Mar 28, 2022

Hydrogeological mapping for Climate Resilient WASH in Ethiopia – LOT 1

Report Phase 3 – BDA/ICB/GW01/2021




Ministry of Water and Energy

ACACIA WATER

aquacon

UHL

aquacon

Colophon

Document title	.	Hydrogeological mapping for Climate Resilient WASH in Ethiopia – LOT 1
Client	.	Ministry of Water and Energy
Status	.	Report Phase 3 – BDA/ICB/GW01/2021
Date	.	Mar 28, 2022
Project number	.	201150
Author(s)	.	T. Kleinendorst, J. Sima, dr. Tarekegn Tadesse, Shiferaw Lulu, dr Dessie Nedaw, dr. Sirak Tekleab, dr. Shimeles Fisseha, dr. M. Waterloo
Peer review		A. Ketema
Released by		Dr. A.C. de Vries

Contents

Acronyms

Abbreviation	Description
BDA	Basins Development Authority
MoWIE	Ministry of Water, Irrigation and Energy
MoWE	Ministry of Water and Energy
MOU	Memorandum of Understanding
DFID	Department for International Development
SDG	Sustainable Development Goal
WDC	Water Development Commission
NGO	Non-governmental Organisation
GIS	Geographic Information System
QGIS	Quantum GIS
UTM	Universal Transverse Mercator
EPSG	European Petroleum Survey Group
WGS84	World Geodetic System 1984
TWI	Topographic Wetness Index
SRTM	Shuttle Radar Topography Mission
SRTMGL1	Shuttle Radar Topography Mission Global 1-arc second dataset
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
ESA	European Space Agency
CCI	Climate Change Initiative
Ksat	Saturated conductivity
AHP	Analytic Hierarchy Process
CI	Consistency Index
T	Transmissivity
Q	Discharge
q	Specific discharge
TDS	Total dissolved solids
CSA	Central Statistical Agency
GTP II	Growth and Transformation Plan
lpcd	Litre per Capita per Day
TOR	Terms of Reference
BOQ	Bill of Quantities
RMS	Risk Mitigation Strategy
DEM	Digital Elevation Model
LIDAR	Light Detection and Ranging
RMM	Risk Mitigation Method
O&M	Operation and Maintenance
WAPOR	Water productivity open access portal
SAR	Synthetic Aperture Radar

1 Introduction

The Ministry of Water and Energy has received funding from DFID for a three-year project entitled "Delivering Climate Resilient Water, Sanitation and Hygiene in Ethiopia". As agreed by an MOU between DFID and the Government of Ethiopia, two of the four programs are being implemented by the Ministry. This project, which runs to 31 March 2022, is part of the UK government's aid strategy to support the poorest people in adapting to climate change, specifically on building climate resilience in water and sanitation services that contributes to achieving Sustainable Development Goal 6. The project complements DFID and Ethiopia's significant programming on water and sanitation and supports effective delivery of the Government of Ethiopia's strategy for sustainable water supply in drought affected areas. A key feature of this program involves funding for groundwater mapping and improvement of groundwater data management.

1.1 Objectives

1.1.1 Overall objectives

The objective of this project is to increase access to safe and sustainable water for the people in drought affected regions by producing hydrogeological maps at the Woreda level and recommend drilling sites which the Government of Ethiopia and other partners can use for developing groundwater.

1.1.2 Specific objectives

A first step of this project is the initial identification of target areas for borehole drilling. The focus of this project is:

- Create detailed groundwater potential maps for each Woreda.
- Identify one optimal drilling site and one alternative (optional) drilling site per Woreda, using the groundwater potential maps and geophysical field investigation results, and recommend the type of drilling methodology(s) to be employed.
- Build the capacity of the former Water Development Commission (WDC), former Basins Development Authority (BDA), regional governments, and NGOs to use/apply overlay analysis techniques for groundwater potential mapping and borehole siting in Ethiopia.

1.2 Project area

The overall project covers a total of 53 woredas throughout the country which is subdivided into four lots. The current project deals with the 13 woredas from Lot 1 in the Tigray, Afar and Amhara Regions (Figure 1).

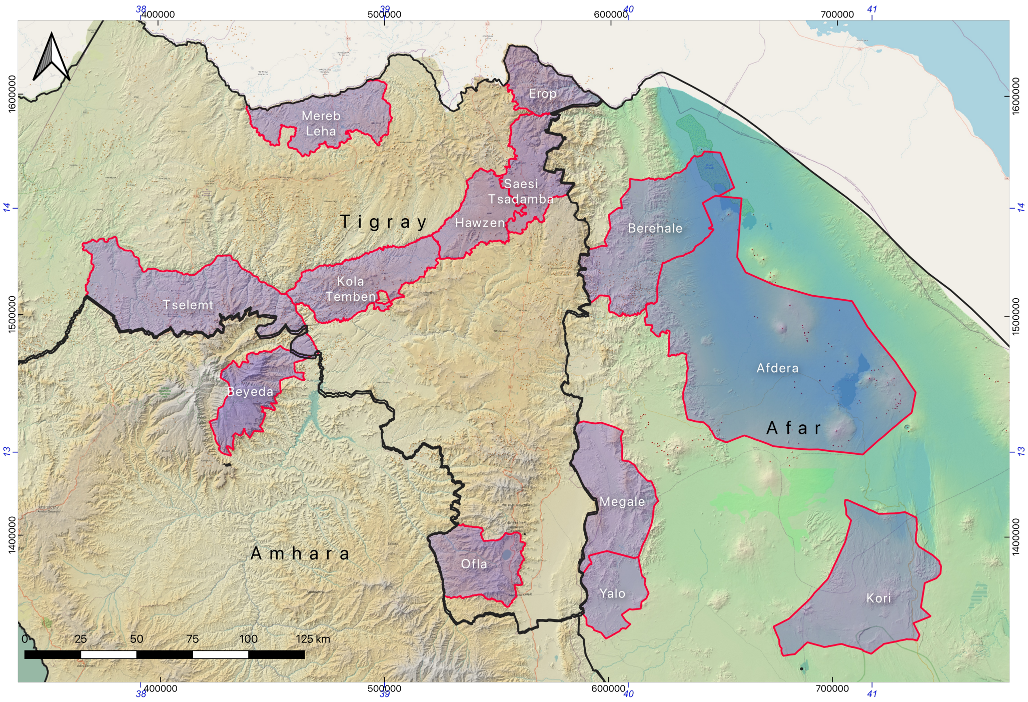

Figure 1. Location of the 13 selected woredas for Lot 1

1.3 The project

The project is designed in 3 phases:

- Phase I (Inception Phase)
- Phase II (Mapping Phase)
- Phase III (Siting Phase)

Phase I has been completed in August 2021, while phase II was finalized in Jan 2022. The current report covers the work for Phase III.

The main outputs of Phase III are:

- A more detailed geological unit distribution, including structural details in appropriate scale, based on higher resolution images;
- Hydrogeological operational maps (1:50,000);
- Detailed geological, hydrogeological, and geophysical (including existing data and satellite geophysics) study in each target area;
- Determination of target drilling sites in the target areas, including drilling sites maps (1:5,000) and geophysical profiles
- Phase III final report per target area;

The outputs are attached as annex 1-3 to this report and can be downloaded from the dissemination website of the project https://mowe.acaciadata.com.

