

# Evaluation of groundwater resources in the Geba basin, Ethiopia

Kibrewossen Tesfagiorgis · Tesfamichael Gebreyohannes · Florimond De Smedt ·  
Jan Moeyersons · Miruts Hagos · Jan Nyssen · Jozef Deckers

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**Abstract** This article presents an assessment of the groundwater resources in the Geba basin, Ethiopia. Hydrogeological characteristics are derived from a combination of GIS and field survey data. MODFLOW groundwater model in a PMWIN environment is used to simulate the movement and distribution of groundwater in the basin. Despite the limited data available, by simplifying the model as a single layered semi-confined groundwater system and by optimising the transmissivity of the different lithological units, a realistic description of the groundwater flow is obtained. It is concluded that 30,000 m<sup>3</sup>/day of groundwater can be abstracted from the Geba basin for irrigation in a sustainable way, in locations characterised by shallow groundwater in combination with aquitard-type lithological units.

**Keywords** Groundwater modelling · Transmissivity · Geba basin · Ethiopia

**Résumé** L'article présente une évaluation des ressources en eau du bassin de Geba en Ethiopie. Les caractéristiques hydrogéologiques sont établies à partir de données de terrain représentées sur SIG. Le modèle hydrogéologique Modflow est utilisé en environnement Pmwin afin de simuler les écoulements d'eau dans le bassin. Malgré le nombre limité de données disponibles, en simplifiant le modèle en un système aquifère stratifié semi-confiné et en optimisant les transmissivités des différentes unités lithologiques, une description réaliste des écoulements souterrains est obtenue. On conclut que 30 000 m<sup>3</sup>/j d'eau souterraine peuvent être extraits du bassin de Geba pour les besoins d'irrigation, de façon durable, en des zones caractérisées par des eaux souterraines peu profondes au sein d'unités lithologiques de type aquitard.

K. Tesfagiorgis · T. Gebreyohannes · F. De Smedt  
Department of Hydrology and Hydraulic Engineering,  
Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

K. Tesfagiorgis (✉)  
NOAA-CREST Center, City College of New York, T-107  
Steinman Hall, 140th St. and Convent Ave., New York,  
NY 10031, USA  
e-mail: ktesfagiorgis@cc.cuny.edu

T. Gebreyohannes · M. Hagos  
Mekelle University, PO Box 231, Mekelle, Ethiopia

J. Moeyersons  
Royal Museum for Central Africa, 3080 Tervuren, Belgium

J. Nyssen  
Department of Geography, Ghent University, Krijgslaan 281-S8,  
9000 Ghent, Belgium

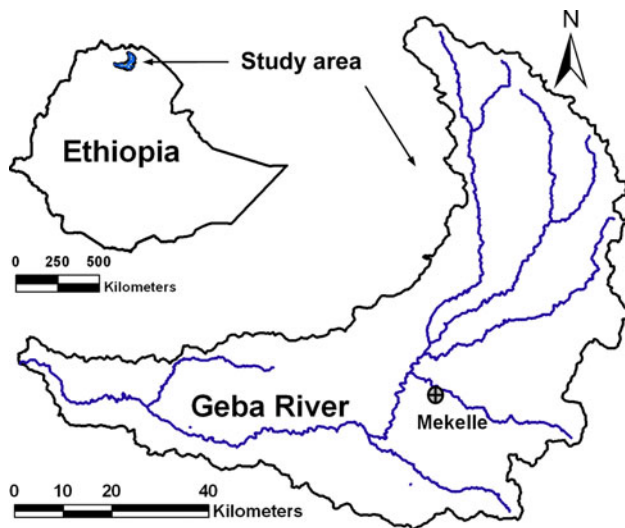
J. Deckers  
Division for Land and Water Management, Department of Earth  
and Environmental Sciences, KU Leuven, Celestijnenlaan 200E,  
3001 Leuven, Belgium

**Mots clés** Modélisation des eaux souterraines ·  
Transmissivité · Bassin de Geba · Ethiopie

## Introduction

Rainfall in Ethiopia is highly variable and erratic in time and space (Yazew 2005). As a consequence, precipitation is generally insufficient to sustain the agriculture needed to alleviate food insecurity, and it becomes very important to develop and manage all other available water resources. Groundwater is one of the renewable water resources that can be exploited in a sustainable way to help rural communities in terms of clean domestic water and irrigation.

