological model selected to meet these objectives was the Soil Water Assessment Tool (SWAT, Arnold et al. 2005) and a summary of the model features is described in the following sections.

2. The Soil Water and Assessment Tool (SWAT) model structure

SWAT is a physical based hydrological model developed by Arnold et al. (1998; 2005). Recent developments of the SWAT model components include the ability to simulate the model as a lumped or distributed structure. Additionally the model has the ability to estimate uncertainties for hydrological simulations. This assignment considered a simple hydrological conceptual structure in a semi-distributed way to represent the basic understanding of the principle of continuity (or mass balance) for the IGAD hydrological basins. Inputs to the mass balance will be formed of precipitation and temperature and the outputs are represented by evaporation, transpiration, discharge and groundwater recharge.

A semi-distributed conceptual model SWAT2005 (Arnold et al. 2005), a model that is coupled to ArcGIS9.2 was applied in the assignment. The model makes use of the GIS environment to prepare input/output files as well as to perform model manipulations. Building a hydrological model involves several strategies including: pre-processing of the required input raster datasets (DEM, soil and land use); delineation and selection of a test basin to calibrate; estimation of a priori parameter values and finally, model structure conceptualization, calibration and validation.

For the several IGAD Sub regions, multiple sub-basins were selected based on the Hydrologic Response Units (HRUs); mainly consisting of dominant land use types and soil types. The delineation was done using a 90m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (http://srtm.csi.cgiar.org/). A drainage area of 200 km2 was preferred as the threshold for the delineation of sub basin (i.e. all sub-basins are larger than this size). This threshold was based on the resolution of the anticipated available information, the required spatial accuracy in representing land use class per sub basin, and the practicality of a SWAT project size.

2.1. Model Uncertainty, sensitivity analysis, and calibration and validation Model Set-up Calibration/Verification/Simulation

A-priori model parameters were specified at two spatial scales, some parameters were specified for the entire basin while others were specific for each sub-basin. A-priori model parameters were derived based on Arnold et al. (1998) and Neitsch et al. (2000, 2005). An explanation of these parameters was beyond the scope of this report and only a limited description is given here:

- Channel morphology parameters (sub-basin scale) were associated with channel morphology and were derived from the DEM datasets using the SWAT-ArcGIS interface. These include channel length and main channel slope.
- Soil parameters were derived from the USGS Global Land Use Land Cover Characterization (GLCC) database for these two layers at a spatial resolution of 10 km (http://edcsns17.cr.usgs.gov/glcc/glcc.html). The soil parameters specified included: soil depth (mm) bulk density (g/cm3), soil albedo, salinity, average available water capacity, saturated conductivity (mm/hr), organic carbon content (%), clay content (%), sand content (%), and rock fragment content (%). This provided a very approximate representation since the vertical soil structure may be more detailed and defined by more than the two-layers structure used. The FAO soil structure is formed of two layers, with the top layer 300 mm deep and the bottom layer a further 1,000 mm deep.

- Land use database: Land use related parameters (e.g. canopy height, canopy storage, biomass-energy ratio, optimum growth temperature, maximum potential leaf area index, minimum leaf area index, maximum stomata conductance and minimum canopy height, etc.) were based on the crop database that is part of the SWAT environment - providing an approximate representation for IGAD Sub-region. A selection of a-priori land cover/plant parameters was done. The curve number parameter was applied for each HRU, based on land use, soil and slope within the drainage sub-basins. For each land use type, up to four curve numbers were possible, depending on the soil drainage efficiency (also referred to as hydraulic classification). Low CN2 values indicate higher soil drainage capacities, where as impervious or concrete surfaces may have CN2 values as high as 98.

Given that most parameters are difficult to measure, allowing for them all to vary in the calibration would mean many degrees of freedom. Ideally a sensitivity analysis should be done for these parameters. Additionally, for each case study sub-basins were allowed to have only one (dominant) land use and soil type. Based on the available information, parameter sensitivity analysis, calibration, validation and uncertainty analysis can be performed based on stream flow data.

The calibration strategy that was proposed for this study involved several steps: Based on topography, the watershed is divided into three different regions assumed to have similar hydrological response. This helps define spatial variability of parameters and hence parameter regionalisation. The hydrological regimes of the IGAD Sub-region are mainly controlled by basin topography and land cover resulting in the following three landform classes:

- steep slopes, responsible for the fast surface runoff;
- gentle slopes to flat plains, covered by mixed land use mainly formed of wetlands, which creates storage of surface runoff and
- gentle slopes to flat plains without wetlands, with somewhat intermediate response between the steep slopes and the wetlands.

A sensitivity analysis was performed to identify the most sensitive parameters, using the Latin Hypercube-One-at-a-time sampling (LH-OAT) method. The result from this step yielded the ranking of parameter sensitivity. The most sensitive parameters were then selected for calibration using a semi-automated algorithm, referred to as SUFI-2. The SUFI algorithm was run as a system analysis tool as shown in Figure 6.

Uncertainty in the simulated stream flows was quantified using the 95% prediction uncertainty (95PPU). Two indices that were used to quantify the goodness of calibration/uncertainty performance are the «P-factor» and the «R-factor» based on the SWAT system analysis optimisation procedure for calibration and validation (Abbaspour, 2008). Stream flow data available for the calibration was treated with a 10% error during the optimisation. A systematic approach to calibration and validation is shown in Figure 6.

Given the quality of the data for the IGAD Sub-region, hydrological modelling presented many challenges including the sensitivity to the hydrology to available climatological inputs and the final parameter space. Simulated variables in blue water, green water flow and green water storage were examined in the context of historical estimates. Generally, it was reasonable to assume higher confidence in model simulations with the least bias (≈ 1) in simulating the historical climate.

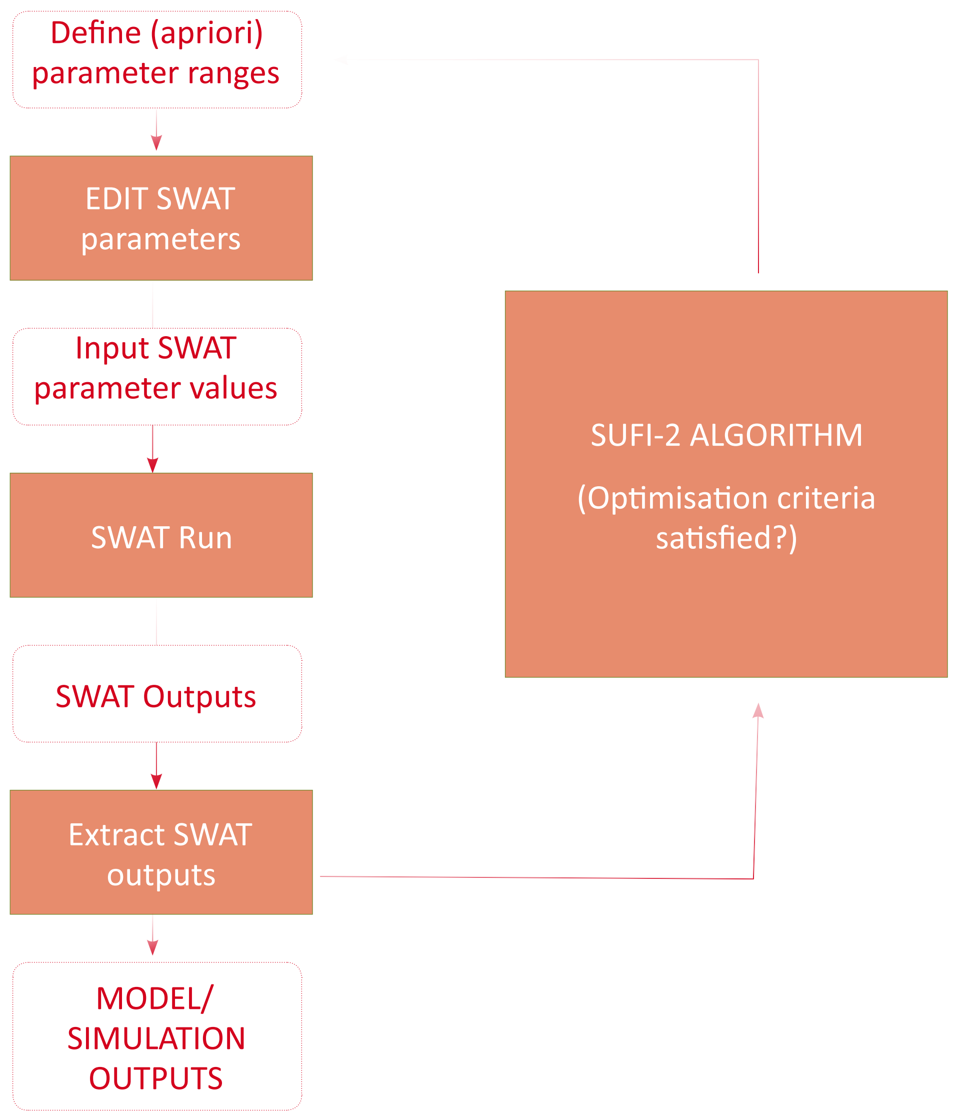

Figure 6: A schematic outline of the different steps in model calibration using SUFI-2