1.4 Acknowledgement

Due to the security constrains in the project area, the workplan for phase III has been revised. The project team could not travel to the field to carry out inventories, hydrogeological or geophysical studies. Instead, we relied on existing data and remote

sensing products. Because fieldwork is essential for updates on the actual water demand and gap analysis, geological and hydrogeological conditions, and geophysical surveys, we can only propose target sites with a certain tolerance radius, not exact drilling sites. Exact drilling sites, drilling depth and estimated yield should be set after detailed geophysical fieldwork.

2 Target areas

Using the groundwater potential maps, socio-economic maps, conceptual models and cross sections, target areas have been selected in every Woreda during phase II of this project. The selection of target areas should have been done in consultation with local experts and stakeholders. Due to the security constraints, this could not be realized. Instead, the project team has prepared a prioritized list of 2 to 4 target areas per Woreda where both groundwater potential, and water demand has been considered. It should be noted here that the water demand is derived from secondary data from CSA census (2007), projected population growth, locations of schools, health centres and existing water point inventories. Please see the report of Phase 2 for a generic description of the methodology. Detailed water demand estimates have been included in the woreda reports.

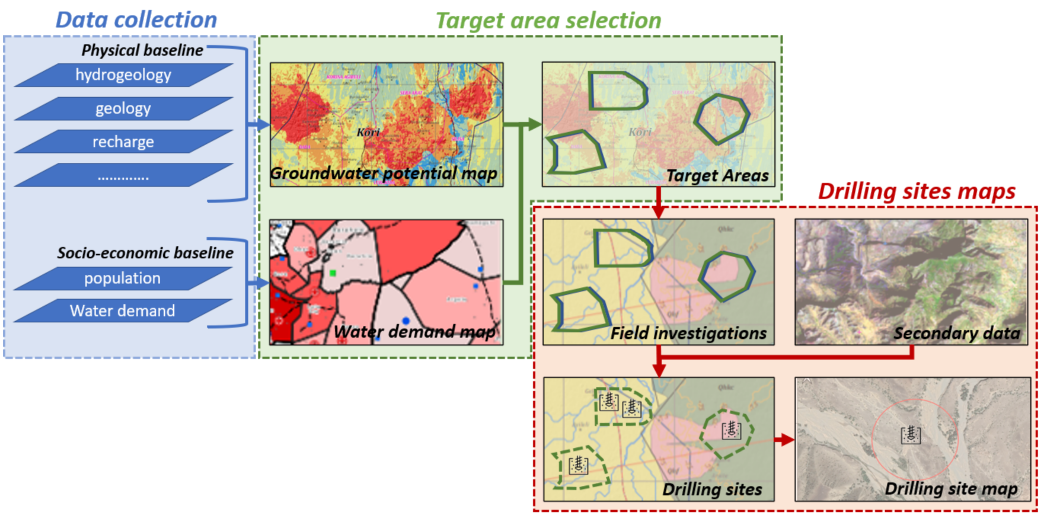

Figure 2 Methdology

The groundwater potential maps from Phase 2 have been used as a starting point to select the target areas. The maps were prepared using GIS overlay analysis which applies the rating and scoring of hydrogeological parameters that controls the occurrence and movement of groundwater in the areas, which considers parameters such as: lithology, lineament and lineament density, drainage, and drainage density, inferred permeability, geomorphology and slope, precipitation, and recharge rate.

Technical and socio-economic aspects of the areas have also been considered during the selection. These include evaluations on geology and geomorphological settings, general hydrogeological conditions, access, water demand and presence of social infrastructures in the area with lack of water supply to get priority in selections.

The target areas are presented as polygons with reference coordinates to their centres to support in ground control during the geophysical survey and pinpointing the actual drilling sites which will be depicted on the 1:50,000 operational hydrogeological maps during phase III.

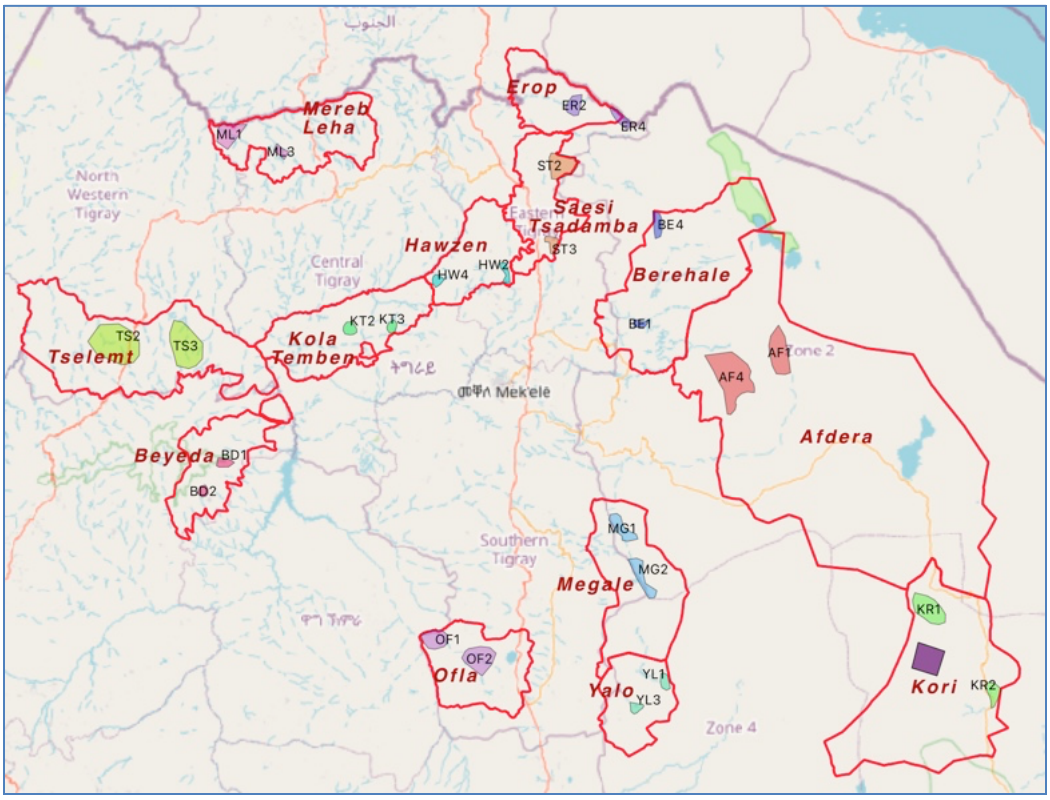

Figure 3 Lot 1 Target Areas

3 Geology

3.1 Description of regional geology

The geology of northern and north-eastern Ethiopia, in which the project areas are situated, was previously mapped at different scales and studied by various researchers. The mapping of the region at a scale of 1:250,000 by the Geological survey of Ethiopia including Adigrat map sheet (Garland, 1972); Mekele map sheet (Beyth, 1972), Axum map sheet (Tadesse, 1997), Adi Arkay map Sheet (Tsegaye, 1974) and, compilation work of geology of Afar area at a scale of 1:100,000 (UNICEF report) are sources of major geological information. These works have identified and described a succession of rock formations ranging in age from Precambrian up to Quaternary. The Precambrian metamorphic rocks include low grade metavolcanic and metasedimentary rocks. The metavolcanic rocks cover relatively larger part of the metamorphic terrain of northern Ethiopia and is regionally known as the Tsaliet Group (Beyth, 1972, Garland, 1972, Tefera et. al., 1996). This is uncomfortably overlain by poorly metamorphosed and weakly deformed younger silciclastic and carbonate units of slates and limestone known as the Tembian Group (Beyth, 1972, Grland, 1972). These slate-carbonate succession are contained in a series of NE-SW, often overturned pairs of synclinal and anticlinal structures. These rocks together with mafic to felsic intrusive bodies of variable size and composition in the region belong to the Arabian Nubian Shield component of East African Orogen (Stern, 1994, Tadesse, 1997; Tadesse et. al,. 1999, 2000, Asrat et al., 2003) and are thought to be the product of plat tectonic process that involved subduction, build-up of intraoceanic island arcs, lateral accretion of the arcs associated with the convergence and subsequent collusion between East and West Gondwana during the Neoproterozoic (900-550 Ma., Stern 1994, Fritz 2013).

