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Groundwater Recharge under Changing Landuses and Climate Variability: The Case of Baro-Akobo River Basin, Ethiopia

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Abstract

Impacts of landuse/landcover changes coupled with climate variability are well felt in areas of pristine environments like the dominantly high rainforest covered Baro-Akobo river basin of Ethiopia that form the Sobbat River system. Recharge is one of the hydrologic components to be influenced by induced anthropogenic changes. Quantifying and understanding changes in recharge and related hydrologic parameters help to properly manage the water resources and protect such vulnerable hydro-ecosystems. Among the various recharge estimation methods, WetSpass model is used for its capability to estimate recharge by coupling surface-subsurface water balances. It is also used to simulate yearly or seasonal averages of groundwater recharge, evapotranspiration and runoff that help to understand the basin's hydro ecosystems dynamics. Modeling is done for the entire river basin of Baro-Akobo, taking into account landuse/landcover changes, varying climate and other physical parameters over the past four decades. Simulation results are validated using previous estimates, empirical methods using data from monitoring wells and isotope measurements. Bias corrected Climate Forecast System Reanalysis (CFSR) data are used to fill gaps in data scarce areas and to generate potential evapotranspiration. Field measurements, secondary data and fifteen months long three hourly well monitoring data are used to determine seasonal depth fluctuations of the groundwater. Landuse/landcover change of three periods, 1973 to 2014, and planned large scale development activities are used as inputs to see induced corresponding changes in the hydro-ecosystem. The simulated result showed small increase in runoff and despite the increase in temperature, there is a decrease in total evapotranspiration and significant increase in recharge in the recent period. The simulated result is also in line with the hydrogeologic characteristics of the basin making it a basin with low recharge as compared to basins in the central and eastern parts of the country. Coupled with other hydrological and hydrogeological characteristics of the basin, the result helps to understand the reason for finding large volume of surface flow entering the Machar wetlands and eventually reaching the White Nile from a relatively small watershed.

Keywords: Land use- Land cover; Recharge; climate variability; WetSpass; Geology

1. Introduction

Three of the four UNESCO registered biodiversity sites in Ethiopia are partially or fully found in Baro-Akobo River Basin. The Yayu Coffee Forest Biosphere Reserve, The Sheka Forest Biosphere Reserve and Kafa Afromontane cloud forests are known to contain unique biological diversity, the remaining moist montane forests, with its dense primeval forests, bamboo thickets, grasslands and wetlands, center of the origin for the most popular coffee in the world, Coffee Arabica (UNESCO 2012). The Gambella high forest encompasses three national forest priority area namely.

The forest is rich in both plant and animal species. There are over 300 higher plants, 50 mammals, 200 birds, and 20 amphibian species, occurring in all habitats. Out of these, at least 55 plants, and 10 birds are endemic to Ethiopia. There are also over 38 threatened species (IUCN Red list) in the area, which include 5 bird, 3 mammals and 30 plant species. It is also source of major rivers like Baro and Akobo rivers, the main tributaries of the White Nile. The forest is also highly regarded for conservation of biodiversity, flood and erosion control, and carbon-sequestration to mitigate the effects of climate change.

The lowland plain, located at the western part of the basin, is also home to hundreds of thousands of wild life. In recent years, the wildlife populations in the region are known to have been negatively affected by a combination of illegal hunting and habitat change (TransFrontierConservationInitiativeTaskForce 2011).

In the past few decades Baro-Akobo river basin has gone through various dynamic processes. Population increase and related anthropogenic pressure and possible climatic variability have brought visible changes to the ecosystem of the basin (TAMS and ULG 1997). Since 1984, widespread drought has brought thousands of settlers and related activities to the basin (Kiros 2005). In addition to the local settlers, this area remained to be home to hundreds of thousands of South Sudanese refugees for decades and continued in a larger scale at present (Haile Mariam Behailu 2011). More pressure is coming to the basin in a form of large scale commercial farming. Resettlement is also going on but with less magnitude. Baro River used to be navigable to connect Southern Sudan with Ethiopia. During the early 19th century, The British opened a port at Gambella town on the wide and navigable Baro River, which during four months of the rainy season was navigable and provide direct access to the sea via the Nile through Khartoum. Ethiopian coffee was exported via this route, up to 1940. At its peak, up to 40 ships would be in dock at any one time (SELKHOZPROMEXPORT 1990). At present the service is limited to only few border towns after joining Akobo River.

Moreover, the basin's trans-boundary nature and its high importance to South Sudan and remaining downstream countries give the basin high geopolitical importance. Despite its high geopolitical and hydrologic importance, for its remoteness and inadequate access, the Baro-Akobo basin is poorly documented and has been the subject of very few studies in the published literature. Little is known about details of the water resources and little is done to understand the possible threat that may happen to the hydrogeologic system as a result of anthropogenic and climate variability impacts. The comprehensive basin level master plan study by TAMS and ULG 1997, the detailed investigation work by the Russia based SELKHOZPROMEXPORT 1990, the geological surveys done by ARDCO-GEOSERV 1993, and the study done by the National Wetlands Working Group, 1997 are still the major works to be referred. Some aspects of impacts of resettlement in the basin were studied by Woube (Woube 2005), Aerial Survey Report by Trans Frontier Conservation Initiative Task Force (TransFrontierConservationInitiativeTaskForce 2011) is a very recent work to undertake census of the wild life in Gambella National Park and show the negative effects on the wild life as a result of a combination of illegal hunting and habitat change. The comprehensive study done by Sutcliffe J. V. and Y. P. Parks (Sutcliffe and Parks 1999), as part of the Nile River system, is a very valuable document to understand regional hydrologic features. There is ongoing study by ENTRO entitled Baro-Akobo-Sobat and White Nile Multipurpose Water Resources Development Study Project, which is expected to provide up-to-date information. Apart from the oil exploration works, whose data is not yet fully available for research, there are a number of geological studies done at regional and semi detail scales. The gap in all these works is failing to give a clear picture about the groundwater-surface water interaction and the basin's unique hydrogeologic features.

The objective of this work is to determine temporal and spatial trends in recharge and major climatic features to help to understand the deteriorating situation, if any, in the hydrologic systems. Reanalysis of the basin's surface flow, its contribution to Machar wetlands and groundwater storage and erosion y water are some of the outputs of this work. In addition to this, the study is aimed to determine suitable model that can be reliably used to characterize the basin, capture the historical trends and testing use of the available global climate models to fill missing data gaps as an input for remote areas, which are lacking weather stations. In addition to these, by providing basic information about the basin, this work set a basis for further research and helps to manage the water resource of the basin.

2. The Study Area: Baro-Akobo River Basin

Baro-Akobo River basin is partially part of the south western Ethiopian Plateau with a peak elevation of 3240masl. Towards west, the rolling and hilly morphology abruptly changes into dominant long chain of sharp escarpments and lowland plain with lowest elevation of 395masl. The basin is the second smallest river basin with an area of 75,912 km^2 (6.9% of the country) among the eight river basin of the country. But it contains the second highest runoff of 23.6 Bm^3 and 27% of the country's potential irrigable land and 8.9 % the hydropower potentials (Awulachew, Yilma et al. 2007). This basin is home to one of the few remaining high rainforest (ARDCO-GEOSERV 1993), more than 60 types of mammal wildlife are contained in the country's largest park. Its land resources potential is attracting from small to mega investments that reached a total request of more than 400,000 ha for palm oil and rice production (OSTERREICHISCHEBUNDESFORSSTE 2009). On top of these, expanding investment, deforestation, uncontrolled fire, charcoal making, etc. are affecting the hydro-ecosystem as seen in all corners of the basin.

One of the peculiar features of the basin is its extensive wetland, which is part of the Machar Marshes. The Baro_Akobo wetland is one of the wettest and best watered areas in the country. The wetlands are fed by a combination of local precipitation, the torrents originating from the western Ethiopian plateau, and spillover from Baro, Akobo, Gilo, and Alwero rivers. While other rivers spill during periods of high flows into the adjoining wetlands, Baro River spills north across the Ethiopia-Sudan border towards the Machar Marshes. Hughes estimate the total area of the wetlands at around 4000km^2 in Ethiopia (Rebelo and McCartney 2012).

2.1. Location

Located between 5°30' to 10°50'N Latitude and 33°00' to 36°18'E Longitude, in the Western part of Ethiopia (Figure 1), Baro-Akobo river basin is one of the six international river systems in Ethiopia and the only one that flows to White Nile after forming Sobbat River system.