The simulation strategy adopted involved several processes including the following:

- Run the SWAT model using current climate, simulating 30-year time series of monthly water resources variables (including stream flows, evapotranspiration, soil water, deep aquifer recharge and water yield) and estimate the average annual runoff from these time series using the calibrated hydrological model. This was done by an ensemble of several precipitation simulations.
- Sum the simulated water resource components for each sub-basin to estimate basin-

scale water resource averages. Given the differences in the physical and hydroloclimatological characteristics over the IGAD Sub-region, each sub basin response was evaluated separately and averaged to get the entire basin response. Spatial patterns in the simulations in water resources were also presented.

- To evaluate the uncertainty of propagation, the combined impact of downscaling with the hydrological parameter uncertainty of the IGAD hydrological model was considered. For each time slice, several 30-year daily hydrological simulations were used to estimate total uncertainty using a simulation ensembles approach. The uncertainty was considered to result from using inputted climate data and parameter uncertainty.

3. Expected Simulation Components for Water Resources Modelling

Given the type of simulation model that was anticipated for Water Resources Modelling, a number of hydrological components were focused on for calibration/validation/simulation, however the lack of daily climatic and hydrological datasets limited this. Hence attention was focused on simulation of Stream flow, Potential Evapotranspiration (PET), Actual Evapotranspiration (AET), soil moisture (SM) and flow paths and travel times through the aquifer system.

4

SWAT MODEL CALIBRATION AND VALIDATION FOR IGAD SUB-REGION

1. INTRODUCTION

A number of transboundary basins for the IGAD Sub-region were set-up. The main challenge in the process was the availability of long-term flows for the several trans-boundary basins: Success in the modelling highly depended on the availability of hydrological data required for model setup, calibration and validation. The different transboundary basins considered for hydrological modelling are summarised in Figure 9.

2. SUMMARY OF AVAILABLE HYDROLOGICAL MODELLING DATASETS

A Digital Elevation Model (DEM) was obtained from the public domain. This was applied to delineate the IGAD-hydrological basins. Most of the datasets provided were of monthly to annual time-step. However SWAT model needs rainfall and temperature datasets at daily time-step. As such, additional hydrological time-series datasets were required for the successful implementation of water resources modelling and the success of the water resource modelling highly depended on the availability of hydrological and climatological time-series for several IGAD sub basins.

To facilitate the hydrological modelling exercise, additional CRU datasets were obtained, including precipitation and temperature at several locations in the IGAD locations (Figure 7 and Figure 8).

3. HYDROLOGICAL MODELLING STRATEGY

3.1. Selection of test basins

A number of trans-boundary basins were considered for hydrological simulations. The hydrological basins were delineated into several sub-basins in order to ensure representative hydrological simulation (Figure 9 and Figure 10).

3.2. Hydrological Model Delineation

Hydrological basins were delineated into multiple sub-basins, which were further subdivided

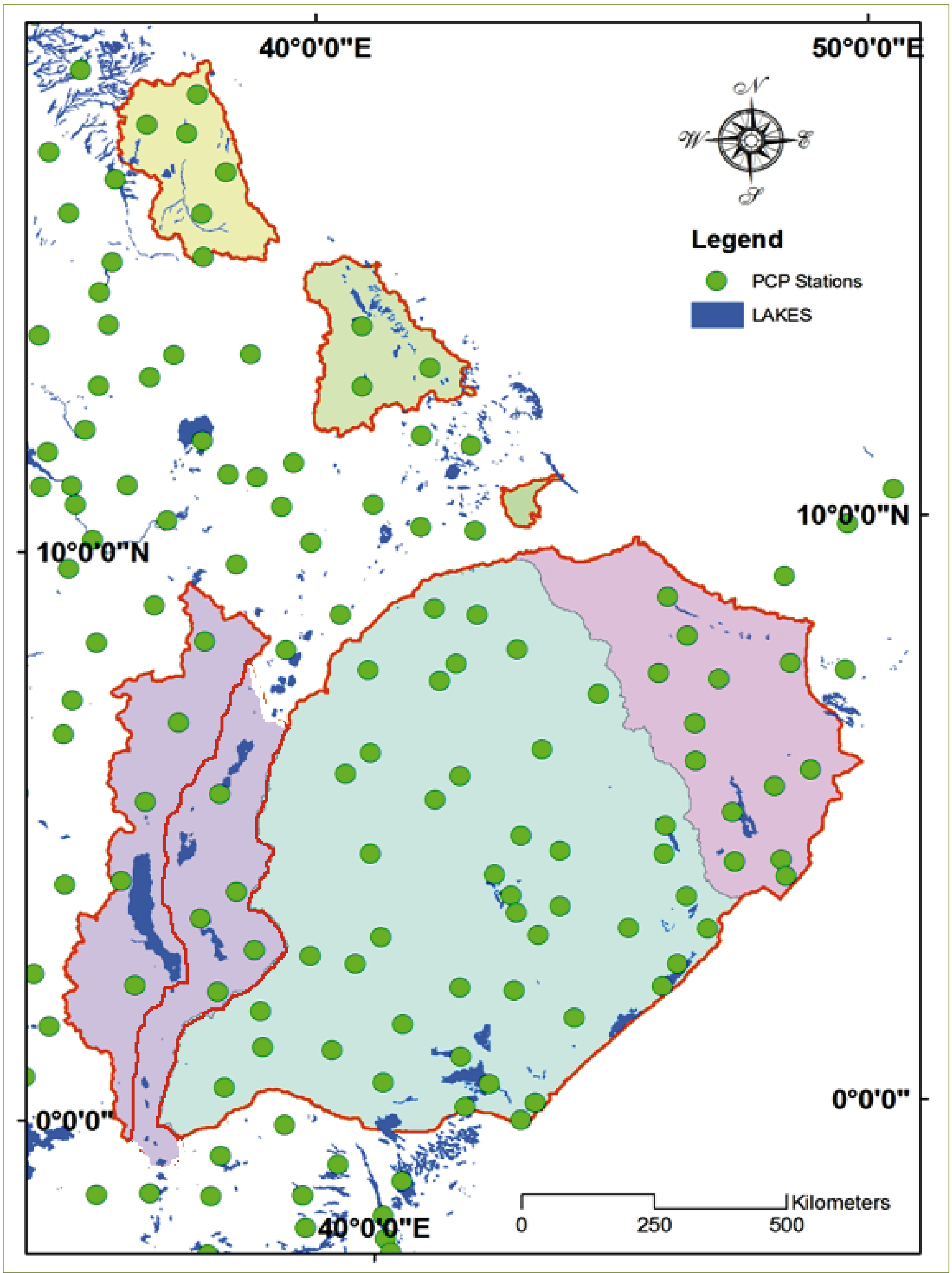

FIGURE 7: Location of Precipitation Monitoring Stations

into Hydrologic Response Units (HRUs). Each HRU consisted of dominant land use types and soil types. The delineation was based on a 90 m resolution obtained from the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (http://srtm.csi.cgiar.org/). A drainage area of 200 km² was selected as the threshold for the delineation of a sub basin (i.e. all sub-basins are approximately 200 km2). This threshold was based on the resolution of the available information, the required spatial accuracy in representing land use class per sub basin, and the practicality of a SWAT project size. The basin sharing countries are shown in Table 2 and a map of the delineated sub-basins is shown in Figure 9 and Figure 10.