This article discusses the groundwater potential of the Geba basin (Fig. 1), Tigray region, northern Ethiopia. The



**Fig. 1** Location map of the Geba basin

Geba river basin is about 5,150 km<sup>2</sup>, and forms part of the Tekeze-Atbara river basin, a tributary of the Blue Nile. The main economy of the area is agriculture, which accounts for more than 40% of the GDP and 80% of the labour force. Water is crucial to support and sustain crop growth, and irrigation is often required (Leul 1994; Gemechu 2006), hence, assessing the location and potential of additional resources of groundwater is essential. However, lack of long-term meteorological, hydrological and hydraulic data in the basin makes accurate assessment of groundwater resources a difficult challenge.

Some groundwater investigations have been undertaken in the Geba basin by federal and regional authorities, local NGOs, or university departments. Tesfaye and Gebretsadik (1982) performed some hydrogeological mapping around Mekelle (Fig. 1), the regional capital of Tigray. DEVECON (1992) investigated the water resources potential of the Mekelle area as part of the Five Towns Water Supply and Sanitation project of the Ministry of Water Resources of Ethiopia. Studies undertaken by local NGOs and the regional government for irrigation purposes have been conducted by REST (1996) and COSAERT (2001). NEDECO (1997) investigated the Tekeze river basin and described the water resources potential by drilling boreholes up to 300 m deep in the Mekelle area. Hussein (2000) investigated the hydrogeology of the Aynalem well field, which supplies Mekelle with potable water. Gebregziabher (2003) used such geophysical techniques as seismic refraction and magnetic and electrical profiling to investigate the hydrogeology of the Aynalem basin. WWDSE (2006) performed some hydro-meteorological, geological and hydrogeological investigations around Mekelle, supplemented by a quasi three-dimensional groundwater flow model. However, these studies only provide local and

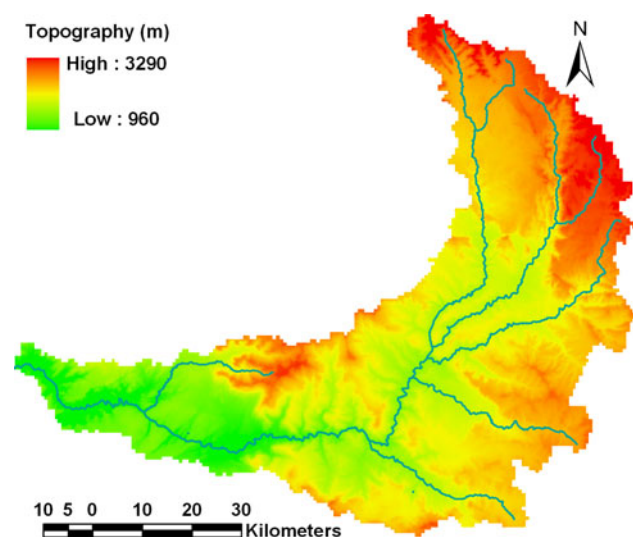
fragmental information, whilst a comprehensive insight into the groundwater resources of the Geba basin remains largely unavailable. In this study, the groundwater resources of the Geba basin are investigated using groundwater flow modelling integrated with GIS-derived basin characteristics.