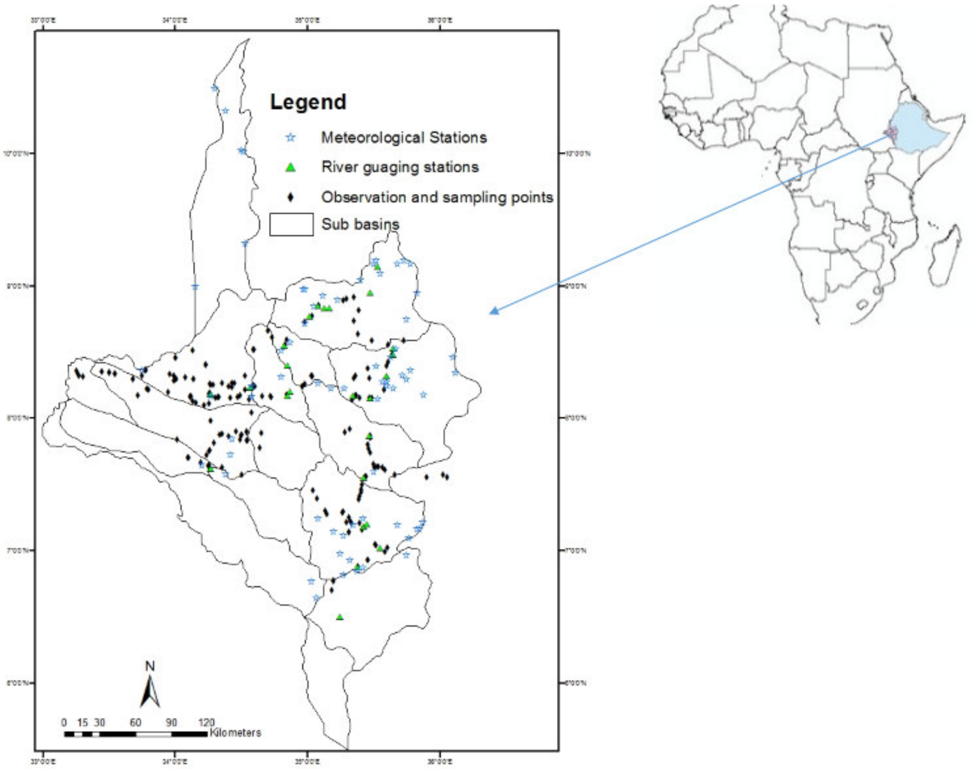


Figure1: Location Map of Baro-Akobo River Basin showing distribution of river gauging and meteorological stations, sub-basins divisions and observation and sampling points in this work

2.2. Climate and Hydrology

Distribution of meteorological stations in the basin is sparse and sufficient records are not available (Figure 1). Although the basin is small in size, available records show high correlation of rainfall and temperature with altitude. The basin enjoys varied climatic conditions due to its wide elevation differences ranging between from 395 to 3240masl. As a result, temperature varies from about 40°C in the lowlands and less than 22°Cin the highlands. Similarly, rainfall varies between <1000mm in the western lowlands and >2500mm in the eastern highlands (ARDCO-GEOSERV 1993). The estimated mean rainfall for the whole basin is about ~1450 mm/year.

2.3. Geology and hydrogeology

From hydrological and hydrogeological point of view, the basin looks environmentally delicate. Unlike other major rivers of the country, the source of the rivers in Baro-Akobo basin is predominantly the high rainforest, which is underlain by Precambrian Basement rocks and Tertiary Volcanics. As compared to the other watersheds in the country, large rivers are originating from a relatively small area. As can be deduced from its physiographic and geologic setting, and characteristics of adjacent basins, the Baro-Akobo basin may not get significant deeper recharge from afar places (Figure 2).

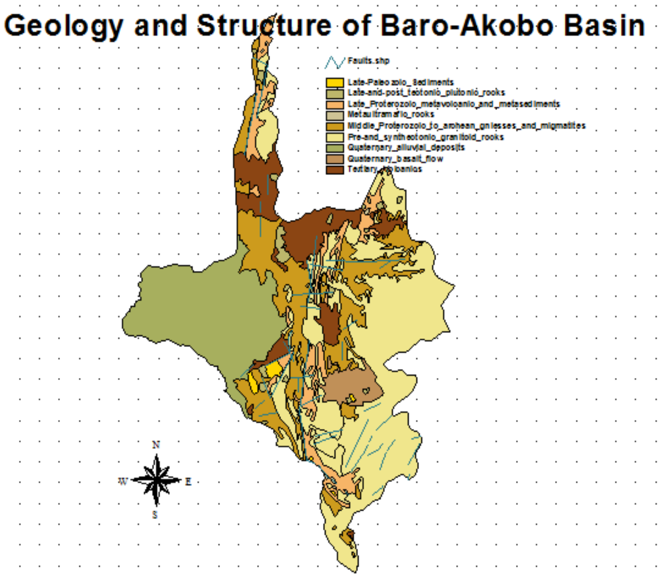


Fig. 2: Updated Geological Setting of the study area (Terefe and Woldie 1996)

The main geologic outcrop in the basin are Tertiary and Quaternary Volcanics, covering ~41% of the basin, mainly in the recharge zone. 78% of these are Tertiary Volcanic, which are fractured and weathered to become moderate aquifers. The remaining volcanic cover is Quaternary with poor aquifer system development. The basement rocks, which is a poor aquifer, covers ~39% of the area and found at shallow depths even in most areas covered by Tertiary Volcanic and sediments. The lowlands areas are predominantly covered by Neogene and Quaternary sediments. These sediments cover ~ 20% of the basin forming the Gambella Basin. This basin is an extension of the Melut Basin of Sudan, which has several proved oil and gas discoveries. According to gravity survey undertaken,

Gambella basin, is an extension of the oil rich South Sudan's prolific Melut Basin have enough sedimentary thickness reaching 9 kilometers to make it promising target for oil exploration (SOUTHWESTENERGY 2012). Southwest-Northeast trending geological structures are dominant followed by east-west trending ones. These structures play significant role in shaping the hydrogeological characteristic of basin. The contribution of regional faults that run for hundreds of kilometers cutting across more than one basin, like Yerer-Tulu Welel regional faults (Alemu and Abebe 2007), is a subject of further research.

2.4. Hydro-geomorphology

The Baro-Akobo River basin is partially part of the south western Ethiopian Plateau, which is characterized by rolling and hilly morphology. But towards west this rolling and hilly morphology abruptly changes into dominant long chain of sharp escarpments and lowland plain. The slope range varies from level (0%) to very strong slope of 170% and has an average slope of 10.7%. The recharge zone is predominantly is strong slope with an average slope of 14%. The intermediate zone is steeper with an average slope of 17.6%. The lowland plain is nearly level. The geomorphology of the area is largely governed by geologic and structural set up of the area. Unlike the other parts of the country, due to its high forest cover, climate has relatively lower role in modifying the geomorphology of the area, as the area is known for its virginity in terms of its cover.

There is big contrast between the plateau area in the east and the hill and lowland plain areas of the western part. Fault scarps, and horst and graben features dominate the middle parts of the basin lying in between the lowland plains in the west and the hilly volcanic terrain in the east. The well-defined fault escarpment bound the lowlands plains and generally trends north-south and curve the area as far as the Sudan border (Figure 2).

Within the highland plateau, the northern plateau is relatively washed and denuded as compared to the less encroached southern part. The plateau is an uplifted erosion surface with remnants of various sizes of Trap basalts. Such surfaces are conspicuous features of the morphology of other plateaus in Ethiopia. The surface is lateritized, sometimes carrying lacustrine deposits and sands, and rounded pebbles are fairly common to be found. Strong relief is mainly confined to other fracture zones and the escarp representing the eroded edges of the major lava flows (ARDCO-GEOSERV 1993).