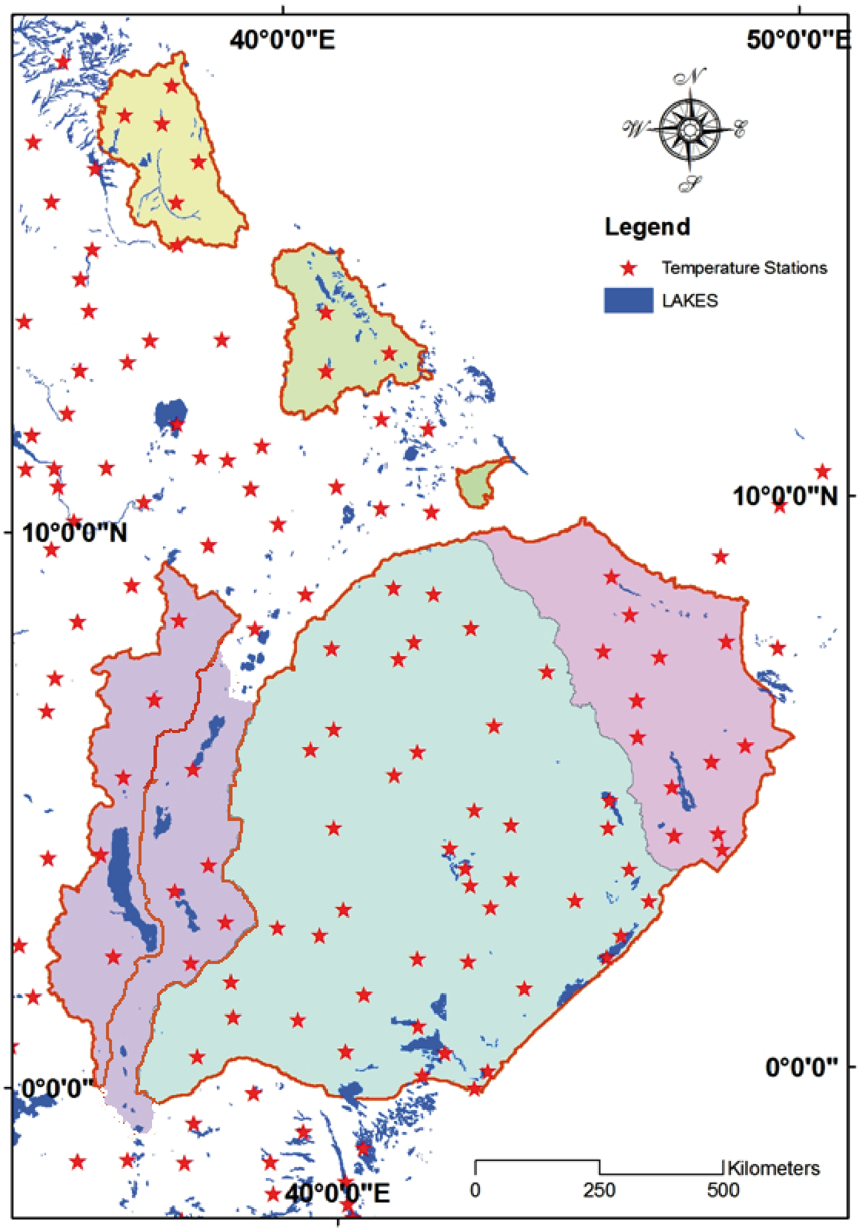

Figure 8: Location of Temperature Monitoring Stations

Basin Name (Figure 1)	Basin Number	Catchment Area (km^2)	Sharing Countries
Danakil	TB-1 (1)	61,549	Ethiopia, Eritrea
Gash Baraka	TB-2 (2)	66,549	Eritrea, Sudan
Juba Shebelle	TB-3 (3)	753,202	Ethiopia, Kenya, Somalia
Ogaden	TB-4 (4)	207,363	Ethiopia, Somalia
Turkana Omo	TB-5 (5)	140,052	Ethiopia, Kenya, Sudan, Uganda
Ayesha	TB-6 (6)	4,963	Ethiopia, Somalia

Table 2. IGAD Transboundary basins

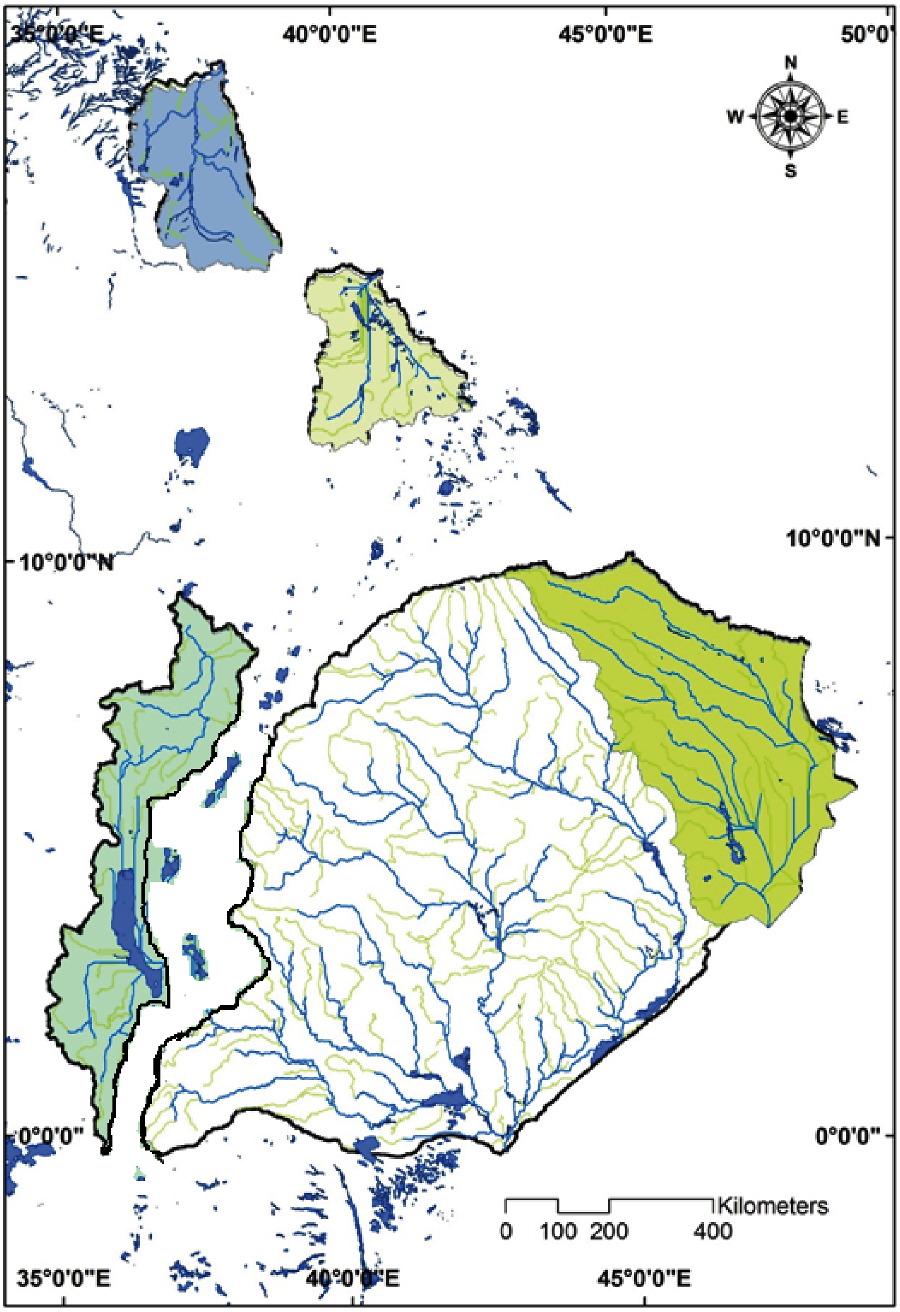

FIGURE 9: Major Hydrological Stream Network for the delineated IGAD hydrological basins.