## Methods

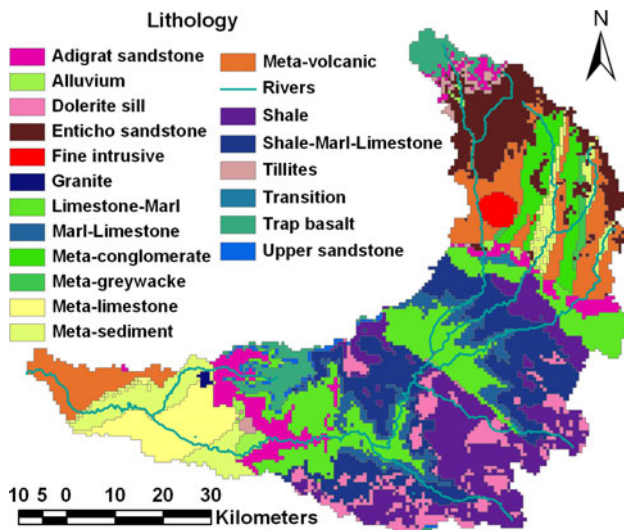
### Development of hydrogeological data

The Geba basin is characterised by rugged terrain, with topography ranging from 960 to 3,280 m. A digital elevation map (DEM), shown in Fig. 2, was derived from NASA SRTM data with 3 arc-second or a resolution of 90 m by 90 m. SRTM tiles of N12E038, N12E039, N13E38, N13E39, N14E038 and N14E039 were considered for bounding the area and subsequently preparing the DEM.

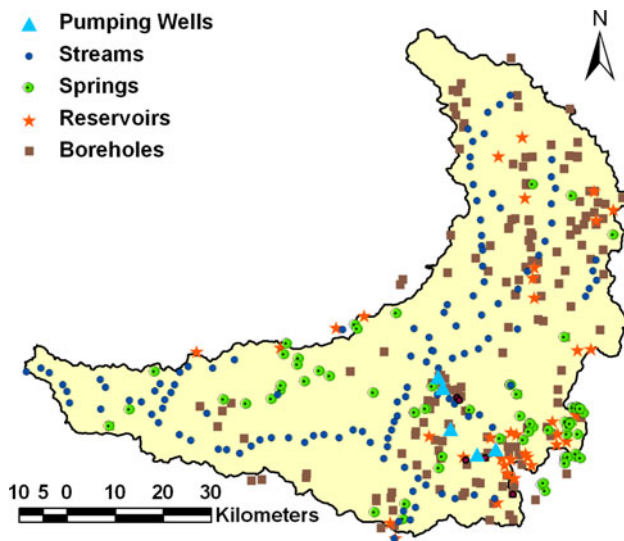
For regional groundwater characterisation, considerable test borings and water well-log data are required to determine the sequence and type of geological deposits. However, for the Geba basin such knowledge is lacking, except for some well-logs of the Aynalem well field, 3 km east of Mekelle city (DEVECON, 1992). Instead, hydrogeological characteristics were derived from a digital map, indicating 20 major lithological units in the basin. The map, shown in Fig. 3, was prepared in ArcView grid format (90 m pixel size) from a geological map (Arkin et al. 1971), previous geological studies (Beyth 1972; Merla et al. 1979; Tesfaye and Gebretsadik 1982; Getaneh and Valera 2002; Sifeta et al. 2005), field surveys, and satellite images.



**Fig. 2** Topographic elevation map for the Geba basin



**Fig. 3** Map showing lithological units in the Geba basin



**Fig. 4** Locations of surface and groundwater levels observed during field campaigns

In addition, 358 surface and ground water levels were recorded during the field surveys. The observation points included water levels in wells, boreholes, springs, reservoirs and perennial river courses during base flow conditions (Fig. 4). The geographical location and elevation of these observation points were recorded by GPS. However, as the recorded elevations are liable to error, only horizontal coordinates from the GPS readings were considered accurate whilst the water levels were adjusted by subtracting the water depth measured from the soil surface from the DEM values. Another problem with these observations is the erratic nature of the rainfall which causes large variations in water levels in hand dug wells, reservoirs and streams in the region. Moreover, water levels

usually are seasonal (REST 2005). To simplify the model, these effects were ignored in this study and all observations were considered as steady state.