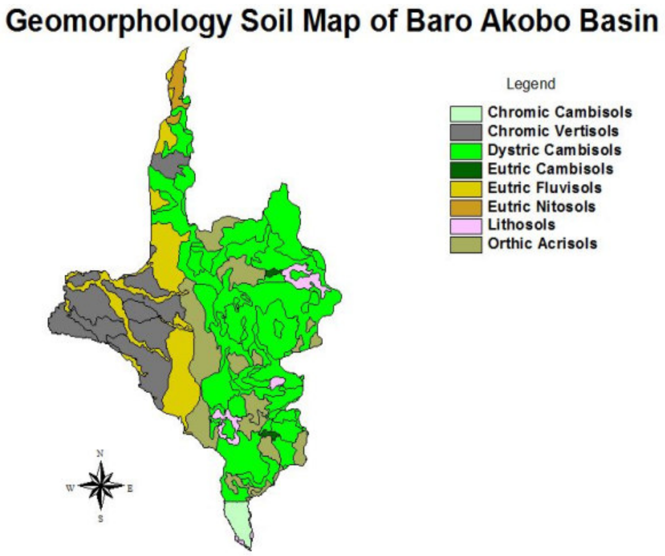


Fig. 3: Geomorphology soil map of Baro-Akobo Basin Updated from(FAO 1984)

The Gambella basin's hydro-geomorphic characteristic is also highly governed by its soil cover types. The levees along the rivers are the only porous media in the lowland plain. According to the classification of FAO's nation-wide work(FAO 1984), soils of the Baro-Akobo basin are dominantly Cambisols, Vrtisols, Fluvisols and Acrisols, followed by small coverage of Nitosols and lithosols. The highland area is predominantly covered by Dystric Cambisols. Litosols are found very much localized within the highlands. The escarpment/the intermediate zone has predominantly Eutric Fluvisols followed by Orthic Arcisols. The lowland plain is mostly covered by Chromic Vertisols. Minor Eutric Fluvisols are found along the rivers banks. Conversion of these soil classes with SPAW Hydrology (hydrolab 2007) into texture soil class shows the soils of the basin to be 79.7% clay, 10.8% clay loam and 9.4% sandy clay. This is one of the unique features of the basin to shape the basins hydrologic characteristics.

3. Datasets and Methodology

3.1. Data

Three categories of data types are used in this research. These are: landuse land cover, geological and hydrogeological, and climate and hydrological data. Validation of both secondary data and satellite images interpretation are done through field survey and interviews.

I. Land use/ Land cover and topographic data

The major source of Land use land cover data is satellite image acquired through internet download. Four sets of Landsat images from USGS's (http://earthexplorer.usgs.gov/) that cover the period 1973 to 2014 are used to capture the change in landuse/landcover. Due to the high cloud cover over the basin ALOSPLASAR, acquired from JAXA, are fused into one of the sets to enhance interpretability of the Landsat images. SRTM_DATA_GeoTiff (Jarvis A. 2008) is used to generate topographic and slope data. Topographic maps from Ethiopian Mapping Agency and 170 control points taken with GPS camera in the field are used to validate image interpretation results.

II. Geological, Hydrogeological and Soil data

The sources of geological and hydrogeological information used in this work are mainly derived from master plan and project studies. The following are major ones. The Baro-Akobo River Basin Integrated Development Master Plan by TAMS and ULG (1997), the Baro-Akobo Basin Master Plan Study of Water & Land Resources of Gambela Plain by SELKHOZPROMEXPORT (1990), Survey and Analysis of The Upper Baro-Akobo Basin by ARDCO-GEOSERV (ARDCO-GEOSERV 1993), Hydrogeological Report of Gore Area (NC36-16) by Asfaw, B., B. Abaire, et al.(Asfaw, Abaire et al. 2001), The Gore-Gambela Geotraverse, Western Ethiopia by Moore and Teklewold (Moore and Teklewold 1989), Geological Map of Ethiopia by Terefe, and Woldie (Terefe and Woldie 1996) and Hydrogeological Map of Ethiopia by Tesfaye Chernet (Chernet, Kumbi et al. 1988).

In addition to these borehole and spring inventory data are collected from government and non-government offices, and drilling and consulting companies. Data loggers installed in four places within the recharge and discharge areas provided a three hourly continuous fifteen months record of groundwater level, temperature and pressure. Compiled data from these sources are revised and updated using remotely sensed data and field survey.

III. Climate and hydrological data

Two types of meteorological data, observed and estimates, are used in this study. Observed data are available mainly for rainfall and temperature. Data for evapotranspiration, humidity, and wind speed are found only for Gambella and Gore towns. Apart from the Rainman data from Department of Agriculture and Fisheries of The Queensland Government (DepartmentofAgricultureandFisheries 2015) that provide long term rainfall data for some areas of the basin, all observed data are collected from Ethiopian National Meteorological Agency.

Due to the limited spatial and temporal coverage of the observed data and complete absence of observed climatic elements like evaporation, humidity, wind speed and solar radiation in the basin, bias corrected estimates from Global Climate Models. In this regard, Climate Forecast System Reanalysis (CFSR) from the National Center for Atmospheric Research (NCEP 2010) is found to be better than others in its temporal coverage, spatial resolution and providing all the above mentioned data type. Evapotranspiration is generated using inputs from this source. Available river flow data of all gauging stations in the study area, nearly 20 in number, are obtained from Ministry of Water Irrigation and Energy.

3.2. Methods

There are three major steps followed during this work that have their own respective methods. These are: 1 data preparation and field investigation, 2 data integration, interpretation and analysis, and 3 modeling stages. The following methods are used in each stage.

I. Data preparation, quality check and field investigation

All secondary thematic spatial data, like geological, hydrogeological and soil maps which are in hard copies are digitized for update and integration with other data. Missing data in meteorological and hydrological records were filled using statistical daily mean values of respective months. Field survey routs, observation and sampling points are designed based on desk review of collected secondary data and interpretation of satellite images (Figure 1). Templates are prepared in EXCEL to generate monthly average of 35 years from daily CFSR data. Another template in EXCEL is used to calculate potential evapotranspiration using Penman Monthiz formula.

Time series analysis of four decades old satellite images, using techniques like image differencing, rationing or change vector analysis (CVA) are done to detect land use land cover changes in the research area (Coppin et al., 2004, Mwita 2010). Synergistic use of both satellite and aerial photography is used for detailed investigation of the wetlands, especially where different vegetation types and landscape features are mapped. Optical sensors such as Multi Spectral Scanner (MSS), LANDSAT Thematic Mapper (TM), Enhanced Thematic Mapper plus (ETM+) and SPOT images are used to identifying wetland types, hydrologic regimes and various landuse/landcover and landscape changes (Ramsey &Laine, 1997; Kindscher et al., 1997; Haack, 1996).

Microwave remote sensing is used to compliment the limitations of optical sensors, for its ability to penetrate clouds and (depending on sensors frequencies) vegetation canopy (Lunetta, Knight et al. 2006; Mwita 2010). By virtue of day and night observation and cloud penetration capability, and the sensitivity of radar backscatter to the moisture content of terrain media and the sensitivity of the radar cross-sections to the geometry of the vegetation growing on the terrain surface the active microwave data from Synthetic Aperture Radar (SAR), and PALSAR were used for mapping the wetland vegetation, the high rainforest area and geologic structures (Baghdadi *et al.,* 2001; (Mwita 2010), Kasischke & Bourgeau- Chavez, 1997). Higher frequencies (i.e., shorter wavelengths such as X-band) were used to detect open-surface water and the lower microwave frequencies (i.e., longer wavelengths such as P- and L-band) were used to map features under canopy cover (Henderson & Lewis, 2008).

Finally results of the optical, thermal and microwave data were used in an integrated manner in attempting to identify and delineate different landuse/land cover types and locate and quantify observation and sampling spots. The remotely sensed data was combined with numerical modeling, geographic information systems, and ground-based information for the final analysis (Brodie, Sundaram et al. 2007).

Satellite-based remote sensing of ground water was used to determine spatial distribution of aquifers, ground water discharge and recharge areas potential, water fluxes sites, and storage changes over the wetlands and upper catchments. In addition to this, combination of optical, thermal and microwave remote sensing are applied to identify potential location of groundwater-surface water interaction, the ‘hot spots’. This information is used to select appropriate site to install groundwater monitoring devices and taking measurements. The contrast in spatial and spectral resolutions on various images of the ground water/surface water and ground water/land surface interfaces is found to be a key for feature discrimination. In this regard characterizing different vegetation cover type was used as indicator (Becker 2006; Brodie, Sundaram et al. 2007).

Four Rugged Troll 100 data logger devices were installed in four boreholes to record three hourly water level, temperature and pressure. All data loggers were functional for a continuous 15 months (December, 2013 to the first week of March 2015).This data with other field measurement and secondary information gathered from the basin and the adjacent basins are used to determine seasonal and diurnal groundwater fluctuations and depths to groundwater.

II. Data integration, interpretation and analysis

Data was integrated in a GIS for interpretation and analysis. The main purpose was to qualify and quantify environmental changes that took place in the past four decades. The purpose of doing this part of the research is to see the impacts of anthropogenic and climate variability on the hydrogeologic system of the Baro-Akobo River basin, particularly; on the wetlands. The work was based on analyzing remotely sensed data, ground validation, field measurements and looking into past socio-economic events. The Digital change detection and the whole analysis can be used to predict future trends and assist in the decision-making process regarding future resources use (Diallo, Hu et al. 2009). The spatial distribution of the land use/land-cover changes was monitored to establish links between policy decisions, regulatory actions and subsequent land-use activities that were happening in the past.