3.3. Selection of hydrological components for hydrological modelling

For hydrological simulations several components that were required for simulation included surface runoff, evapotranspiration, soil water and recharge. Given the limited information that was available regarding wetland characteristics and the several small lakes in the basins, the simulation of lakes and wetlands was compromised using linear reservoir set-up.

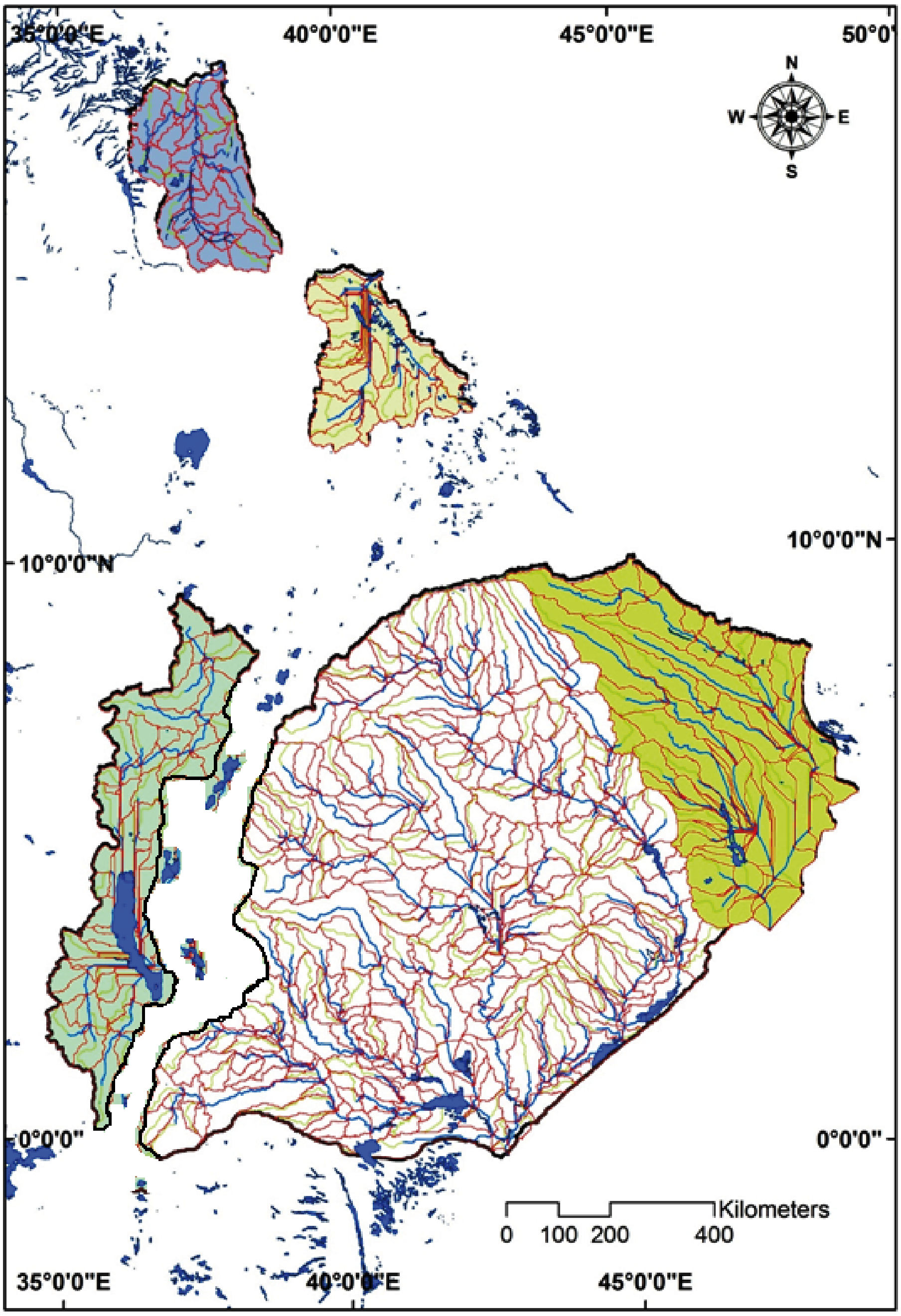

Figure 10: Delineated Transboundary Sub-basins for IGAD countries and the Major Lake/River System

3.4. Estimation of a-priori parameter values

A-priori model parameters were specified at two spatial scales: (a) the entire basin level and (b) at sub-basin level. Each sub-basin had several HRUs. A priori model parameters were derived based on Arnold et al. (1998) and Neitsch et al. (1999). This involved several components including channel morphology parameters; soil structures (soil parameters derived from the USGS Global Land Use Land Cover Characterization (GLCC) database for the two layers at a spatial resolution of 10 km (http://edcsns17.cr.usgs.gov/glcc/glcc.html).

The soil parameter specified included: soil depth (mm) bulk density (g/cm^3), soil albedo, salinity, average available water capacity, saturated conductivity (mm/hr), organic carbon content (%), clay content (%), sand content (%), and rock fragment content (%). This provided a very approximate representation since the vertical soil structure was more detailed and defined by more layers than the two-layers structure used.

Land-use related parameters (e.g. canopy height, canopy storage, biomass-energy ratio, optimum growth temperature, maximum potential leaf area index, minimum leaf area index, maximum stomata conductance and minimum canopy height, etc.) were based on the crop database that is part of the SWAT software - providing an approximate representation for the IGAD Sub-region.

3.5. Model calibration strategy

Given that most parameters are difficult to measure, allowing for them all to vary in the calibration would mean many degrees of freedom. Ideally a sensitivity analysis was carried out for these parameters. Based on the available information, parameter sensitivity analysis, calibration, validation and uncertainty analysis was performed based on available stream flow data.

3.6. Parameter sensitivity analysis

The purpose of sensitivity analysis is always to indentify how sensitive hydrological parameters are in determining stream flow (upstream of a particular basin location). Hydrological parameters that influence the flow hydrograph were used in the sensitivity analysis and the eight most sensitive parameters were selected for calibration. Some of the parameters important for the calibration, in terms of fitting the hydrograph include; Surface flow parameters; Soil Water Groundwater flow parameters and Channel parameters.

3.7. Limitations and likely sources of uncertainty

Due to data constraints, a detailed regionalization scheme based on identifying relationships between parameter value and catchment descriptors was not feasible. However, a simplified regionalisation scheme was tested by transferring model parameters between basins. The implication of this was that in the absence of gauged sub basins data, model parameters may not be transferrable to ungauged sub-basin within the IGAD Sub-region, although this does not compromise the need to carry out regionalisation of model parameters based on physical catchment descriptors.

4. RECOMMENDATIONS FOR HYDRO-METEOROLOGICAL MONITORING EQUIPMENT

A number of equipment has been recommended for hydro-meteorological data collection. Most equipment tend to measure multiple variables and in most cases and the successful use of this equipment depends on the detailed intended purpose. Most of the equipment is modern, electronic and operators may require training before being able to operate the equipments.

The following lists briefly give a list of anticipated equipment for hydro meteorological operations:

1. Electronic Hydro-Meteorological Equipment:
   - Acoustic Doppler Current Profiler (ADCP) for river flow measurement;
   - Pressure Transducers for water level recording in volatile rivers;
   - Automatic Weather Stations;
   - Automatic evaporation measurement stations.
2. Water Level and Flow Equipment:
   - Level Indicator & Logger
   - Digital Water Depth Indicator
   - Transducer Water level Recorder Water Discharge Recorder
   - Propeller Pigmy Current Meter and Standard Propeller Current Meter
   - Graph Water Stage Recorder

The different locations of the several IGAD basins experience different rainfall depth over the year, hence different techniques aim at obtaining representative temperature and rainfall over the area to which the measurements refer. However there is a critical; need to ensure accurate measurements of precipitation. To the same effect the choice of the location determines how accurate the measurements are, given the choice of site, the type of gauge, the means of preventing loss by evaporation and the effect of wind and splashing. As an example, the precipitation gauge location determines several factors such as the impact due to wind, the obstacles around the gauge in term of accurate estimations and given that precipitation occurs in form of snow, wind can have adverse effects, although windshields have shown some effectiveness in reducing precipitation measurements errors.