Alene (2006) applied the WetSpas model (Batelaan and De Smedt 2001) to estimate seasonal and annual groundwater recharge in the Geba basin. He found that annual recharge ranges from zero to 215 mm per year and varies from location to location depending on slope, soil type, land use and climate. On average, the total annual recharge was found to be 22 mm per year with a standard deviation of 33 mm, which accounts for 4% of the average annual rainfall in the area. This small amount of recharge is due to the high evapotranspiration in the region (Getnet 2005). The spatial distribution of the recharge obtained from the WetSpas model was converted to a 90 m grid digital map as an input for the groundwater model.

### Groundwater modelling

The behaviour of the groundwater system was simulated using the MODFLOW groundwater model (Harbaugh et al. 2000) in a PMWIN Pro 7 environment (Chiang and Kinzelbach 2005). PMWIN Pro 7 has a capacity of a million computational cells. However, all GIS grid data available for the study are raster data with a  $90 \times 90$  m pixel size, which results in a larger number of cells than the model capacity. As a consequence, the grid was modified to a cell size of  $180 \times 180$  m. The number of cells in the  $x$  and  $y$  directions then becomes 696 and 587, respectively, resulting in a modelled area of 125.28 km Easting and 105.66 km Northing. Active and inactive cells were defined to delineate the exact shape of the basin, and the boundary of the basin was considered as a no flow boundary condition.

The groundwater system was conceptualised as a single layered semi-confined aquifer, hence the following groundwater flow equation applies in a steady state

$$\frac{\partial}{\partial x} \left( T \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( T \frac{\partial h}{\partial y} \right) + R - Q = 0, \quad (1)$$

where  $h$  is the groundwater head or elevation (m),  $R$  is the groundwater recharge (m/day),  $Q$  is the groundwater discharge (m/day),  $x$  and  $y$  are horizontal dimensions (m) and  $T$  is the transmissivity ( $\text{m}^2/\text{day}$ ), which is assumed to vary spatially depending on the geological conditions. Equation 1 allows a groundwater model to be set up without specifying any vertical dimensions of the ground layers. Nevertheless, this simple model concept can produce realistic results for the regionally complex groundwater flow system if transmissivity values are optimised by calibrating the model such that a good fit is obtained between simulated and observed groundwater heads.

Groundwater discharge was modelled with the drain package of MODFLOW

$$Q = C \times \max[h - h_d, 0], \tag{2}$$

where  $h_d$  is the drain level (m) and  $C$  is the drain conductance ( $\text{day}^{-1}$ ). Following a procedure proposed by Batelaan and De Smedt (2004), drain levels equal to topography minus 1 m were imposed over the whole basin and a large value specified for the drain conductance, such that any groundwater level reaching the ground surface within 1 m results in groundwater drainage to the surface. The model was therefore able to locate automatically all drainage and discharge areas as perennial rivers and springs and to quantify the corresponding discharge with Eq. 2.

In order for the model to provide accurate results, it is necessary to calibrate uncertain parameters until observations are reproduced with confidence. The transmissivity values of the geological formations, which are believed to be the most uncertain parameters, were therefore optimised with PEST, a parameter estimation tool embedded in PMWIN Pro. 7. The optimisation process was based on comparing simulated groundwater heads with the measured water levels inventory (Fig. 4) using three error criteria: mean error (ME), mean absolute error (MAE) and root-mean-squared error (RMSE). The ME is the mean difference between computed heads  $h_c$  and observed heads  $h_o$

$$ME = \frac{1}{n} \sum_{i=1}^n (h_c - h_o)_i \tag{3}$$

The MAE is the mean of the absolute value of the differences in the measured and simulated heads

$$MAE = \frac{1}{n} \sum_{i=1}^n |h_c - h_o|_i \tag{4}$$

and the RMSE is the average of the squared differences in the measured and simulated heads

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (h_c - h_o)_i^2}, \tag{5}$$

where  $n$  is the number of observations.