These Neo-Proterozoic metamorphic rocks of the region are unconformable overlain by Palaeozoic (Ordovician) tillites (Edaga Arbi Galcials) which is laterally inter-fingered with carbonate cemented, white clastic Enticho Sandstone (Graland, 1972; Beyth, 1972). These rocks, where not covered by the later Jurassic sedimentary and Tertiary volcanic sequence or eroded deep, they represent potential ground water aquifers of the region. Following the Ordovician deposit, intra-continental rifting in Permian initiated the break-up of Gondwana and led to continental mass subsidence and subsequent transgression of Indian Ocean (Hunegaw et al., 1998; Boselline et al., 2001). The transgression lain down thick clastic, passive continental margin deposit followed by shallow and deep marine sedimentary deposits during the Jurassic (Hunegnaw et al., 1998; Bosellini et al., 2001). The base of transgression event was marked by the deposition of clastic lower sandstone known as the Adigrat Sandstone in the northern Ethiopia; followed upwards by scission of limestone marl, and shale and ended when the region was uplifted by mantle plum under the Afro-Arbain plate (Mohr and Zanettin, 1988). The up-doming resulted in the withdrawal of the Indian Ocean and deposition of regressive facies; marine sediments caped by clastic sedimentary rock (the upper Sandstone or Abaradam sandstone (Hunegnaw et al., 1998; Bosellini et al., 2001).

Plum related voluminous Tertiary Flood basalt eruption between 42-29Ma on the top of Mesozoic Sedimentary succession is believed to be approximately coeval with northeast-directed extension in the southern Red Sea and Gulf of Aden (Ebinger et al., 1993; Baker et al., 1996; Hofman et al., 1997; Ayalew et al., 2002; Ayalew & Yirgu, 2003). The volcanics are made up repeating sequences of thick (up to 2km) basaltic lava flows overlain by rhyolites including ignimbrites, air fall tuffs and lavas. These volcanic rocks cover much of the NW and SE Ethiopian Plateau. The edge of Afar depression is made of heavily faulted and weathered Eocene to early Miocene (25-15Ma) Trap basaltic volcanic rocks (Beyene & Abdelsalam, 2005). The most extensive volcanic sequence covering about two thirds of the NW-SE Afar Depression is the Pliocene-Pleistocene Afar Stratoid Series of up to 1500 m thick (Barberi & Varet, 1977; Hayward & Ebinger, 1996; Hofstetter & Beyth, 2003). These and overlying younger sequences are believed to be controlled by the NW-SE rifting parallel to the Red Sea rift axis. East and west of the Afar depression, Transverse volcanics of mainly basaltic composition occur (Barberi & Varet, 1977; Hayward & Ebinger, 1996; Hofstetter & Beyth, 2003). The axial zone of the Afar Depression is covered by Quaternary Axial Volcanic Ranges and are characterized by fault controlled fissure eruptions and shield volcanoes with basaltic flows and alkaline and per-alkaline silicic rocks. They occur along northwest-southeast trending narrow rift zones ((e.g. Mohr and Zanettine, 1988)). The Quaternary sediments of the Afar Region are mostly fluvial/ or lacustrine In origin, commonly thin, often terrace forming but occasionally thick pile of sediments occur in deeply faulted narrow grabens.

3.2 Update of the geological maps

Detailed, 1:50,000 scale geological maps have been constructed for the target areas. The maps form the basis for the 1:50,000 hydrogeological maps that are annexed to the 13 woreda reports.

Existing 1:100,000 and 1:250,000 scale maps have been used as a base map for lithological naming and where possible to get the dip and strike of structural data. These maps have been produced by most experienced geologists, using ground traverses augmented with black and white aerial photo interpretation of approximately 1:60,000 scale.

The present 1:50,000 maps for the target areas have been created using satellite imagery with very good resolution (Sentinel-2, Landsat-8). Use of image enhancement techniques (band ratioing) produced colour mosaic map of the areas with clear geological boundaries defined by different hues of colour, faults and lineaments. The tracing of geological contacts and major structures are done more accurately than the 1:250,000 scale map. In most cases, we have obtained enhanced detailed geological information, modified the contacts of geological units with good precision.
The mapping production of the TAs is completed by geologists who have physically mapped the region in person with input from the GIS-Remote sensing expert.

4 Hydrogeology

The hydrogeological characteristics and groundwater potential of the areas are highly affected by the complexity of the geology, physiography, climate and geological structures. The classification of different lithological units is based on the qualitative and quantitative parameters of the hydrogeological characteristics of various rocks. Since quantitative data such as permeability, yield, aquifer thickness and transmissivity are not sufficient or evenly distributed throughout the area, it was essential to apply a qualitative approach in order to achieve a complete and detailed potential classification. Qualitative investigation includes field observations of the geological, hydrogeological, geomorphological, physical and geographical setup. Hence, the lithological units are characterized as having porous or fissured permeability, or they are impermeable.

Based on the hydrogeological character of the lithological units and their topographical position, the study area can be divided into aquifers – non aquifers with different occurrences of groundwater, as follows:

- Porous aquifers developed in Quaternary alluvial and eluvial sediments;
- Fissured and karstic aquifers in limestone, fossiliferous and sandy limestone;
- Fissured aquifers developed in Paleozoic to Mesozoic sedimentary rocks (non-karstic), Tertiary and Quaternary volcanic rocks;
  - Fissured aquifers developed in Precambrian basement rocks;
- Aquitards and aquicludes.

The hydrogeological map shows aquifers defined based on the character of groundwater flow (pores, fissures) and the yield of springs, boreholes and dug wells.

5 Geophysical exploration

The main objectives of geophysical investigation have been the identifications of structural elements with depth estimates of anomalous subsurface sources using potential data, namely, regional airborne gravity data. The main objective is to delineate all possible structural features and examine their roles on the regional groundwater dynamics of Northern and North-eastern Ethiopia.

Overview of geophysical methods being widely used for variety of purposes in groundwater studies, such as:

- Geologic characterization, including assessing types and thicknesses of strata and the topography of the bedrock surface below unconsolidated material, and generating fracture mapping and paleochannels;
- Aquifer characterization, including depth to water table, water quality, hydraulic conductivity;
- Contaminant plume identification, both vertical and horizontal distribution including monitoring changes over time.