Changes in ecological indicators such as specific vegetation communities or biota are used to mark changes in locations of groundwater discharge to surface water features. Changes in the extent and composition of biota that inhabit the hyphoreic zone are also used to indicate the processes of near-stream groundwater and surface water mixing (Brodie, Sundaram et al. 2007).

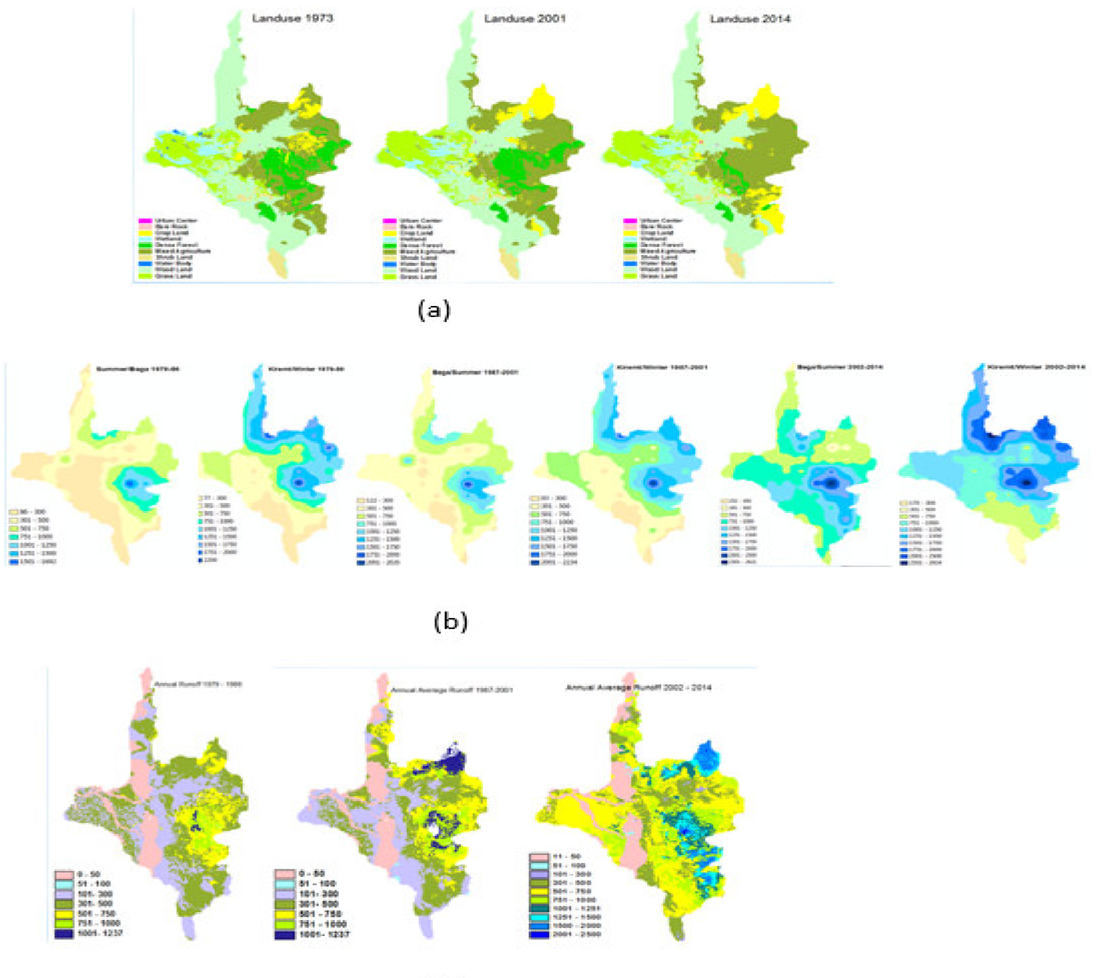
Spatio-temporal changes in the hydrogeology behavior of areas surrounding major rivers and the wetlands are extracted from remotely sensed data. In addition to these, changes in hydrogeologic features such as aquifer geometry, host geology, faults, facies changes or river geomorphology and stratigraphy and hydraulic properties (such as transmissivity and storativity) are used to monitor changes that happened as a result of exerted impacts (Brodie, Sundaram et al. 2007). The stream hydrograph is processed and analyzed in R Program to see changes in the magnitude and timing of groundwater discharge to streams in time. The monitoring wells are used to generate well hydrographs and see their relations with stream hydrographs.

III. Modeling in WetSpass

This model, termed WetSpass, an acronym for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi Steady State, has the capacity to integrate a water balance in a geographical information system (Batelaan and De Smedt, 2001). Among the various recharge estimation methods, WetSpass model is used for its capability to estimate recharge by coupling surface-subsurface water balances. It is also used to simulate yearly or seasonal averages of groundwater recharge, evapotranspiration and runoff that help to understand the basin's hydro ecosystems dynamics. Its basin level application to study the influence of long-term effects of land cover changes on the water regime has made it preferable (BatelaanandSmedt. 2007, Woldeamlaket,al 2007, Dams et, al 2008).

WetSpass simulates long-term average recharge depending on landcover, soil texture, topography and hydrometeorological parameters. This is used to measure changes induced in the hydrogeologic system as a result of changes in the above elements. Moreover, the model simulates recharge iteratively connected to a groundwater model, such that the recharge estimate is also influenced by the groundwater depth and vice versa. Attempts have been done to modify parameter estimation for the model, which is performed on the basis of literature values of water balance fluxes from mainly Belgium and The Netherlands, to fit to the local condition.

Both observed and forecasted long-term average monthly hydro meteorological parameters are used as inputs. Bias corrected Climate Forecast System Reanalysis (CFSR) data are used to fill gaps in data scarce areas and to generate potential evapotranspiration. Landuse/cover change of three periods and planned large scale development activities are also used as inputs to see induced corresponding changes in the hydro-ecosystem (Figure 4). The model simulated the temporal average and spatial differences of surface runoff, actual evapotranspiration, and groundwater recharge.



(a)

(b)

(c)

Figure 4: Major model inputs used in WetSpass Model a. Precipitation – seasonal, b. Land use, c. Annual Runoff

This is the rare advantage of this model capability to incorporation of the depth to the groundwater. Since evapotranspiration from shallow groundwater is significant, especially in the wetlands, depth to the groundwater table is taken into account in the estimation of recharge (O. Batelaan et.al, 2003). Field measurements, secondary data and fifteen months long three hourly well monitoring data are used to determine seasonal depth fluctuations of the groundwater and generate seasonal basin-wide depth to groundwater.

The basin is threated by the model as a regular pattern of raster cells of 2000 meters in size. Every raster cell is further sub-divided in a vegetated, bare soil, open water, and impervious surface fraction, for which independent water balances are, maintained. This allows accounting for sub-cell land cover heterogeneity. The bare soil fraction of a raster cell is also used to describe the part of the surface, which is not fully covered by vegetation. Especially, in the non-growing season this percentage can increase considerably for certain covers. The processes in each cell are simulated seasonally, while semi temporal information is brought into the approach by assuming a cascading of the precipitation, interception, runoff, evapotranspiration and recharge.

The model calculates water balance based on varying land cover types considering corresponding indexes. For example seasonal water balance for a vegetated fraction of a raster cell is given as:

$$P = I + S_v + T_v + R_v$$

Where P is precipitation, I the interception, Sv the surface runoff, Tv the actual transpiration and Rv the groundwater recharge [L] in the vegetated fraction of the raster cell.

Similarly, water balance for impervious surfaces is given as:

$$P = S_i + E_i + R_i$$

Where index i refers to impervious surfaces (Batelaan and De Smedt, 2007).

Simulation results are validated using previous estimates, empirical methods using data from monitoring wells and isotope measurements.

4. Results

4.1. Introduction

Spatial and temporal change detection in the Baro-Akobo basin and determining the possible causes are the main objectives of this research work. As discussed above, there are different kinds of environmental problems that are caused both by the anthropogenic and natural factors. The environmental change detection coverage in this research work deals more with the anthropological influences and the induced changes that modified the hydrologic systems.

During the field survey a large change in the land use system was observed. Attracted by natural endowment of the basin and forced by wars and conflicts, legal and illegal settlements have taken place; to subject the area under high human pressure for more than four decades. Most detectable changes have taken place in the commercialized farm areas of the lowland plain and the highly encroached recharge areas of the highland. The intermediate zone of the study area has minimal human influence and hence minimum detectable change. This is mainly due to the hostile nature of the environment for human interaction.