### Results and discussion

Because of the wide spatial coverage of the basin and the large number of observations, it was not possible to optimise all transmissivity values automatically at the same time. Therefore, optimisation was achieved by using three or four parameters at a time whilst other parameters were kept constant. For calibration, PEST uses RMSE as a criterion. Ideally, this value should be as small as zero, but with the

complex geological conditions of the Geba basin the RMSE target was set at 10 m. Figure 5 shows the comparison between the observed and final simulated groundwater heads. The maximum error, minimum error, ME, MAE and RMSE values obtained were 19.0, -19.1, 2.0, 5.7 and 7.1 m, respectively, which can be considered fair in view of the regional scale and large variation in topography.

The optimised transmissivity values are shown in Table 1 for each geological formation and for the river

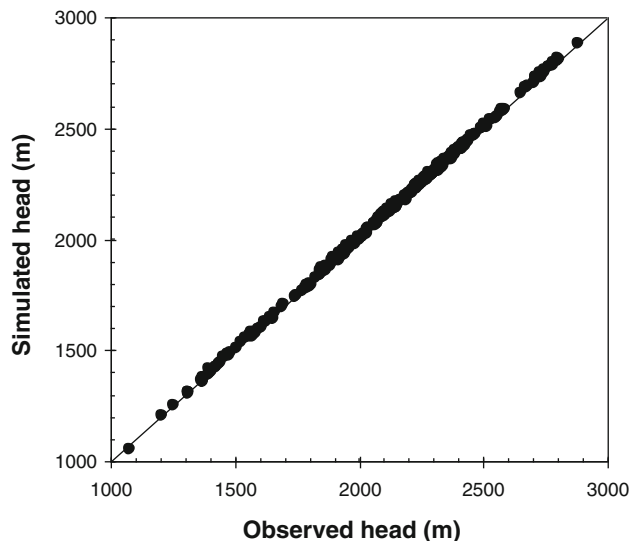


Fig. 5 Scatter plot of calculated versus observed groundwater heads

Table 1 Calibrated transmissivity values for the lithological units

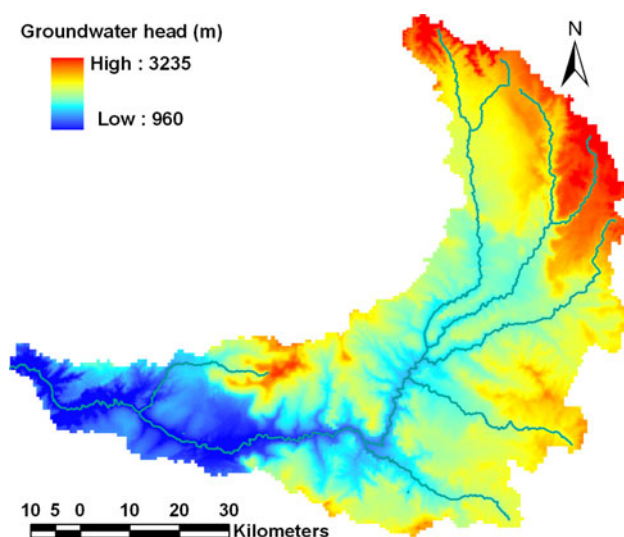
Geological formations	Transmissivity ( $\text{m}^2/\text{day}$ )
Adigrat sandstone	0.13
Alluvium	0.5–5
Dolerite sill	0.017
Enticho sandstone	5
Fine intrusive	4
Granite	2.35
Limestone-Marl	0.2
Marl-Limestone	0.0016
Meta-conglomerate	0.1
Meta-greywacke	0.01
Meta-limestone	1
Meta-sediment	2
Meta-volcanic	0.015
River beds	200–500
Shale	0.054
Shale-Marl-Limestone	0.0015
Tillite	0.1
Transition	0.1
Trap basalt	13.8
Upper sandstone	16