There are several geophysical methods that are common to most groundwater studies. The first most important step is collecting high-quality data using the geophysical method or methods that are most likely to provide crucial parameter that can help resolving a particular hydrogeological characterization or monitoring objective and that work well in the given environment. Although the corresponding geophysical properties.

Maximum effort has been exerted to review of all existing geophysical works within the project area and use the data to assist the ongoing integrated ground water assessment program in Lot 1, which comprised Woredas in Tigray, Afar and Amhara Regions.

The first desirable component, readily available for regional evaluation, was a countrywide Airborne Gravity data. The existing aero-gravity data covering the North and Northeast regions is obtained from the airborne gravity surveys over Ethiopia, acquired in the period from 2006 to 2008, through the collaboration between the Geophysical Observatory (the current IGSSA) of the Addis Ababa University, the Ethiopian Geological Survey, (GSE) and the Danish National Space Centre (DNSC).

The other usable input is that of geoelectric data resulted from previous geophysical works, Vertical Electrical Survey (VES), in the LOT1 project area. The vast majority number of the sounding points are from east central Tigray regions. A good number of usable VES data were also found from Afar region. Unfortunately, there has not been any VES data from Woredas in the Amhara region.

Those set of geoelectrical data, whose sounding points are within the boundary of the target areas of the current project, would be used for quantitative appraisal of the subsurface layer parameters.

Existing geophysical datasets provide a useful, yet highly limited, perspective on geophysical signatures of groundwater occurrence in the project area. This constitutes a major limitation that the subsurface hydro geophysical parameters were sought from the scarce previous works in the area.

6 Hydrology

The hydrological study aims at characterization of catchment areas, streams and rivers within or adjacent to the study areas and assessments on recharge patterns and rates, existence of springs and their hydrogeological implications and surface water and groundwater relationships. The assessment of the hydrology of the target areas is part of the development of Conceptual Models (Phase II) since analyzing the interaction between surface and groundwater is essential to understand the hydrogeology of the area.

The sustainability of groundwater use is a balance between recharge volumes of groundwater in a source area and subsequent extraction for domestic, agricultural and industrial use. Agricultural use of water is related to irrigation, mainly in the dry season. As irrigated water is lost to the atmosphere by evapotranspiration, the extraction of groundwater for irrigation results in increased evapotranspiration, and therefore will affect river runoff if groundwater levels are structurally lowered by the extraction.

Groundwater recharge is one of key input in the overlay analysis and is investigated using multiple approaches so at to arrive at acceptable values. Recharge is estimated for each woreda based on the recharge generated by validated SWAT models, which has been a proven approach in Ethiopia. The recharge values obtained in this study serve to assess the sustainability and limits of groundwater extraction for use in agriculture or drinking water supply.

This study is a continuation of Phase I and II of hydrogeological mapping of climate resilient WASH project in Ethiopia. For the surface water hydrological study, meteorological and hydrological data available on daily time scale were collected and analyzed. The study envisages the rainfall-runoff processes with the objective of estimating the water balance components of the target areas on monthly and annual time scales. Groundwater recharge was estimated using the Soil and Water Assessment Tool (SWAT) model at sub-watershed level. The water availability within the target areas for different competing needs, i.e. for domestic, irrigation, industrial and livestock use, have been estimated through accepted techniques. Due to many sources of uncertainties, such as in the temporal input data, spatial data heterogeneities, hydrological model spatial representation and model parameter uncertainties, the estimated water balance components and recharge are subject to a certain degree of uncertainty. Hence, the study first and foremost was limited to use merged rainfall satellite products from the Climate Forecast System Re-analysis (CFSR) and CHIRPS data (Climate Hazards Centre, n.d.; Dinku et al., 2018) as forcing inputs into the SWAT model in order to estimate the water balance components and recharge. However, one could get different outcomes using different forcing inputs, hydrological models and approaches. The other limitation of this study is that the estimated baseflow and the spatio-temporal variation of the water availability have not been validated through field exploration. This could not happen due to the current security issue in the study area.

The determination of the water balance components, including river flow amounts and groundwater recharge estimates, was based application of the Soil Water Assessment Tool (SWAT) model (Arnold et al., 2012; Srinivasan et al., 2010; Tibebe and Bewket, 2011) to several catchments in the project area.

7 Hydro-geochemistry

The chemical quality of the groundwater in Afar region ranges from fresh groundwater to brine. The Total Dissolved Solids (TDS) which is the major indicator of salinity ranges from about 300mg/l in the western rift margins to over 100,000mg/l in the Danakil Depression. The salinity increases from west and northwest towards east and northeast following the general trend of the groundwater flow. The groundwater from the mountains dissolves different chemicals on its way towards the Danakil Depression that increases the salinity of the groundwater. The salinity is as a result of the long and deep circulation of the groundwater from the western and southeastern plateau towards the Afar depression, the geothermal activities within the Afar Depression, dissolution of the salt deposits and high evaporation rate in the Afar depression that leaves salty crust on the surface that leaches into the groundwater during rainy seasons.

The springs that feed the lakes are brackish to brine that form saline lakes of Afdera, Assale and salt flats. The water quality analysis result from the 550m deep test well situated 44km west of Afdera Lake / Town shows that the groundwater is saline with TDS range 22,000 mg/l to 42,000 mg/l. At the beginning of the test the TDS was high and at the end of the test the TDS has reduced almost by half. This is as a result low TDS water was being attracted from the western mountain side with the expansion of the cone of depression with increased duration of test. The electrical conductivity (EC) monitoring of the drilling mud during drilling indicates a general declining trend of EC values up to 360m depth and then shown increasing trend. This indicates that the deeper groundwater is more saline than the shallow ones probably related to density difference.

The major ions of the groundwater are sodium, calcium and chloride. The chemical analysis result of the water sample shows that the groundwater is chemically Na-Ca-Cl and Ca-Na-Cl type. The groundwater from the deep aquifer has fluoride over 2.5 mg/l. in addition to salinity; developing the deep groundwater may result with higher concentration of chemicals of health risk such as fluoride, boron, chromium, arsenic, etc.. The water quality indicates the major sources of the water chemistry are dissolved carbonates and salts such as carbonates, dolomites, anhydrite, sylvite and halite deposits.

8 Climate resilience

We have used model output from the Coupled Model Intercomparison Project (CMIP) and analysed the forecasted changes in temperature, precipitation and evapotranspiration in order to assess the impact on the long-term sustainability of groundwater development in the project area.

8.1 Climate projections

The projection of climate change until 2100 is one of the factors that is key to the climate proofing of the water supplies at a certain location. The future is inherently uncertain, and the climate projections are therefore strongly dependent on carbon emission pathways (scenarios) that will be materialized in the coming decades. Four representative concentration pathway scenarios were developed by the scientific community (van Vuuren et al., 2011a, 2011b), which are adopted by the Intergovernmental Panel on Climate Change (IPCC), to simulate a range of developments and include:

1. **RCP2.6**: a best scenario where greenhouse gas (GHG) emissions would decline due to implementation of measures;
2. **RCP4.5**: described by the IPCC as an intermediate scenario where GHG emissions peak around 2040, then decline to reach roughly half of the levels of 2050 by 2100;
3. **RCP6.0**: GHG emissions peak around 2080, then decline;
4. **RPC8.5**: worst scenario where GHG emissions continue to rise throughout the 21st century, having the highest impact on climate change.