4.2. Landuse/landcover Situation

Information on the contemporary scenario was derived from interpretation of Landsat 8 image of the Month of December 2014 to February 2015 (NASALandsatProgram 2015), and field survey. According to this work, the dominant land cover types in the area are sparse and dense woodland (32.5%), followed by stocked and lightly to moderately stocked cultivation (25.3%), open and dense to closed Montane broadleaf forest (16.8%) and grass cover with and without trees (14%). In the remaining parts of the basin open and dense to closed semi evergreen forest, perennial and seasonal swamp and open to dense shrub land constitute 4.7%, 3.4% and 2.8%, respectively. Three sets of historical landuse/landcover situations are generated from three Landsat product sets of the 1972, 1986 and 2001(NASALandsatProgram 2014). The dominant cover in the oldest data set, in 1972, was the same open and dense to closed woodland but the cover during that period was much denser. Open Montane broadleaf forest, followed by more closed and dense ones was the second largest cover (22%). Cultivated land was about 20% during this year, but 97% of the farms were lightly to moderately stocked. Perennial and seasonal swamps were bigger by 40% than their current size.

Loss of open water body is the biggest decline in terms of percentage (547.94%), in the past four decades. The biggest loss during the same period, in terms of aerial coverage, is the loss of dense to closed Montane broadleaf forest. More than 640,000 ha of land is affected. Similarly, the dense woodland and the riparian forest are affected by -162% and -145%, respectively. The shrinkage of the swamp by more than 40% and the open lowland semi evergreen forest by more than 56% are the other major environmental losses (Figure 5, a & b).

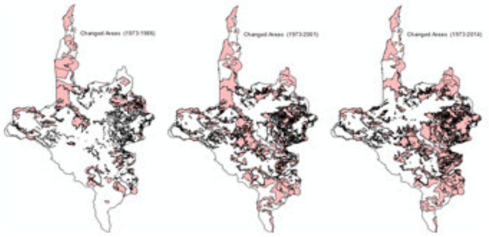
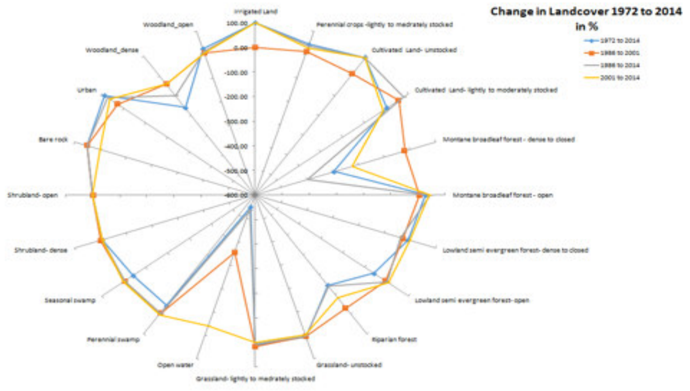


Figure 5: Change in Land use/Landcover (1973 to 2014) a. Areas subjected to change during the three period (shaded); b. gains and losses by land use classes

(a)



(b)

The biggest gaining land covers are irrigated farming, unstocked dry cultivated land, and urban expansion growing by 100%, 89.9% and 87.9%, respectively. The lightly to moderately stocked perennial crops and the bare lands have shown dramatic increase during this period. These gaining land cover types are taking over, mainly, on the land that was occupied by the high rainforest and the woodland. Irrigated farming, although gradually increasing, took insignificant proportion of the land. Most of the changing areas are used for different agricultural activities, such as commercial coffee, tea and cotton cultivation, dry farming, and other small holder mixed farm activities near residential areas (Figure 5, a & b).

In terms of affected hydro-geo-environments, most of the changes are taking place over the basement rocks and strong slopes. 75 % of the land covered by crop cultivation is on the most vulnerable basement rocks, overlain mainly by few meters of regolith and clay loam soils, with average slope of 15%. Changes that happened in the lowland plains are predominantly over the thick Chromic Vertisols (Figure 3). The east-west (highlands to the lowland plains) cross section of the NDVI values over the past four decades also shows the relatively higher decline of the green cover in the highlands (Figure 6).

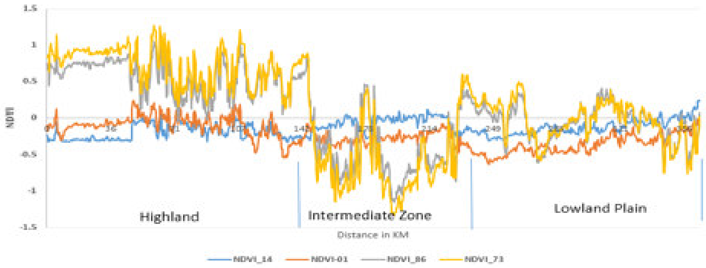


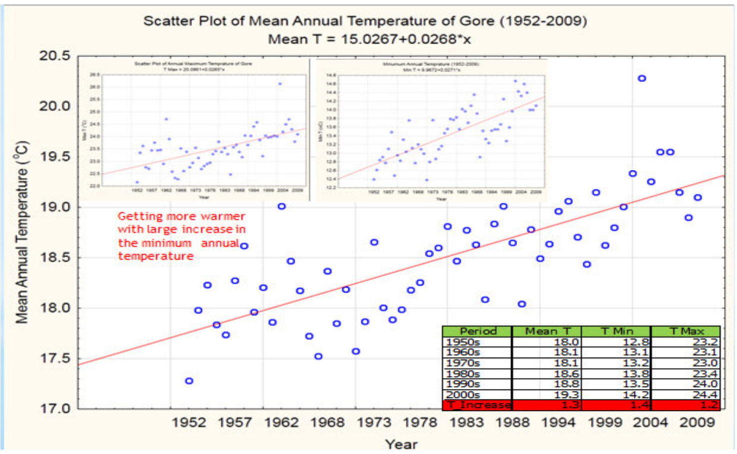
Figure 6: NDVI Values (1973-2014) from East to West (Highland to Lowland plain) across the Baro-Akobo Basin

Apart from the mapped land cover classes, introduction of thorny plants and weeds and changes in soil texture are observed in all affected localities. As a result of human pressure, environmental degradation is seen in these areas. Pristine forest areas have been cleared for crop cultivation. Analysis in a GIS using DTM has revealed that 75% of the crop cultivation and plantations are done on rolling and hilly and moderately dissected mountainous grounds with nonsystematic farming practices. These areas, which have been covered with thick high rainforest, have been exposed to erosion due to their slope and deforestation. The overall change in the past four decades is over 40% of which 20% happened only in 13 years, between 1972 and 1986.

4.3. Climatic Conditions and Changes in Rainfall-Runoff Situation

Although the induced changes are varying from place to place, changes in climate conditions is observed in the basin. These changes are manifested as increasing temperature, decreasing rainfall, decreasing river flows, and increasing potential evapotranspiration.

During the past four decades, significant increase is observed in both minimum and maximum temperatures. Data from one of the longer period recorded stations, Gore town, shows increase of 1.4 °C in minimum temperature and 1.2 °C in maximum temperature, between the period 1952 to 2009 (Figure 7). Such trends are also observed in other stations within the basin.



Period	Mean T	T Min	T Max
1950s	18.0	12.8	23.2
1960s	18.1	13.1	23.1
1970s	18.1	13.2	23.0
1980s	18.6	13.8	23.4
1990s	18.8	13.5	24.0
2000s	19.3	14.2	24.4
T_Increase	1.3	1.4	1.2

Figure 7: Trend in Temperature

A longer period analysis of rainfall data (1900 to 2012) has shown change in rainfall pattern and amount. The basin is getting 19% of the rainfall in the commonly known none-rain months (January, February, October, November and December (JFOND), 22% in the months of March, April and May(MAM) and 60% from the rainy months of June, July, August and September(JJAS). As shown in figure 8 below, observed data from Gore station, for the period 1900-2010, shows declining trend in all the three periods, with the highest decline being in JJAS followed by that of MAM and JFOND.

When the yearly rainfall amounts of recent decades are compared with that of the rainfall amounts of the 1950s and 60s a deficit of 499mm, 650mm, 548 and 959mm/annum are observed for the average annual rainfalls of the 1970s, 1980s the 1990s and for the period 2000-2010, respectively.