1. Non- Recording gauges
   - General gauges: These are non-recording gauges used by most hypogeal and metrological purposes
   - Standard gauges: Usually considered as ordinary gauges for daily readings;
   - Storage gauges: Used for the measurements of total seasonal precipitation especially for remote places
2. Recording gauges

These types of gauges in general use the weighting type, float type or tip-ping bucket type and normally include the following types

- Weighting type: the weight of the received precipitation is measured continuously
- Floating type: the rainfall is fed into a float chamber containing a float whose vertical movement is transmitted to a recorder

- Tipping bucket type: the precipitation is lead from a two compartment metal container to a collecting funnel and the collecting bucket tips after a certain amount of precipitation is recorded
- Rainfall intensity recorders: these are not recommended for general purpose given their complexity and yet intensity can be easily determined.

In summary the different types of precipitation gauges that could be considered include recording and non-recording gauge for Rainfall Monitoring (as mentioned above these mainly include Ordinary Rain Gauge; Transducer Rain Gauge; Non-Recording Rain Gauge; Graph Recording Rain Gauge; Tipping Bucket Rain Gauge; Digital Wireless Rain Gauge; Data-logger based Rain Gauges).

Whatever the method chosen for recording precipitation, it is crucial that the right areal coverage is representative of the catchment where the gauge is installed. Recent developments have also provided means of precipitation measurements by radar systems. This permits the observation of the location and movement of areas of precipitation for areal extents of 40 - 200 km depending on the radar characteristics. However several factors affect this development and to mention but s a few, these include: precipitation type; bean width; refraction of beam; atmospheric attenuation and range attenuation. Precipitation measurements can also be conducted by satellite means, by the use of images registered by scanners or by imaging microwave radiometers, however, imaging microwave radiometers tend to provide limited amount of data and not commonly used operationally. A detailed outline of the measurements methods for other weather parameters is given in the WMO guide to Meteorological instruments and methods of observation. For the IGAD basins, Figure 11 shows the proposed location of weather station for the IGAD basin.

5. HYDROLOGICAL MODEL RESULTS

The Soil Water and Assessment Tool (SWAT) model was chosen to model the Water resources. Although physically based models such as SWAT are currently widely used and offer very detailed results, the general limitation is always that, in general, physically-based distributed models pose the disadvantages of over-parameterisation, scale issues which complicate the search for a truly physical based description of processes. Often, such models may not always provide a good fit to the historically measured data for a number of reasons, including structural errors, parameter identification errors and data errors - because the description of the processes modelled may not be accurate or complete in the model, all models are imperfect and even when measured physical parameters are used, they are not error free.

Model calibration involved adjusting parameter values until the model result satisfactorily matched the observed reality. The procedure can be either manual or automated and the success of a manual calibration depends on the skill and expert knowledge of the modeller, while the use of automatic calibration may be favoured because it is more objective, more efficient in terms of exploring the range of possible parameter values (the parameter space).

The IGAD delineated sub basins have different physical, climatic and hydrological

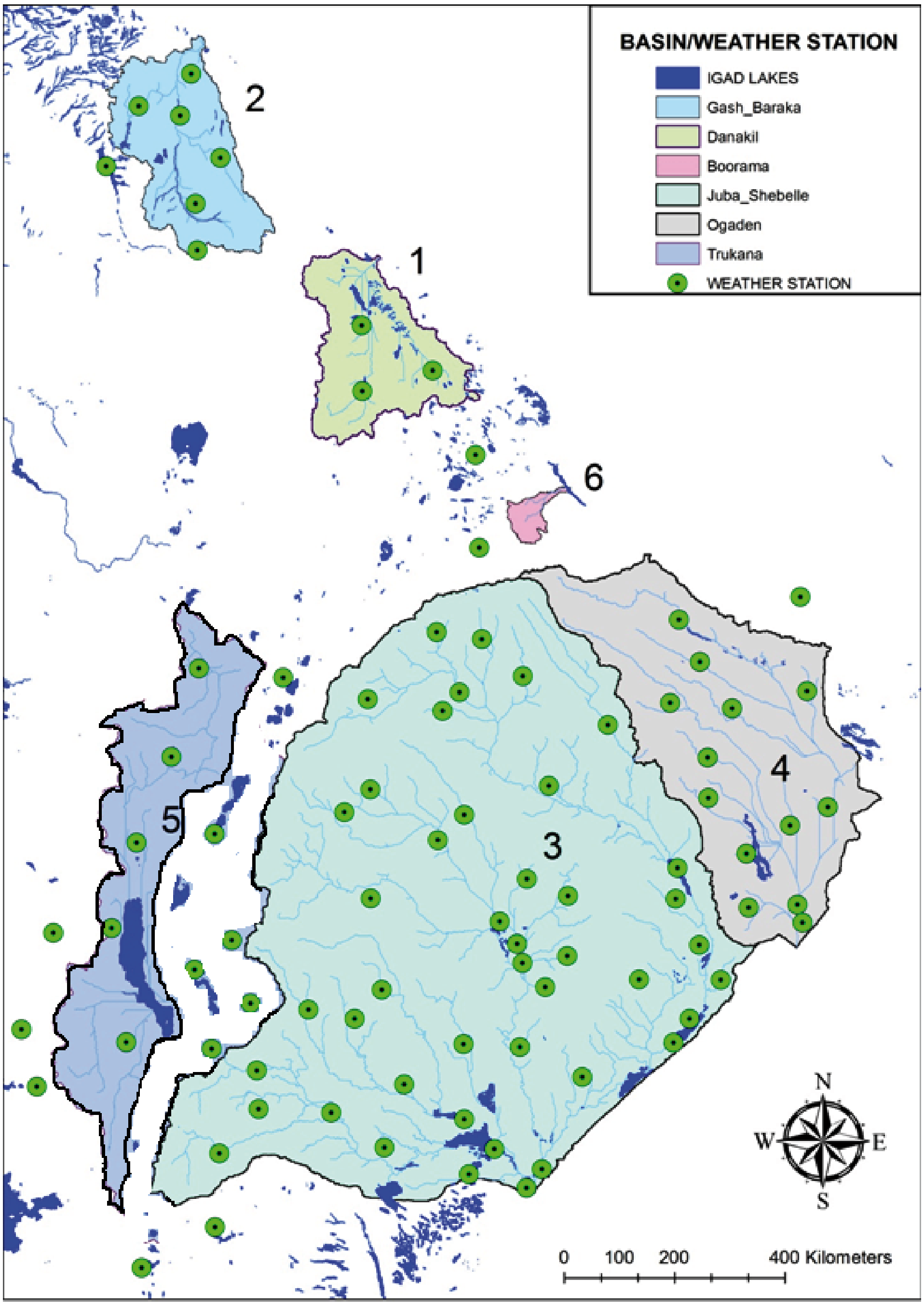

Figure 11: Proposed Locations of Proposed IGAD Weather Stations.

characteristics and therefore the sensitivity of the runoff to precipitation will vary spatially. The basins have varying climatologic regimes and most are typically dry and warm. A distributed HRU based model set-up was deemed to be most useful for the IGAD water resources study. The main limitations were data constraints and the complex topography of the basin. Stream flow records are barely available to facilitate calibration.

To facilitate these limitations model set-up considered a simple hydrological conceptual structure in a semi distributed way to represent the basic understanding of the principle of continuity (or mass balance) for the IGAD transboundary basins. Inputs to the mass balance were formed of precipitation and the outputs were represented by evaporation, transpiration, discharge and other groundwater related components such as recharge, soil moisture and others. A semi-distributed conceptual model, the SWAT2005 model that is coupled to ArcGIS9.2 was selected for this study. The model makes use of the GIS environment to prepare input/output files as well as perform model manipulations. Building a hydrological model continues and involves pre-processing of the required input raster datasets (DEM, soil and land use); delineation and selection of a test basin to calibrate; estimation of a priori parameter values and finally, model structure conceptualization, calibration and validation strategy. Successful completion of all these steps highly depends on the availability of data and time limits.