In addition, uncertainties in the projections arise from the simulations by different models that are used for making climate projections. In the CMIP5 modelling experiment 21 global circulation models were used to make climate projections until 2100 for several scenarios (Taylor et al., 2012). Use of these data has been intended for research purposes and was not recommended for design studies without expert knowledge. However, these data do provide an insight into temperature and precipitation trends for the future. The later CMIP6 experiment includes 23 models (Eyring et al., 2016) and uses different scenarios, but projections have not been downscaled for regional assessments.

8.2 Climate projection data

CMIP5 data is available as a Google Earth Engine dataset “NASA Earth Exchange Global Daily Downscaled Climate Projections” (NEX-GDDP). The NASA NEX-GDDP dataset is comprised of downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 5 (CMIP5, see Taylor et al. 2012) and across two of the four greenhouse gas emissions scenarios known as Representative Concentration

Pathways (RCPs, see Meinshausen et al. 2011). Data for the 21 models used in the CMIP5 modelling experiment were downscaled to 0.25˚ x 0.25˚. The dataset contains daily projections until 31 December 2099.

The data consist of daily projection values of precipitation, maximum and minimum temperatures derived from the 21 models. The 21 models used are: inmcm4, CSIRO-Mk3-6-0, bcc-csm1-1, NorESM1-M, MRI-CGCM3, MPI-ESM-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, IPSL-CM5A-MR, IPSL-CM5A-LR, GFDL-ESM2M, GFDL-ESM2G, GFDL-CM3, CanESM2, CNRM-CM5, CESM1-BGC, CCSM4, BNU-ESM, and the ACCESS1-0 models.

The 66-member CMIP6 projection data were downloaded from KNMI Climate Explorer web site https://climexp.knmi.nl and processed.

CMPI5 RCP4.5 model predictions have been used to generate regional trends in temperature and precipitation changes for the years 2006-2100, and CMIP6 for detailed analysis (1866-2100) of a single, central location in the project area of Lot-1 (Mekele, Tigray).

For Ethiopia, CMPI5 models predict an increase in annual precipitation between 0 and 3 mm/y. The largest increase is predicted for the south of the country (Figure 4).

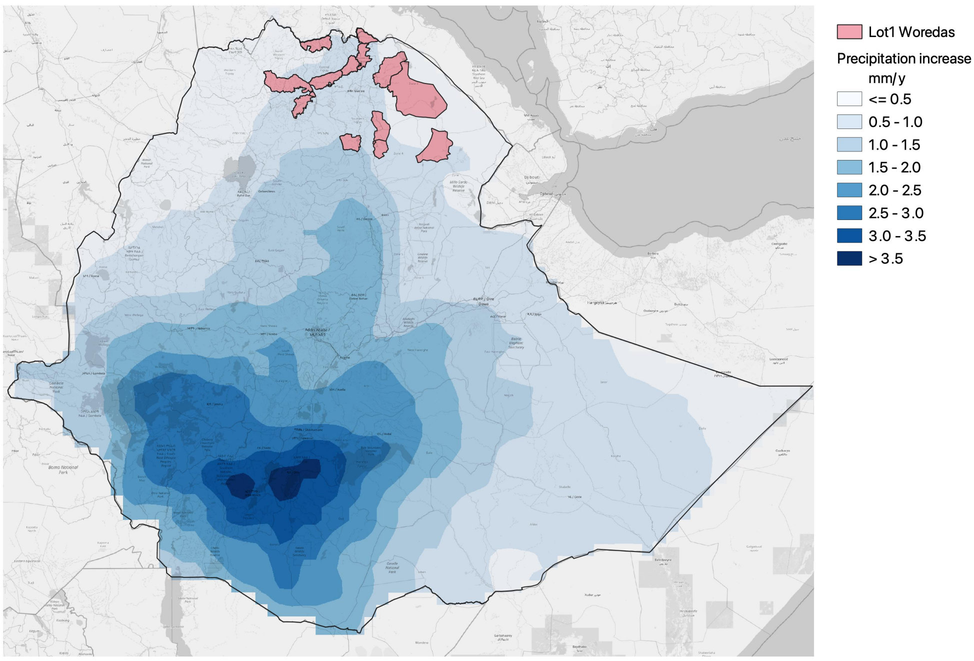

Figure 4 CMIP5 rcp45 scenario: linear precipitation trend 2006-2100

CMIP6 output for Mekele (Figure 5) shows a similar trend: increase of annual precipitation (25 mm) and average temperature (1.2 degrees Celsius) between the year 2006 and 2100. A statistically significant change in precipitation is only apparent during the month of August (+11 mm).
The average forecast for the annual potential evapotranspiration shows a large increase of 100 mm for the same period. This means that the Aridity Index (P / PET) will decrease considerably (from 0.6 to 0.575) which may lead to reduced groundwater recharge and reduced drought resilience.

In Tigray region, where basement aquifers dominate, shallow groundwater is the main source for water supply. In Afar deep groundwater exists, but it is not always of good quality. In Afdera woreda, shallow, fresh groundwater may be found at the foot of the alluvial fans that are recharged from the plateau around Mekele and Amba Alaji.

Although strong soil and water conservation practices exist in the project area, strengthening these land management activities and reinitiating additional artificial recharge structures will contribute to the climate resilience.