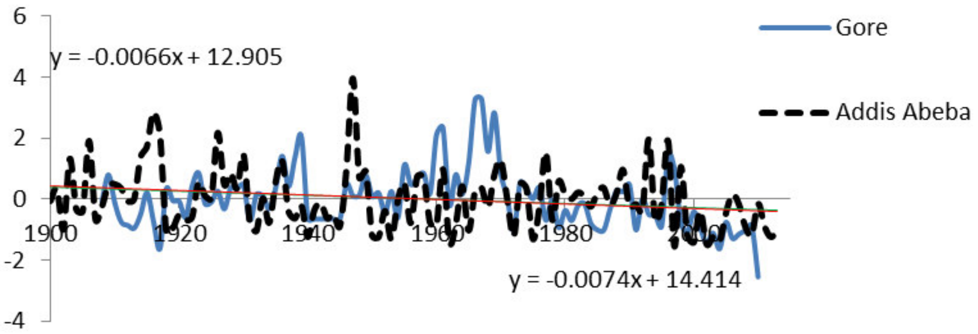


Figure 8: Time series (1900 to 2010) of annual rainfall z-scores for Gore and Addis Ababa with Gore showing more declining trend

Comparison of rainfall intensity between the 1950s and 1960s against the 1990s up to 2010 shows 19% increase in light intensity rainfall of 1 to 10mm/day and decrease (12 to 70%) in high intensity rainfall of more than 10mm/day and number of rainy days (Figure 9).

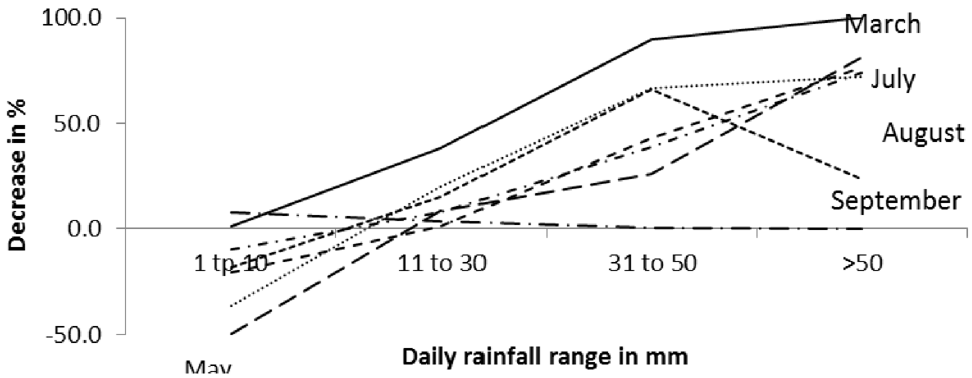


Figure 9: Changes in rainfall intensity during the past four decades

As can be seen in Figure 10 below and the flow duration corves on figure 11, the flows in the biggest river of the basin, Baro River, and one of its biggest tributaries also show continuous declining trends with some erratic high flows in few of the recent years. The most affected period is the flow during the months of March, April and May; which is highly sought rain for good coffee harvest in the area.

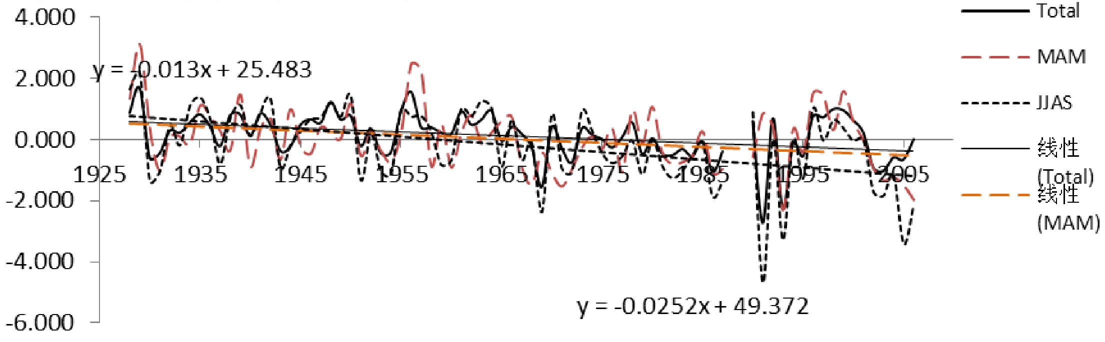


Figure 10: Time series of flow z-scores for Baro River at Gambella town with declining trend: during June-July-August-September (JJAS) and March-April-May (MAM)

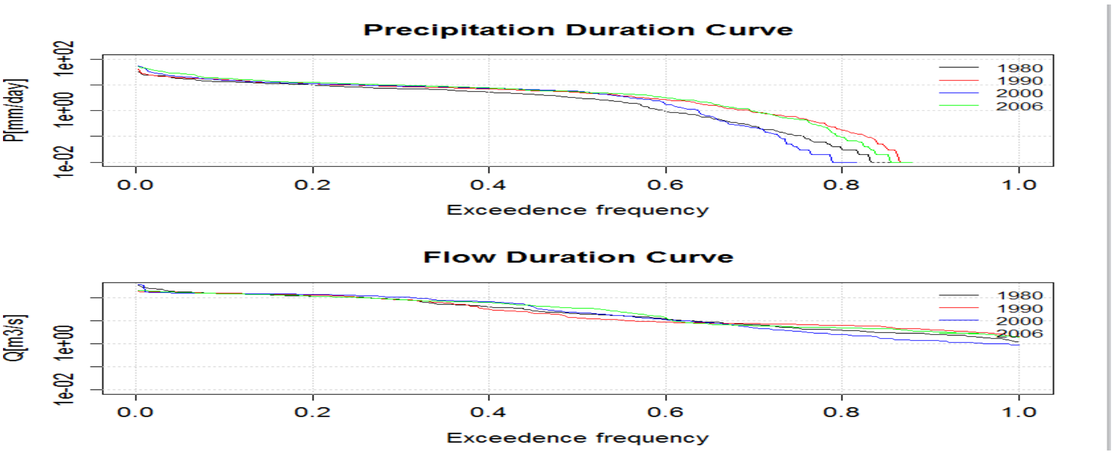


Figure 11: Precipitation and flow duration curves for Sor River at Metu Town

Well monitoring result undertaken for a contours fifteen months as part of this research activity has shown a well hydrograph to behave in a very similar manner with the river hydrograph, showing the senility of the groundwater (Figure 12). The three hourly log data also shows significant diurnal fluctuation in the shallow aquifers.

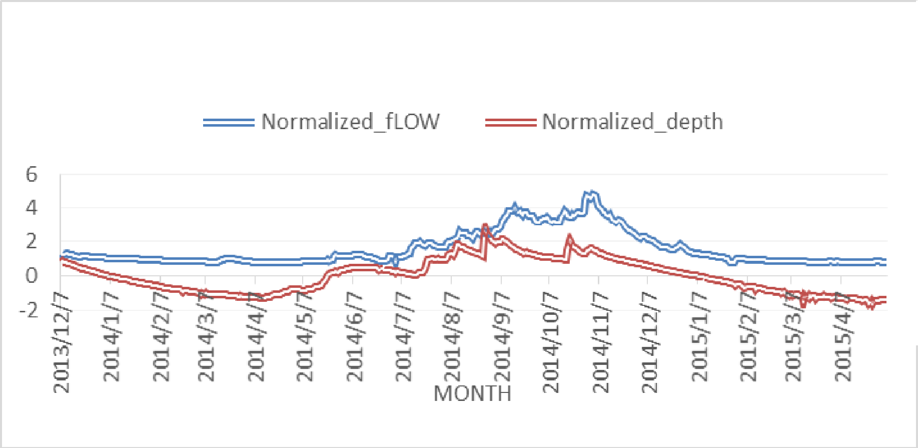
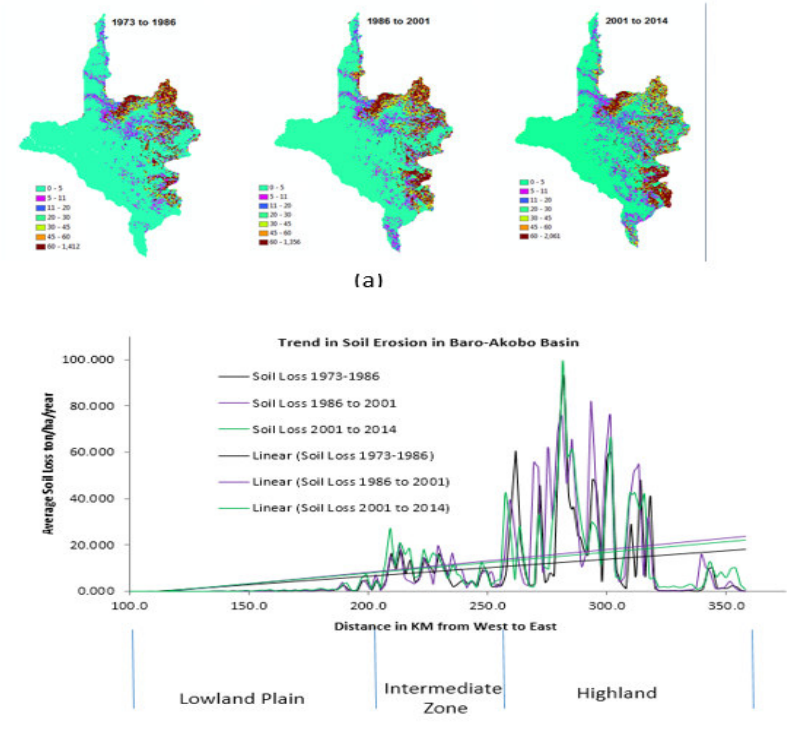