Results of the simulated average monthly stream flows and evapotranspiration are shown in Figure 12 and Figure 13 respectively. The results were obtained at basin-wide scales (i.e. basin averages) and should be interpreted with caution. Observed flows on a daily scale were still missing, hence minimal calibration was effectively carried out to obtain the results presented here. However, the results give a general overview of the expected water resources components for the IGAD transboundary basins.

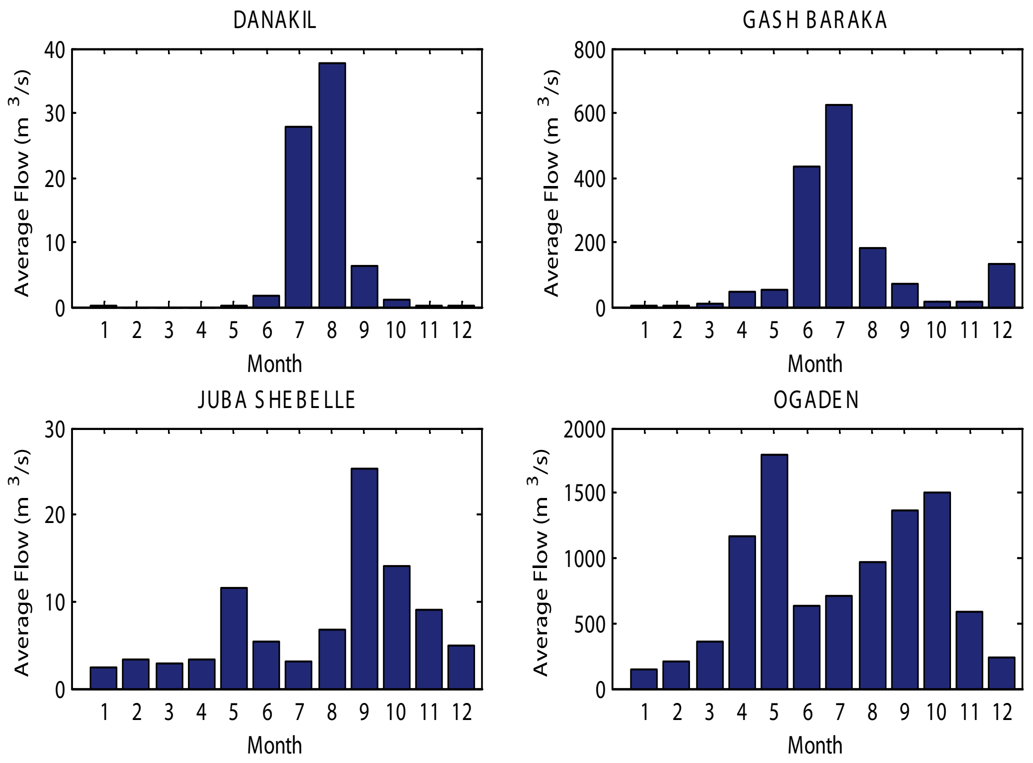

FIGURE 12: Simulated Average Monthly Stream Flows (1971 - 1990)

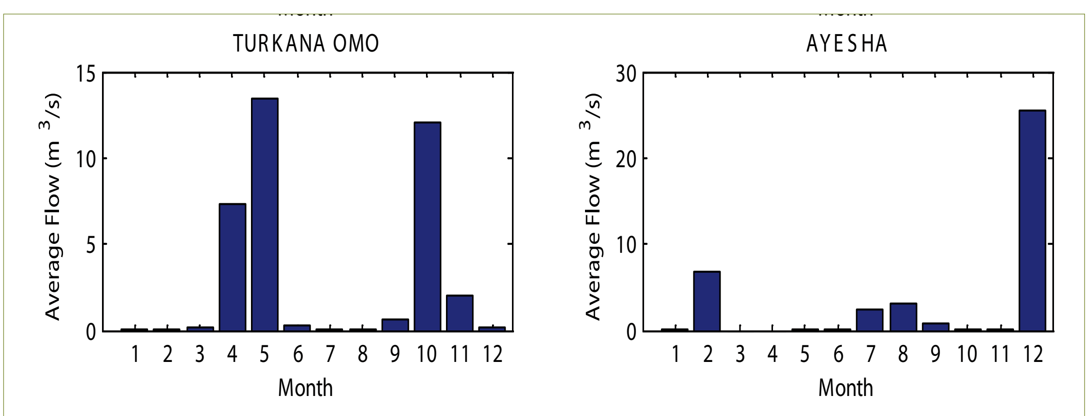

FIGURE 12 (continued): Simulated Average Monthly Stream Flows (1971-1990)

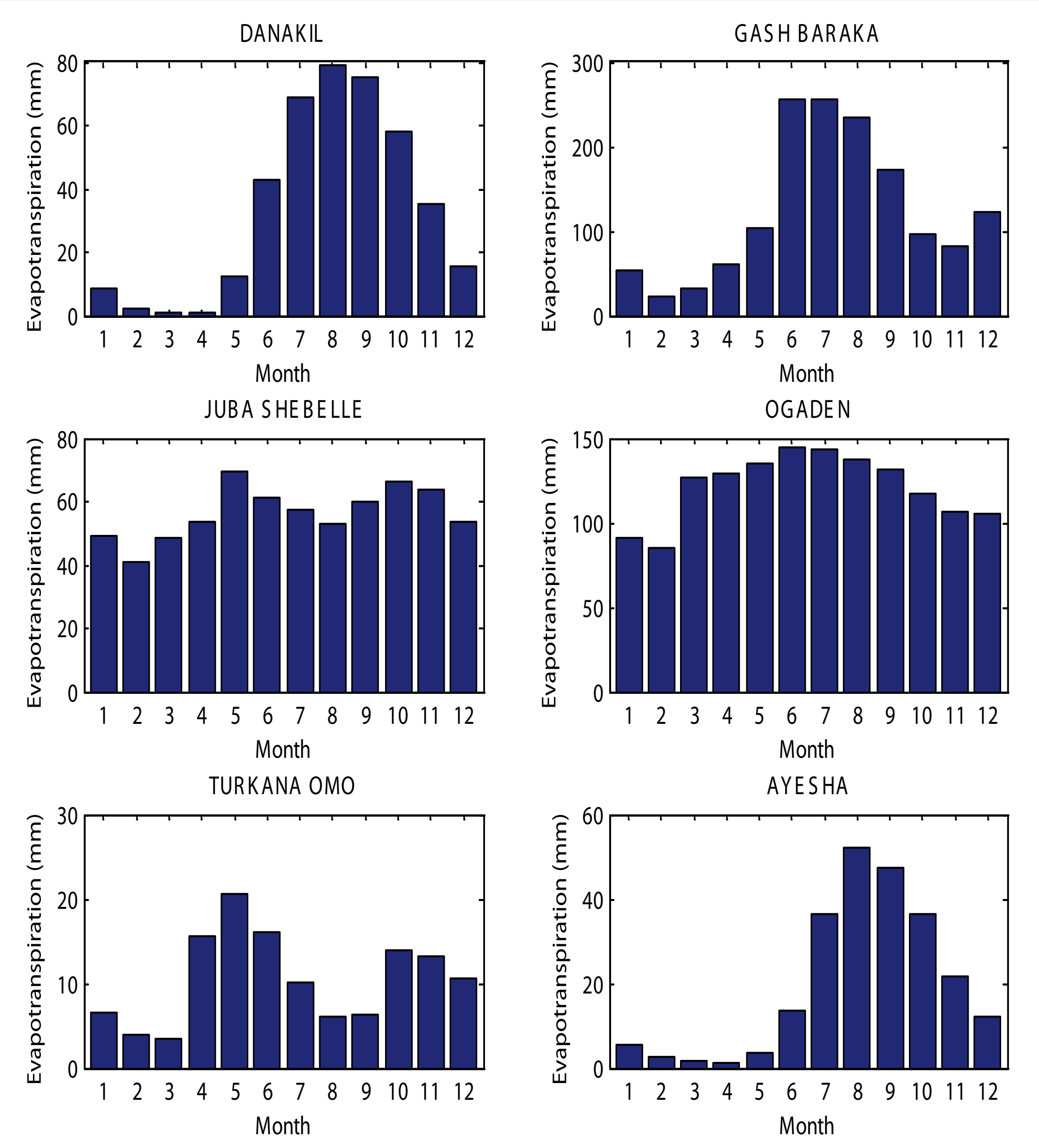

FIGURE 13: Simulated Average Monthly Evapotranspiration (1971-1990)