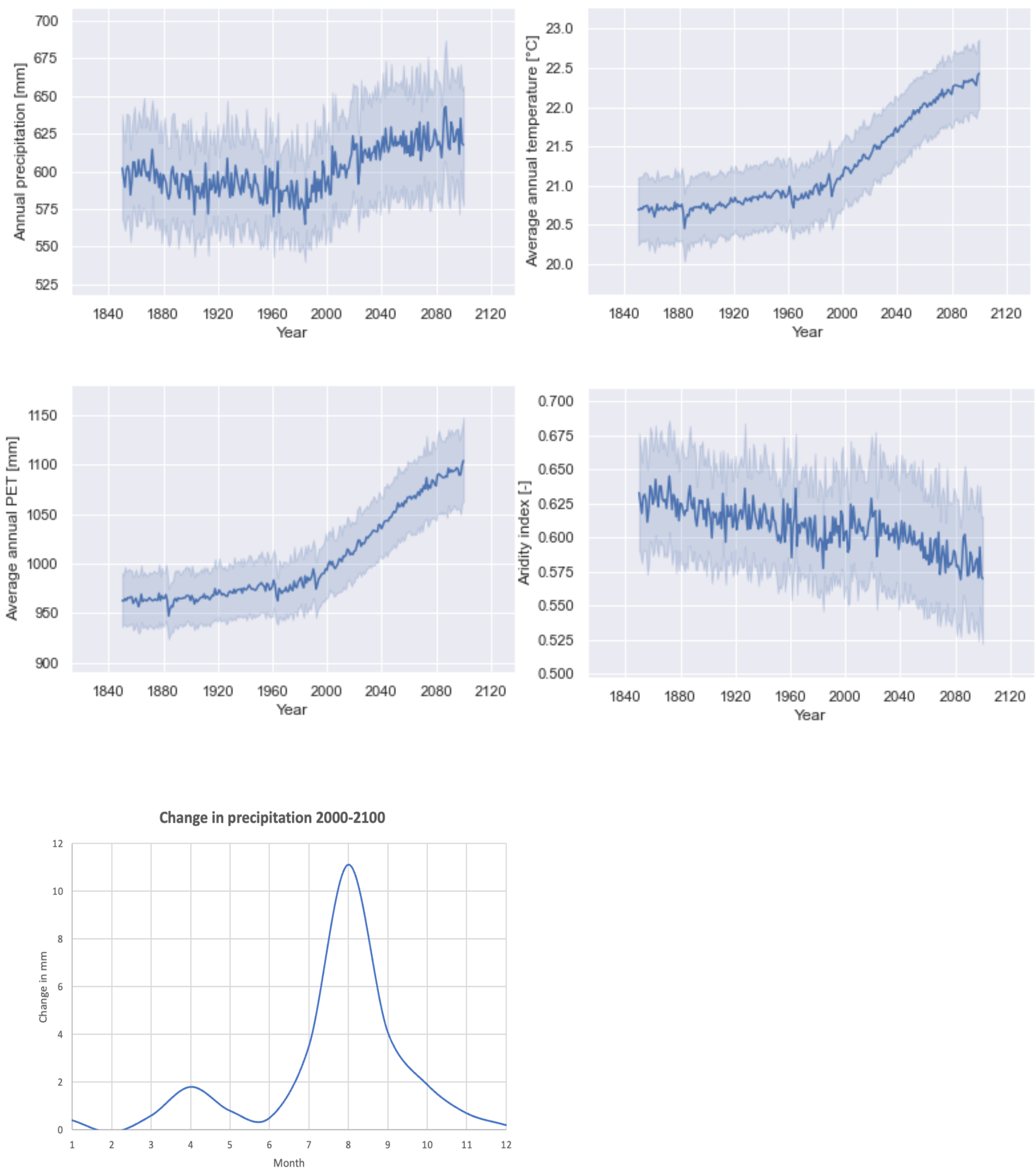

Figure 5 CMIP6 forecast for Mekele (Tigray)

9 References

Adeba, D., Kansal, M.L., Sen, S., (2015). Assessment of water scarcity and its impacts on sustainable development in Awash basin, Ethiopia. Sustain. Water Resour. Manag. 1, 71–87. https://doi.org/10.1007/s40899-015-0006-7

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao Rome 300, D05109.

Arısoy, M. Ö., Dikmen, Ü. (2013). Edge detection of magnetic sources using enhanced total horizontal derivative of the tilt angle.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Griensven, A. van, Liew, M.W. van, Kannan, N., Jha, M.K., (2012). SWAT: Model use, calibration and validation. Trans. ASABE 55, 1491–1508.

Asrat, A., Gleizes, G., Barbery, P., & Ayalew D. (2003). Magma emplacement and mafic-felsic magma hyberdiztion: Structural eviedence from the Pan-African Negash pluton, Northern Ethiopia. Journal of Structural Geology, 25(9), 1451-1469.

Awulachew, S.B., Erkossa, T., Namara, R.E., (2010). Irrigation potential in Ethiopia. Constraints and opportunities for enhancing the system. International Water Management Institute, Addis Ababa, Ethiopia.

Ayalew, D.& Yirgu, G., (2003). Crustal contribution to the genesis of Ethiopian plateau rhyolitic ignimbrites: basalt and rhyolite geochemical provinciality, J. geol. Soc. Lond., 160, 47–56.

Ayalew, D., Barbey, P., Marty, B., Reisberg, L., Yirgu, G. & Pik, R. (2002). Source, genesis and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts. Geochimica et Cosmochimica Acta, 66, 1429-1448.

Balist, J., Malekmohammadi, B., Jafari, H.R., Nohegar, A., Geneletti, D., (2022). Modeling the supply, demand, and stress of water resources using ecosystem services concept in Sirvan River Basin (Kurdistan-Iran). Water Supply ws2021436. https://doi.org/10.2166/ws.2021.436

Beiki, M. (2010). Analytic signals of gravity gradient tensor and their application to estimate source location. Geophysics, 75(6), I59–I74. https://doi.org/10.1190/1.3493639

Beyene, A. & Abdelsalam, M. (2005). Tectonics of the Afar Depression: A review and synthesis. J. African Earth Sci., 41, 41-59.

Beyth, M. (1972) “The geology of central and western Tigre, Ethiopia” Draft report, Ministry of Mines, Ethiopian Institute of Geological Surveys, Addis Ababa, Ethiopia.

Blakely, R. J. (1995). Potential Theory in Gravity and Magnetic Applications. Cambridge University, Cambridge. https://doi.org/10.1017/CBO9780511549816

Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., Sabater, S., (2014). Assessment of the water supply:demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Sci. Total Environ. 470-471C, 567–577. https://doi.org/10.1016/j.scitotenv.2013.10.003

Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., Sabater, S., (2014). Assessment of the water supply:demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Sci. Total Environ. 470-471C, 567–577. https://doi.org/10.1016/j.scitotenv.2013.10.003

Bosellini, A., Russo, A. & Assefa, G., (2001). The Mesozoic succession of Dire Dawa, Harar province, Ethiopia, J. Afri. Earth Sci., 32, 403–417.

Buchhorn, M., Smets, B., Bertels, L., Roo, B.D., Lesiv, M., Tsendbazar, N.-E., Li, L., Tarko, A., (2021). Copernicus Global Land Service: Land Cover 100m: version 3 Globe 2015-2019: Product User Manual. Zenodo. https://doi.org/10.5281/zenodo.4723921

Cibin, R., Sudheer, K.P., Chaubey, I., (2010). Sensitivity and identifiability of stream flow generation parameters of the SWAT model. Hydrol. Process. 24, 1133–1148. https://doi.org/10.1002/hyp.7568

Climate Hazards Centre, n.d. CHIRPS: Rainfall Estimates from Rain Gauge and Satellite Observations | Climate Hazards Center - UC Santa Barbara [WWW Document]. CHIRPS Rainfall Estim. Rain Gauge Satell. Obs. URL https://www.chc.ucsb.edu/data/chirps (accessed 4.10.20).

Cooper, G. R. J., Cowan, D. R. (2006). Enhancing potential field data using filters based on the local phase. Computers & Geosciences, 32(10), 1585–1591. https://doi.org/10.1016/j.cageo.2006.02.016

CSA, (2013a). Population Projections for Ethiopia 2007-2037. Central Statistical Agency, Addis Ababa, Ethiopia.

CSA, (2013b). Inter-censal Population Survey Report. Central Statistical Agency, Addis Ababa, Ethiopia.

CSA, (2017). Population Projection of Ethiopia for All Regions at Woreda Level from 2014 – 2017. Central Statistical Agency, Addis Ababa, Ethiopia.

CSA, (2021a). Agricultural sample survey. Volume II. Report on livestock and livestock characteristics (private peasant holdings). (Statistical Bulletin No. 589). Central Statistical Agency, Addis Ababa, Ethiopia.

CSA, (2021b). Population Size by Sex, Region, Zone and Wereda: July 2021. Central Statistical Agency, Addis Ababa, Ethiopia.

Davis, J. C., Sampson, R. J. (1986). Statistics and data analysis in geology (Vol. 646). Wiley New York et al.