Figure 12: Groundwater Depth Fluctuation in Upper Baro vs Baro River hydrograph at Gambella

4.4. Trend in Water Soil Erosion

One of the manifestations of the changes in environmental quality is the significant increase in erosion rate. The total annual soil loss calculated with RUSLE method (USDA 1978) using input parameters developed for Ethiopia’s context (Hurni 1985), for the period 1973-2001 was 107million tons. This value rose to 137 million tons and further to 140 million tons, for the period 1986 to 2001 and 2001 to 2014, respectively. Nearly 95% of the increment happened during the period 1973 to 2001. The annual average loss is also the highest during this period. The recharge area, which is being intensively cultivated, is the most affected area (Figure 13 a & b).



(a)

(b)

Figure 13: (a) Annual average soil loss (ton/ha/year) over the basin for the three periods (b) Trend in soil erosion across varying hydro-geomorphic regions.

4.5. Changes in Hydrogeolical System

Simulation result in WetSpass show small increase in runoff and despite the increase in temperature there is a decrease in total evapotranspiration and significant increase in recharge during the recent decade (Figure 14 a & b, Table 1). The basin shows a very low recharge amount, making it a basin with very low recharge as compared to the basins in central and eastern parts of the country, which is in line with the hydrogeologic characteristics of the basin.

Coupled with other hydrological and hydrogeological characteristics of the basin, the result helps to understand the reason for finding large volume of surface flow entering the Machar wetlands and eventually reaching the White Nile from a relatively small watershed.

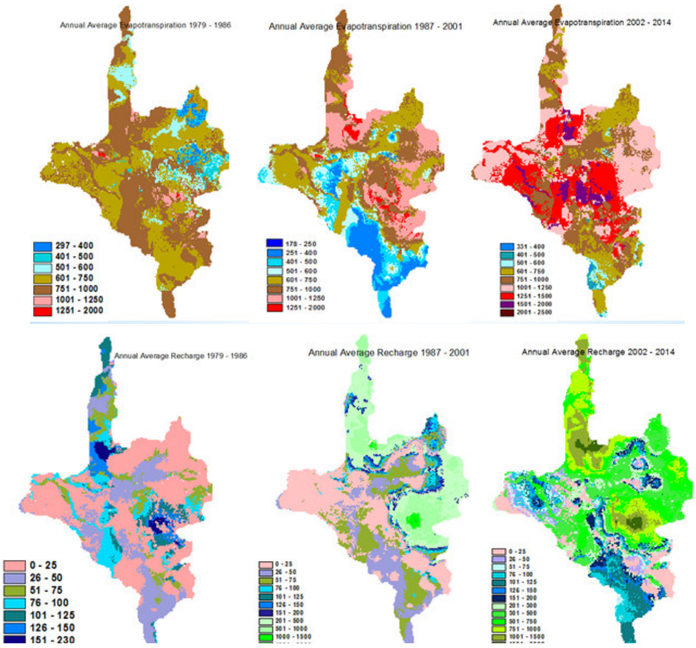


Figure 14: Model outputs- changes over the three periods (a) Change in Annual Evapotranspiration, (b) Change in Annual Recharge

The model was run with bias corrected rainfall and uncorrected rainfall estimates. The one with bias corrected rainfall gave outputs closer to previous total discharge estimates for the whole basin done during the master plan studies (SELKHOZPROMEXPORT 1990; TAMS and ULG 1997), 21 to 23 BCM/Year. Bias correction is done using "delta approach" that corrects only the mean and which resulted in a better match (Gebrie and Engida 2015). The formulas used for temperature and rainfall bias correction are indicated in Equations 1 and 2. Corrections factors were computed for each month.

(1)

$$P_{bc} = P_p \times \bar{P}_o / \bar{P}_r \qquad T_{bc} = T_p + \bar{T}_o - \bar{T}_r$$

Where,

Pbc is Bias corrected future rainfall amount in mm; *Pp* i (2) :ted future rainfall amount in mm;
Po is mean of observed rainfall amount in mm; *Pr* is mean of computed historical rainfall during the observation period in mm.
Tbc is Bias corrected future temperature in °C; *Tp* is predicted future temperature °C;
T o is mean of observed temperature °C; *T r* during the observed period in °C

Table 1: Model outputs- changes over the three periods (mm/year) (a) with bias corrected rainfall input, (b) without bias corrected rainfall input

Period/ Parameter	Mm/year							Basin-wide discharge (BCM)
	Runoff	Recharge	ET	Soil Evaporation	Trans-piration	Interc-eption	Total Discharge	
1979 - 1986	275.3	7.02	576.7	158.0	284.3	126.3	282.0	21.433
1987 - 2001	296.0	5.4	635.8	161.0	325.6	147.7	301.4	22.906
2002 - 2014	454.7	44.8	985.0	219.9	530.6	232.0	499.5	37.962

(a)

Period/ Parameter	Mm/year							Basin-wide discharge (BCM)
	Runoff	Recharge	ET	Soil Evaporation	Transpir ation	Interce-ption	Total Discharge	
1979 - 1986	396.8	40.2	797.5	207.2	401.7	180.3	437.0	33.212
1987 - 2001	426.1	37.6	884.8	213.3	458.8	210.7	463.7	35.241
2002 - 2014	657.8	165.7	1313.7	272.5	716.8	321.3	823.5	62.586

(b)

5. Discussion

5.1. Anthropogenic Impacts on the Environment

The more than 40% induced land use/land cover change that is negatively affecting the basin is mainly due to anthropogenic pressure. As a small and delicate river basin, the population pressure looks evident from the nature of its population dynamics. The basin is a destination for three types of people movement into the basin- legal resettlement, illegal resettlement and refugee influx. Hundreds of thousands of refugees from South Sudan have settled in the area for decades. Since the beginning of 2014, Ethiopia has accepted almost 226,000 refugees who fled the recent conflict in South Sudan (TheUNRefugeeAgency 2015) to this basin. There were 400,000 refuges whose influx is not only initiated by instability the current climatic change also forecasted to displace many people from lower altitude Sudan Sahel to the high land Ethiopia as a result of shortage of water, lack of rain, and loss of production capacity of the lowland plains South Sudan (Haile Mariam Behailu 2011).

Resettlement programs have been going on for the past four decades (Woube 2005). Results of two consecutive national censuses taken in 1994 and 2007 clearly show the attractiveness of the basin (PopulationCensusCommission 1996; PopulationCensusCommission 2008). The migrant population, excluding refugees, is almost half of the total indigenous population in the basin. Unlike nature of migrations in other parts of the country, migrants to this basin are dominantly men that may eventually bring their families after getting well established. Migrants' preference destination is the pristine rural areas that provide them with fertile land to cultivate, mining and all kinds of land and forest related activities. Zones within the basin have higher migrant population than their respective regions and their population growth rate is higher than their respective regional averages (Table 2).

Table 2: Population dynamics, Excluding the Refugee Population, in Baro-Akobo Basin

	Regional level			Contained within the Basin			
Region/Zone	GRS	Oromia	SNNPRS	GRS	IlluAbabaora (Oromia)	Keffa_Sheka Zones(SNNPR)	Bench Maji(SNNPR)
Population increase (1994 to 2007)	47.16	30.61	30.49	47.16	33.39	32.49	50.59
Migrant population in 2007 (% of total population)	47.12	16.36	13.90	47.12	21.53	19.01	18.90
- Male	53.76	48.76	47.99	53.76	51.19	49.34	50.83
- Female	46.24	51.24	52.01	46.24	48.81	50.66	49.17
- Rural	66.04	61.89	66.13	66.04	78.11	76.39	76.75
- Urban	33.96	38.11	33.87	33.96	21.89	23.61	23.26
Migrant pop. (%increase)	62.45	41.16	51.24	62.45	49.12	44.80	59.46

Source: Population and Housing Census Commission, 1996, 2008

The bulk of the change also mark the time of change in Ethiopian land policy. Following the 1974 Ethiopian Revolution land become a public property that lead to loss of sense of ownership and diminishing trend in land care. Interviews made to the local people and observations made has revealed competition for land ownership tittle at an alarming rate. Land clearance by burning the high rainforest is practiced even by the indigenous forest dependent communities in the remaining forested land. Total absence of sense of ownership and the temporary nature of their living style have made illegal settlers the worst enemy of the environment.