6. SIMULATED WATER RESOURCE COMPONENTS FOR IGAD TRANSBOUNDARY BASINS

A summary of the simulated water balance components including Precipitation (PCP), Potential Evapotranspiration (PET), Evapotranspiration (ET), Soil Water (SW), Surface Flow Depth (SURQ), Recharge/Percolation (PERC), Overland Surface Flow (SURQ), Groundwater Flow (GWQ), and Water Yield (WYLD). For each IGAD basin modelled in this project has been summarised and presented in Table 3 to Error! Reference source not found.. However, interpretation of these summaries should be done cautiously given that despite the minimal calibration due to the general absence of daily stream flows to facilitate effective calibration, the quantities have been presented as basin wide depths (in «mm») to facilitate comparison and future accurate estimation/calibration.

MON	PCP (mm)	PET (mm)	ET (mm)	SW (mm)	PERC (mm)	SURQ (mm)	GWQ (mm)	WYLD (mm)
JAN	6.2	168.9	8.5	19.1	0.2	0	0.3	0.3
FEB	8.5	173.9	13.7	13.5	0.2	0.1	0.1	0.3
MAR	17.2	277.6	27.6	2.3	0.3	0.5	0.2	0.7
APR	15.5	275.9	14.7	2.1	0.2	0.6	0.2	1
MAY	13.1	256.4	13.3	1.5	0.2	0.1	0.2	0.3
JUN	12.2	263.6	10.9	2.8	0	0	0.1	0.2
JUL	56	274.7	32.4	19.6	3	3.1	0.5	3.9
AUG	68.9	249.9	39.3	32.4	6.3	9.6	2	12
SEP	17.1	226.9	23.2	25.3	0.4	0.6	3.2	4
OCT	4.6	226.6	9.6	20.2	0	0	1.7	1.7
NOV	6.2	197.1	6.8	19.5	0.2	0	0.5	0.6
DEC	7.7	168.4	7.3	19.2	0.3	0.1	0.3	0.5
ANNUAL (mm)	233.2	2759.9	207.4	177.5	11.3	14.7	9.3	25.5
ANNUAL (km³)	15.9	187.7	14.1	12.1	0.8	1.0	0.6	1.7

TABLE 3. Simulated Monthly Water Resources for Danakil basin (mm spread over 68,000 km², unless otherwise stated).

MON	PCP (mm)	PET (mm)	ET (mm)	SW (mm)	PERC (mm)	SURQ (mm)	GWQ (mm)	WYLD (mm)
JAN	6.8	156.7	8.4	18.7	0.3	0.1	0.6	0.7
FEB	3.2	162.9	7.7	14.1	0	0	0.3	0.3
MAR	5	265.4	14.8	4.2	0.1	0	0.1	0.2
APR	7.9	275.9	8	3.3	0.6	0.2	0.2	0.4
MAY	14.9	263.1	10.8	4.1	1.6	1.5	0.5	2.1
JUN	23.7	273.9	15.1	8.6	2.4	1.6	1	2.7
JUL	65	274.2	27.7	20.9	8.7	15.1	2.7	18
AUG	64.7	257.2	29.4	27.2	8.8	19.9	5.4	25.5
SEP	21.2	237.4	19.6	24.7	1.7	2.5	5.7	8.3
OCT	10.4	227.6	13.4	20.2	0.8	0.6	3.2	3.9
NOV	8.8	192.6	10.3	18.5	0.1	0.1	1.2	1.4
DEC	10.5	161.2	9.3	18.5	0.8	0.3	0.6	1
ANNUAL (mm)	242.1	2748.1	174.5	183	25.9	41.9	21.5	64.5
ANNUAL (km^3)	16.0	181.4	11.5	12.1	1.7	2.8	1.4	4.3

Table 4. Simulated monthly water resources for Gash Baraka basin (mm spread over 66,000 km^2, unless otherwise stated);

MON	PCP (mm)	PET (mm)	ET (mm)	SW (mm)	PERC (mm)	SURQ (mm)	GWQ (mm)	WYLD (mm)
JAN	11.5	175.9	15.7	46.2	1.4	1	2.7	3.7
FEB	13.2	179.8	24.7	31.8	1.3	1.4	1.6	3
MAR	35.4	265.8	40.9	20.4	2.6	3	1.6	4.7
APR	114.9	220.2	60.3	46	11.7	16.1	3.1	19.2
MAY	95.6	213.2	54.7	55.4	11.2	19.7	7.2	26.9
JUN	27.7	217.4	31.8	45.8	2.6	3.2	7.9	11.2
JUL	29	225.1	24.5	42.8	3.3	4	5.3	9.4
AUG	29.8	222.1	21.3	41.9	4.5	4.6	3.8	8.5
SEP	37.3	203.7	22.3	43.8	5.8	7	4	11
OCT	73.7	192	36.2	56.5	9.7	14.3	5.4	19.7
NOV	49.8	164.5	34	61.1	5.8	5.1	6.4	11.6
DEC	17.6	163.3	23	53.1	1.5	1.2	5.5	6.7
ANNUAL (mm)	535.5	2443	389.4	544.8	61.4	80.6	54.5	135.6
ANNUAL (km^3)	429.5	1959.3	312.3	436.9	49.2	64.6	43.7	108.8

Table 5. Simulated monthly water resources for Juba Shebelle basin (mm spread over 802,000 km^2, unless otherwise stated).

MON	PCP (mm)	PET (mm)	ET (mm)	SW (mm)	PERC (mm)	SURQ (mm)	GWQ (mm)	WYLD (mm)
JAN	5.4	174	9.1	36.2	0.5	0.5	1	1.5
FEB	8.4	177.7	16.5	26	0.8	1.2	0.6	1.8
MAR	21.9	273	29.4	14.6	1.3	2.4	0.8	3.2
APR	82.3	244.9	47.7	33.5	4.4	10.5	1.4	11.9
MAY	86	226.2	50.9	47.3	5.4	15.1	3	18.2
JUN	21.2	226.3	27.5	35.9	2	3.4	3.8	7.2
JUL	23.5	237.5	17.9	33.7	3.1	4.5	3	7.7
AUG	29.6	230.8	18.6	34.7	4.5	5.3	3.1	8.5
SEP	38.1	208.5	21.6	38.7	4.6	7.5	3.6	11.1
OCT	64.1	201.7	33	50.6	5.5	12.9	4.3	17.3
NOV	24.2	180.4	23.5	46.2	1.7	3.5	4	7.6
DEC	7.5	167.5	13.6	39.6	0.4	0.4	2.5	2.9
ANNUAL (mm)	412.2	2548.5	309.3	437	34.2	67.2	31.1	98.9
ANNUAL (km³)	86.6	535.2	65.0	91.8	7.2	14.1	6.5	20.8

TABLE 6. Simulated monthly water resources for Ogaden basin (mm spread over 210,000 km², unless otherwise stated).