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., Ceccato, P., (2018). Validation of the CHIRPS satellite rainfall estimates over eastern Africa. Quaterly J. R. Meteorol. Soc. 154, 292–312.

Dobrin, M. B. (1976). Introduction to geophysical prospecting Mc Graw-Hill Publ. Co., New York.

Ebinger, C.J., Yemane, T., WoldeGabriel, G., Aronson, J.L.& WalterR.C., (1993). Late Eocene–Recent volcanism and faulting in the southern main Ethiopian rift, J. geol. Soc. Lond., 150, 99–108.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., Alsdorf, D., 2007. The Shuttle Radar Topography Mission. Rev. Geophys. 45. https://doi.org/10.1029/2005RG000183

Fritz, H., Abdelsalam, M., Ali, K., Bingen, B., Collins, A., Fowler, A., Ghebreab, W., Hauzenberger, C., Johnson, P., Kusky, T., Macey, P., Muhongo, S., Stern, R., Viola, G., (2013). Orogen styles in the East African Orogen: a review of the Neoproterozoic to Cambrian tectonic evolution. Journal of African Earth Sciences 86, 65–106.

Garland, C.R. (1980). Geology of the Adigrat area. Ministry of Mines; Memoir, No. 1, Addis Ababa, Ethiopia.

Hagos, E.Y., (2005). Development and management of irrigated lands in Tigray, Ethiopia. (PhD Thesis). Wageningen University, UNESCO-IHE Institute for Water Education, Wageningen, The Netherlands.

Haile, G., G., T.G., Kifle, M., Gebremedhin, T., (2019). Effects of irrigation scheduling and different irrigation methods on onion and water productivity in Tigray, northern Ethiopia. https://doi.org/10.1101/790105

Hayward, N. J., & C. J. Ebinger (1996). Variations in the long-axis segmentation of the Afar rift system, Tectonics, 15, 244–257.

Hofman, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E.& Pik, R., (1997). Timing of the Ethiopian flood basalt event and implications for plume birth and global change, Nature, 389(6653), 838–841.

Hofstetter, R., & Beyth, M., (2003). The Afar Depression: interpretation of the 1960–2000 earthquakes, Geophys. J. Int., 155, 715–732.

Howard, G., Bartram, J., (2003). Domestic Water Quantity, Service Level and Health (No. WHO/SDE/WSH/03.02). World Health Organization, Geneva, Switzerland.

Hunegnaw, A., Sage, L., & Gonnard, R., (1998). Hydrocarbon potential of the intra-cratonic Ogaden Basin SE Ethiopia: Journal of Petroleum Geology, v. 21, p. 401–425.
Izzeldin, A.Y. Seismic, gravity and magnetic surveys in the central part of the Red Sea, their interpretation and implications for the structure and evolution of the Red Sea. Tectonophysics 143 (1987), pp. 269–306.

Ibraheem, I. M., Gurk, M., Tougiannidis, N., Tezkan, B. (2018). Subsurface investigation of the Neogene Mygdonian Basin, Greece using magnetic data. Pure and Applied Geophysics, 175(8), 2955–2973. https://doi.org/10.1007/s00024-018-1809-x

Jacobsen, B. H. (1987). A case for upward continuation as a standard separation filter for potential-field maps. Geophysics, 52(8), 1138–1148. https://doi.org/https://doi.org/10.1190/1.1442378

Joint Research Centre (European Commission), Thiombiano, L., Yemefack, M., Van Ranst, E., Spaargaren, O., Micheli, E., Kilasara, M., Montanarella, Luca, Jones, R., Hallett, S., Dampha, A., Gallali, T., Deckers, J., Breuning-Madsen, H., Jones, A., Brossard, M., Jones, Arwyn, Le Roux, P., Dewitte, O., Jones, Robert, Montanarella, L., Zougmoré R, (2013). Soil atlas of Africa. Publications Office of the European Union, LU.

Kebede Hailemichael, Alemu, A., Fisseha, S. (2020). Upward continuation and polynomial trend analysis as a gravity data decomposition, case study at Ziway-Shala basin, central Main Ethiopian rift. Heliyon, 6(1), e03292. https://doi.org/10.1016/j.heliyon.2020.e03292

Kebede, B., Mammo, T. (2021). Processing and interpretation of full tensor gravity anomalies of Southern Main Ethiopian Rift. Heliyon, 7(4), e06872. https://doi.org/10.1016/j.heliyon.2021.e06872

Lenhart, T., Eckhardt, K., Fohrer, N., Frede, H.-G., (2002). Comparison of two different approaches of sensitivity analysis. Phys. Chem. Earth Parts ABC 27, 645–654. https://doi.org/10.1016/S1474-7065(02)00049-9

Lyngsie, S. B., Thybo, H., Rasmussen, T. M. (2006). Regional geological and tectonic structures of the North Sea area from potential field modelling. Tectonophysics, 413(3–4), 147–170. https://doi.org/https://doi.org/10.1016/j.tecto.2005.10.045

Mammo, T. (2010). Delineation of sub-basalt sedimentary basins in hydrocarbon exploration in North Ethiopia. Marine and Petroleum Geology, 27(4), 895–908. https://doi.org/10.1016/j.marpetgeo.2009.12.009

Mammo, T. (2013). Crustal structure of the flood basalt province of Ethiopia from constrained 3-D gravity inversion. Pure and Applied Geophysics, 170(12), 2185–2206. https://doi.org/10.1007/s00024-013-0663-0

McCartney, M.P., Shiferaw, A., Seleshi, Y., (2008). Estimating environmental flow requirements downstream of the Chara Chara weir on the Blue Nile River, in: Abtew, W., Melesse, A.M. (Eds.), Proceedings. Presented at the Workshop on Hydrology and Ecology of the Nile River Basin under Extreme Conditions, 16-19 June 2008. Sandy, UT, USA, Aardvark Global Publishing, Addis Ababa, Ethiopia, pp. 57–75.

Mengesha, T., Tadiwos, C., Workneh, H. (1996). The geological map of Ethiopia, 1: 2,000,000 scale. Ethiopia: EIGS Addis Ababa.

Mickus, K. L., Aiken, C. L. V, Kennedy, W. D. (1991). Regional-residual gravity anomaly separation using the minimum-curvature technique. Geophysics, 56(2), 279–283. https://doi.org/10.1190/1.1443041

Miller, H. G., Singh, V. (1994). Potential field tilt—a new concept for location of potential field sources. Journal of Applied Geophysics, 32(2–3), 213–217. https://doi.org/10.1016/0926-9851(94)90022-1

Mohr, P.A. & Zanettin, B. (1988). The Ethiopian flood basalt province. In: MacDougall, J.D. (ed) Continental Flood Basalts. Kluwer Academic, Dordrecht, 63-110.

Monteith, J.L., (1965). Evaporation and the Environment, in: Symposium of the Society of Experimental Biology No. 19. pp. 245–269.