5.2. Changes in Climatic Conditions and Rainfall-Runoff Situation

The Baro-Akobo basin's hydro ecosystem is disturbed, the natural forests of the region nowadays are not in a position to perform its ecological, economic and social functions. There is clearly noticeable and measurable climate change in the basin. Increase in temperature, particularly the mean temperature, erratic nature of the rainfall and its changing patterns are creating negative impacts at micro watersheds and basin level. Increase in temperature increased evapo-transpiration from the subsurface soil creating moisture stress to the plants. Increasing fire incidence, loss of forest species, reduction in forest regeneration, invasion of new species are emerging problems in the basin. The diminishing size and volume of wetland areas is mainly caused by decreasing rainfall and flow, silting up due to floods coming from the highlands, increasing evaporation as a result of increasing temperature (Haile Mariam Behailu 2011). The changing rainfall pattern has also created accelerated water erosion. Coupled with a number of catchment specific factors such as soil property and slope rainfall characteristics such as intensity, duration and distribution, have created a direct bearing on the occurrence and volume of runoff. Water scheme inventory in rural areas of Gambela region has shown 56.47% of the schemes to be nonfunctional (Haile Mariam Behailu 2011). Although technical failures is the main reason, lowering of the water tables, drying up of springs have left hundreds of schemes non-functional. More than 50 meters drops in water table are measured in wells located in some localities of the arid areas. Large scale drought happened in the year 2008/09. Although not wide spread, drought is occurring every year in different parts of the basin as a result of rainfall variability and seasonal shift of rainfall at the production season.

5.3. Increasing Water Soil Erosion

The continuous increase in water soil erosion and the great leap during the 1973 -2001 period marks the period of land policy change and coincides with land degradation rates. For its pristine nature, the Baro-Akobo basin is known for its lowest rate of soil erosion when compared with all other basins across the country. The degraded parts which have undulating nature in the high lands and steep slope in the intermediate zone with mainly clay soil cover yield more runoff than those with gentle slopes (Sharma et al. 1986). The runoff efficiency (volume of runoff per unit of area) increases with the decreasing size of the catchment i.e. the larger the size of the catchment the larger the time of concentration and the smaller the runoff efficiency. The undulating nature and the small size of the watersheds also a reason for the increased runoff. The physical conditions of a catchment area are not homogenous. Even at the micro level there are a variety of different slopes, soil types, vegetation covers etc. Each catchment has therefore its own runoff response and will respond differently to different rainstorm events (Feng 2008). The dominant clay cover has also great contribution for increased run-off.

Runoff is positively affected by clay. Surface runoff has a good correlation with the rainfall energy. Coarse sand, organic matter and lime contrary to silt positively affected soil permeability and consequently reduced runoff. Spatial variability of the soil infiltration capacity is related to the high spatial variability of soil properties (structure, organic matter content, antecedent soil moisture, etc.) that affect the runoff generation in the hillslopes. Runoff significantly related to soil texture. Effect of coarse sand in enhancing soil permeability and in consequence reducing runoff due to presence of macro pores, rate of water enter to soil is higher than of fine textured soils and so generation of runoff is lower than them (A. R. Vaezi 2010). Soil loss increase exponentially with the degree of slope and distance from gully head. Erosive force of run-off increases with both slope steepness and distance down slope gradient alone explains about 63% of the spatial variations in the intensity of gully erosion (Ibid). Increase in runoff is greatly attributed to forest clearing. An area densely covered with vegetation, yields less runoff than bare ground(Rita D. Winkler, Moore et al. 2010).

5.4. Changes in Hydrogeolical System

The main governing factor for the sensitivity of the hydrogeological system that made the basin most vulnerable is its hydrogeological characteristics. The 39% basement lithology and the 79% clay soil cover of the basin coupled with the multi-sets regional and local structures has aggravated the anthropogenic pressure mentioned above. The dominant Precambrian terrain with its north-south dominant orientation and the undulating geomorphologic setting in the recharge areas and steep to gradual surface gradient towards west of the discharge area, which is covered by thick Quaternary sediments, are probably the main reason to make the basin sensitivity to anthropogenic activities and climate variability. These Geologic structures act as conduits to the sub-surface flow and most river routs cut perpendicular to the basement orientation following the east-west fault systems that are younger in age than the other sets. Observed and measured regolith and fracture zones over the basement cover that can act as aquifers rarely exceed 50 meters. Old fractures are filled by secondary mineralization and new ones have shallower depths. The dominant East- West fractures and west ward dipping topography (Tefera and Berhe 1987; Moore and Teklewold 1989) have pronounced flow accelerating effects. The overlying Tertiary Volcanics, which could have acted as good aquifer, have clay and clay loam soils developed on top of them to make them moderate aquifers. Its characteristics are also influenced by topography and fractures.

The wetlands in the plain, which is part of the Machar wetlands, and the great Sudd Wetland complex is developed as a result of the accumulation of thick clayey soils (extensive Vertisols) that may prevent full recharge of the quaternary aquifers (FAO 1984). The dominant heavy clay or loamy soils of the basin have low infiltration capacities. Soils with a high clay or loam content are the most sensitive for forming a cap with subsequently lower infiltration capacities (Usunoff 2012). On top of that, the infiltration capacity is further affected by the moisture content prevailing in a soil at the onset of a rainstorm. In the semi-arid parts of the forest areas capping, crusting or sealing of the pores is observed enhancing Hortonian Flow after high intensity rainfalls. This is happening as result of a breakdown of the soil aggregate as well as soil dispersion with the consequence of driving fine soil particles into the upper soil pores during a high intensity storm with high kinetic energy hitting the soil surface. The high evapotranspiration rate, as a result of the increasing temperature and the predominant forest cover is also one of the prominent influencing factors for the reduced recharge. Hence, the lowest recharge amount, as compared with the rest of the basins in the country, is seen in the basin.

Although this is a general feature of the basin, there is slight increment in recharge in the recent decade. This is due to the transformation of the forest land into open agricultural land, which has improved infiltration capacity than the forest land. As a result of the forest clearing, the amount of rain lost to interception has dramatically reduced. In forested areas, increase in low intensity rainfall leads to more loss of the rainfall as evapotranspiration and decrease in high intensity rainfall leads to minimized amount of rainfall reaching the ground and hence decrease in recharge of the groundwater. The loss of forest cover results in an increase in net precipitation (Rita D. Winkler, Moore et al. 2010). As interception storage on the foliage depends on the kind of vegetation and its growth stage. The more significant is the effect the vegetation has on the infiltration capacity of the soil. The dwindling dense vegetation covers has shielded the soil from the raindrop impact and reduced the crusting effect and eventually enhance recharge. In addition to this, the root system as well as organic matter in the soil of the forest area increase the soil porosity thus allowing more water to infiltrate. Vegetation also retards the surface flow particularly on gentle slopes, giving the water more time to infiltrate and to evaporate. But for the above mentioned reasons, such contributing factors for recharge are not significant enough to have large recharge. Although it has a seasonal shift and low duration, the increase in total annual rainfall has also contributed to the increased recharge in the recent decade.

Conclusions

As well stated by Steel et al (Sileet, Shamy et al.), the Baro-Akobo-Sobat (BAS) sub basin is considered as one of the most promising regions in the Eastern Nile Sub-basin. Baro –Akobo basin, the subject of this research is the upstream and the sources area. Its fragile environment and the hydro- ecosystem is being subjected to unprecedented anthropogenic pressure and negative impacts climate variability. The impacts are long felt by the local residents as flood hazard, dying springs, lowering water tables and lost wetlands. If the current trend continued unabated the impacts will be felt by all downstream riparian countries. The lowland marshy areas act as evaporation pan. In this respect, any water conservation measures in the uplands if coupled with conservation and restorations measures will help to prolong the life of the hydro ecosystems. The studied and planned construction of dams for hydropower production such as: Tams, Birbir A and Birbir R, Baro-1 and Baro-2, Geba-A and Geba-R Dams and Genji Scheme are a very wise decision, if undertaken with great care not to affect the ecosystem.

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