MON	PCP (mm)	PET (mm)	ET (mm)	SW (mm)	PERC (mm)	SURQ (mm)	GWQ (mm)	WYLD (mm)
JAN	15.5	171.1	17.8	49.2	2.1	1.3	3.6	5
FEB	17.7	173.9	26.4	36.5	1.8	2	2.3	4.3
MAR	40.3	256.2	46.7	22.9	3.1	3.9	2.2	6.1
APR	111.7	213.6	62.9	45.8	10.8	13.8	3.4	17.2
MAY	95.6	205.2	57	55	10.6	18.2	7	25.3
JUN	41.8	209.6	35.1	49.1	4.7	7.7	7.8	15.6
JUL	44.5	216.1	29.8	46.9	6.4	10.2	6.3	16.7
AUG	43.3	213.2	25.1	46.7	7.6	10.3	5.9	16.4
SEP	47.8	196	24.3	49.4	8.2	12.3	6.4	18.8
OCT	67.4	187.5	35.1	59.2	9.4	12.3	7.5	19.9
NOV	50.3	161.8	33.8	62.7	7	5.7	7.6	13.4
DEC	19.5	160.5	32.1	55	2.7	1.4	6.4	7.9
ANNUAL (mm)	595.4	2364.7	417.1	578.4	74.4	99.1	66.4	166.6
ANNUAL (km³)	172.7	685.8	121.0	167.7	21.6	28.7	19.3	48.3

TABLE 7. Simulated monthly water resources for Turkana basin (mm spread over 290,000km², unless otherwise stated).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Flow	**0**	**0**	**0**	**0**	**0.3**	**1.6**	**34.8**	**67**	**18.9**	**2.9**	**0.3**	**0**	**125.7**

TABLE 8. Monthly variation of available water resources in Ayesha basin (million m³).

7. GROUNDWATER RESOURCES FOR IGAD TRANSBOUNDARY BASINS

In general there was limited groundwater data available to facilitate calibration; however a summary of some groundwater data available from the British Geological Surveys using global datasets is available at UNESCO. A general summary of the aquifer properties within the IGAD area are summarised in Table 9.

Basin	Aquifer Yield Classification	Aquifer Productivity (l/s)	Mean annual Productivity (m^3/yr)	Aquifer saturated Thickness (m)	Aquifer storage and Flow Types
Danakil	Moderate	1 - 5	88,301	25 - 100	Fracture flow
Gash- Barka	Low	0.1 - 0.5	7,884	< 25	Fractured flow within weathered material
Juba-Shebelle	Moderate	1 - 5	78,840	25 - 250	Intergranular and fracture flow
Ogaden	High	5 - 20	394,200	100 - 250	Intergranular and fracture flow
Turkana- Omo	Moderate to High	1- 20	315,360	25 - 100	Fracture flow
Ayesha	Low to Moderate	0.5 - 1	23,652	25 - 100	Fracture flow

(Source: http://www.bgs.ac.uk)

TABLE 9. Groundwater resources and aquifer properties in the IGAD sub-basins

5

CONCLUSIONS

The work involved data collection, hydrological model set-up, identification of the most sensitive model parameter, model calibration and sensitivity analysis for the IGAD transboundary basins. The main output of the strategy was a clearer understanding of the hydrological response of several IGAD catchments and the potential use in terms of solving controversies surrounding fluctuating stream flows and Lake water levels, sustainable agriculture, rural development, hydropower generation and environmental stewardship.

The Water Resources Modelling section conceptualised and developed of a hydrologic model for water resources assessment of the identified transboundary basins in the IGAD region. This involved close collaboration with the GIS/Database expert for effective preparation, presentation and archiving of water resources and hydrologic data in the agreed format. Substantial knowledge of GIS was required by the potential participant of the water resources modelling modules.

In terms of software requirements, ArcGIS was also required for hydrological models setup/simulation of the water resources modelling component. Several meteorological datasets were acquired for effective modelling; however, the continued lack of daily stream flows still limited the effective calibration of the delineated hydrological IGAD basins. Several attempts were carried out to ensure effective estimation of the Water resources for the IGAD basins. A basin-wide summary of the simulated water resources' components was presented to give a general insight into the water resources components for IGAD transboundary basins.

Most of the results of the current study are comparable to water resources estimates by other studies such as the FAO Water Resource Study. There are some discrepancies in the estimates for Juba-Shebelle and Danakil. The differences may be due to differences in the study datasets and period under consideration. However, the issues of limited hydrologic data availability for the region and the problems related to water resources assessment under such conditions are well documented. Therefore, additional data collection from the countries

Basin	Surface water	Groundwater
Danakil	**1.0**	**0.6**
Gash-Barka	**2.8**	**1.4**
Juba-Shebelle	**64.6**	**43.7**
Ogaden	**14.1**	**6.5**
Turkana-Omo	**28.7**	**19.3**
Ayesha	**0.1**	**-**
Total	**111.3**	**71.5**

Table 10. Simulated estimates of available water resources (km^3) for the IGAD transboundary basins.

is essential for improving the estimates. Implementation of new hydro-meteorological networks is of great urgency as the networks in many of the countries are limited or non-existent in many cases. The use of remote sensing products can also be useful in the short term. However, even if the simulations results may vary for some transboundary basins, the results by this study create a basis for additional investigations in water resource modelling in terms of model set-up and simulation methodology.

Additional data especially daily stream flows at several locations in the basin, are required to improve the water resources simulation. The available hydrological and climatological data from the IGAD databases revealed large deficiencies, especially regarding daily observations - a number of observations are missing. Furthermore the available data from other sources were sparse and not free of errors. The climate in the IGAD basin is rather complex and for accurate use of hydrological models, representative precipitation sequences may be required. For the IGAD hydrological basins, evaluation of the hydrological performance of the SWAT model on a daily/monthly time resolution should reveal the hydrological patterns and the sensitivity of hydrological variables to input rainfall datasets and parameter estimates. A simple sensitivity study helped reduce the dimensionality of the calibration challenge.

6

RECOMMENDATIONS

DDespite the initial successful modelling of the IGAD Trans-boundary basins, additional modelling is required given additional datasets are made available for effective hydrological simulations. There is a need to set up a network of hydrometeorological monitoring - at present, the IGAD basins have limited capacity in terms of gauge network for hydrolometeorological monitoring and operations and each country should have additional capacity for effective operation of the designed hydrometeorological networks. Once the networks are setup, it should be ensured that all stations have complete installation of equipment to guarantee effective monitoring of hydrological events. IGAD should establish a capacity building component especially in fields related to water resource modelling and this should be done in a way that member countries create opportunities for cooperation in water resources assessment at sub-regional levels. To ensure effective data collection for all the IGAD member countries, several programmes that support effective data collection and monitoring should be implemented and these should as well ensure mechanism for data achieving and sharing among IGAD member countries.

Given the significant lack of hydrological and Meteorological data required for water resources monitoring and modelling, it is recommended that throughout the entire IGAD trans-boundary basins, weather stations should be deployed after an appropriate study of where each station should be installed. A recommended source of such hydro-meteorological equipment can be attained from http://www.geonica.com/index.php. However, a separate study is recommended to show explicitly where to install such systems.

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Mapping, Assessment & Management of Transboundary Water Resources in the IGAD Sub-Region Project

V

WATER RESOURCES MODELLING COMPONENT

The Water Resources Modelling section conceptualized and developed of a hydrologic model for water resources assessment of the identified transboundary basins in the IGAD region. Despite the lack of data (meteorological data, daily stream flows, etc.) which limited the effective calibration of the model, several attempts were carried out to ensure effective estimation of the Water resources for the IGAD basins.

The evaluation of the hydrological performance of the SWAT model on a daily/monthly time resolution for the IGAD basins faced large deficiencies in the database, especially regarding daily observations - a number of observations are missing. Model calibration requires the availability of reliable flow data for major rivers within the basins in both temporal and spatial terms. These data were not available for the current study. Consequently, the study used the available data from other sources which are sparse and not free of errors. Furthermore, the model helped clearer understanding of the hydrological response of several IGAD catchments and the potential use. A simple sensitivity study helped reduce the dimensionality of the calibration challenge.

The Water Resources Modelling of the Six (6) identified transboundary river basins (Danakil, Gash-Baraka, Turkana-Omo, Ayesha, Juba-Shebelle and Ogaden) represent a first attempt to comprehensively model their water resources within the IGAD sub-region. For most of the basins, the estimated available annual water resources were in good agreement with results from other studies. As such the estimates for all basins need further investigations before they can be used as a basis for comprehensive decisions about the basins. There is need for collection of additional data from the member countries as soon as a mechanism for data sharing can be implemented.

The model assessed the available water resources for the IGAD transboundary basins to 182.8 km^3 (111.3 km^3 for Surface water and 71.5 km^3 for Groundwater). Additional data especially daily stream flows at several locations in the basin, are required to improve the water resources simulations ■

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