Moreira, L.L., Schwamback, D., Rigo, D., Moreira, L.L., Schwamback, D., Rigo, D., (2018). Sensitivity analysis of the Soil and Water Assessment Tools (SWAT) model in streamflow modeling in a rural river basin. Rev. Ambiente Água 13. https://doi.org/10.4136/ambi-agua.2221

Moreira, L.L., Schwamback, D., Rigo, D., Moreira, L.L., Schwamback, D., Rigo, D., (2018). Sensitivity analysis of the Soil and Water Assessment Tools (SWAT) model in streamflow modeling in a rural river basin. Rev. Ambiente Água 13. https://doi.org/10.4136/ambi-agua.2221

Nash, J.E., Sutcliffe, J.V., (1970). River Flow Forecasting through Conceptual Models part I – A Discussion of Principles. J. Hydrol. 10, 282–290.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., (2011). Soil and Water Assessment Tool Theoretical Documentation Version 2009 (Texas Water Resources Institute Technical Report). College of Agriculture and Life Sciences, Texas A&M University, College Station, Texas, USA.

NPC, (2016). Ethiopia Growth and Transformation Plan II (GTP II) (Volume I No. 2015/16-2019/20). National Planning Commission, Federal Democratic Republic of Ethiopia, Addis Ababa, Ethiopia.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, Jiande, Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, Jun, Hou, Y.-T., Chuang, H., Juang, H.-M.H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J.-K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C.-Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R.W., Rutledge, G., Goldberg, M., (2010). The NCEP Climate Forecast System Reanalysis. Bull. Am. Meteorol. Soc. 91, 1015–1058. https://doi.org/10.1175/2010BAMS3001.1

Sahilu, G., Abate, E., Tadesse, D., (2018). The Study of Water Use and Treated Wastewater Discharge Charge. Water Abstraction Charge Setting for Domestic and Non-Domestic

Water Supply (Final report). School of Civil and Environmental Engineering Addis Ababa Institute of Technology (AAiT) Addis Ababa University., Addis Ababa, Ethiopia.

Salem, A. S. K., Campell, S., Derek, J. D., Dickinson, J., Murphy, C. (2011). Interpretation of Tensor Gravity Data Using an Adaptive Tilt Angle Technique. In 73rd EAGE Conference and Exhibition incorporating SPE EUROPEC 2011 (p. cp-238). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.20149566

Salem, A., Williams, S., Fairhead, J. D., Ravat, D., Smith, R. (2007). Tilt-depth method: A simple depth estimation method using first-order magnetic derivatives. The Leading Edge, 26(12), 1502–1505. https://doi.org/https://doi.org/10.1190/1.2821934

Shiferaw, A., McCartney, M.P., (2009). Investigating Environmental Flow Requirements at the Source of the Blue Nile River (No. H041853). Addis Ababa University and International Water Management Institute, Addis Ababa, Ethiopia.

Sileshi, Z., Tegegne, A., Tsadik, G.T., (2003). Water resources for livestock in Ethiopia: Implications for research and development, in: Proceedings. Presented at the MoWR/EARO/IWMI/ILRI international workshop, 2-4 December 2002, International Water Management Institute, Addis Ababa, Ethiopia, p. 14.

Smakhtin, V., Revenga, C., Döll, P., (2004). A Pilot Global Assessment of Environmental Water Requirements and Scarcity. Water Int. 29, 307–317. https://doi.org/10.1080/02508060408691785

Srinivasan, R., Zhang, X., Arnold, J., (2010). SWAT Ungauged: Hydrological Budget and Crop Yield Predictions in the Upper Mississippi River Basin. Trans. ASABE 53, 1533–1546. https://doi.org/10.13031/2013.34903

Stern, R.J. (1994). Arc assembly and continental collision in the Neoproterizoic East African Orogen—implication for the consolidation of Gondwanaland, Annual Review Earth Planetary Science 22, pp. 319–351.

Tadesse, T, Hoshino, M., Suzuki, K., & Iizumi, S. (2000). SmNd, RbSr and ThUPb zircon ages of syn- and post-tectonic granitoids from the Axum area of northern Ethiopia. Journal of African Earth Sciences, 30(2), 313–327.

Tadesse, T., (1996). Geology of the Axum area. Geological Survey of Ethiopia, Memoir 9, 192pp.

Tadesse, T., Hoshino, M., & Sawada, Y. (1999). Geochemistry of low-grade metavolcanic rocks from the Pan-African of the Axum area, northern Ethiopia. Precambrian Research, 96(1–2), 101–124.

Tallaksen, L.M., (1995). A review of baseflow recession analysis. J. Hydrol. 165, 349–370.

Tefera, M., Chernet, T., & Haro, W., (1996). Geological Map of Ethiopia: Ethiopian Institute of Geological Surveys, scale 1:2,000,000, 1 p.

Tesfaye, T.W., Dhanya, C.T., Gosain, A.K., (2020). Modeling the impact of climate change on the environmental flow indicators over Omo-Gibe basin, Ethiopia. Model. Earth Syst. Environ. 6, 2063–2089. https://doi.org/10.1007/s40808-020-00813-x

Thiessen, A.H., (1911). Precipitation for large areas. Mon. Weather Rev. 1082–1084.

Tibebe, D., Bewket, W., (2011). Surface runoff and soil erosion estimation using the SWAT model in the Keleta Watershed, Ethiopia. Land Degrad. Dev. 22, 551–564. https://doi.org/10.1002/ldr.1034

Tsegaye H. (1974). Geological map of Adi Arkay map sheet with explanatory side note. Unpublished document, Geological survey of Ethiopia.

UNICEF-UNESCO Report (2003). "Improving Available Information and Drilling Success rate in the Afar Regional State Government": Report and accompanying geological map of the Afar Depression, PP 41.

USDA-NRCS, (2004). Estimation of Direct Runoff from Storm Rainfall (Part 630 Hydrology No. Chapter 10), National Engineering Handbook. United States Department of Agriculture.

van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., Srinivasan, R., (2006). A Global Sensitivity Analysis Tool for the Parameters of Multi-Variable Catchment Models. J. Hydrol. 324, 10–23. https://doi.org/10.1016/j.jhydrol.2005.09.008

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289, 284–288. https://doi.org/10.1126/science.289.5477.284

Williams, J.R., (1969). Flood Routing With Variable Travel Time or Variable Storage Coefficients. Trans. ASAE 12, 0100–0103. http://dx.doi.org/10.13031/2013.38772

Williams, J.R., (1969). Flood Routing With Variable Travel Time or Variable Storage Coefficients. Trans. ASAE 12, 0100–0103. http://dx.doi.org/10.13031/2013.38772

Xie, H., You, L., Dile, Y.T., Worqlul, A.W., Bizimana, J.-C., Srinivasan, R., Richardson, J.W., Gerik, T., Clark, N., (2021). Mapping development potential of dry-season small-scale irrigation in Sub-Saharan African countries under joint biophysical and economic constraints - An agent-based modeling approach with an application to Ethiopia. Agric. Syst. 186, 102987. https://doi.org/10.1016/j.agsy.2020.102987

Yihun, Y.M., (2015). Agricultural water productivity optimisation for irrigated Teff (Eragrostic Tef) in water scarce semi-arid region of Ethiopia (PhD Thesis). Wageningen University, UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

Zhao, C., Nan, Z., Cheng, G., (2005). Evaluating Methods of Estimation and Modelling Spatial Distribution of Evapotranspiration in the Middle Heihe River Basin, China. Am. J. Environ. Sci. 1, 278–285. https://doi.org/10.3844/ajessp.2005.278.285

ACACIA WATER

van Hogendorpplein 4
2805 BM Gouda

Telephone:+31(0)182 – 686 424
Internet: www.acaciawater.com
Email: info@acaciawater.com