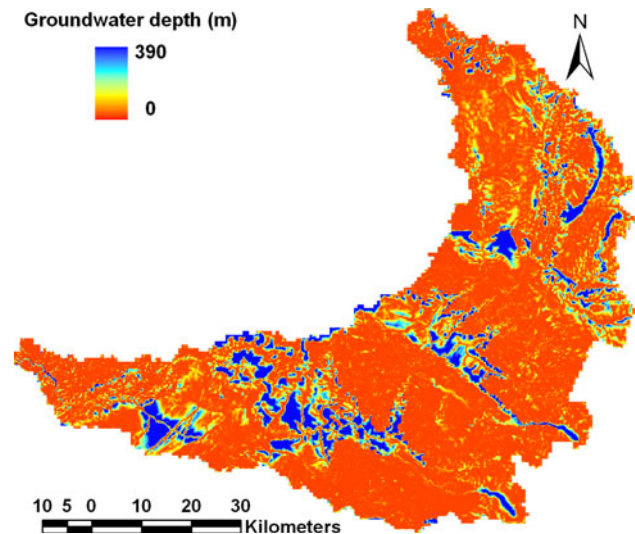
beds, which were considered as a separate unit. All transmissivity values are quite small, except for the river beds, hence none of the formations can be considered as aquifers. The largest values were obtained for the alluvium, the Enticho sandstone, fine intrusive, granite (the weathered crust), meta-sediment, trap basalt and upper sandstone. These formations can be considered as semi-pervious aquitards, able to transmit groundwater and possible sources for abstracting groundwater for irrigation. The other formations have very small transmissivities and can be classified as relatively impervious and are not suited for abstracting groundwater.

Figure 6 shows the final simulated regional groundwater head distribution. The groundwater head varies from a minimum of 960 m around the outlet of the Geba River to a maximum of 3,235 m at the northern extreme. The map indicates that groundwater levels closely follow the topography. Finally, the depth to the groundwater was estimated from the difference between the topography and simulated groundwater levels. Figure 7 shows that whilst there are places where the groundwater is near the surface such that hand dug wells or shallow drilled wells could abstract groundwater for irrigation, in other localities groundwater is situated at depths of up to 200 m from the soil surface.

The groundwater balance can be calculated by aggregating all groundwater flows as predicted by the model. There is only one input (recharge, which amounts in total to about  $3.0 \times 10^5$  m<sup>3</sup>/day on average) and one output (groundwater drainage, which also amounts to  $3.0 \times 10^5$  m<sup>3</sup>/day) yielding an average river base flow of about 3.5 m<sup>3</sup>/s at the outlet of the Geba River. This latter value corresponds well with field observations (MoWR 2002). A fraction of the groundwater transmitted between



**Fig. 6** Simulated groundwater heads in the Geba basin



**Fig. 7** Depth to groundwater map of the Geba basin

recharge and discharge can be abstracted safely without causing adverse effects (Miles and Chambet 1995). This fraction can cautiously be estimated as 10%, which amounts to 30,000 m<sup>3</sup>/day of groundwater which could be abstracted and used for irrigation in the Geba basin in a sustainable way. The possible sites where this can be achieved are locations with shallow groundwater, e.g. <5 m below soil surface, in combination with aquitard-type lithological units, which can be identified by combining Figs. 3 and 7.

## Conclusions

The main objective of the study was to investigate the distribution of groundwater in the Geba basin in Northern Ethiopia. Because of the lack of detailed hydrogeological information, the groundwater system of the Geba basin was conceptualised in a simplified numerical model. However, all local variations and actual conditions were incorporated in the model by calibration of the transmissivity values for each geological unit. A steady state groundwater flow model was applied using the MODFLOW model in a PMWIN package.

Observations of water levels collected from wells, boreholes, springs, reservoirs and perennial river courses were used for calibration of the groundwater model, by optimising the transmissivity values for each lithological unit.

Comparison of the observed and predicted groundwater levels shows a good agreement, with a ME of about 2 m and a RMSE of 7.1 m. These results are acceptable in view of the size of the study area and lack of detailed information regarding hydrogeological conditions.

From the results obtained, it can be concluded some geological formations can be considered as aquitards and could be used for groundwater abstraction, but this should be supported by local geophysical explorations. The results also show that in many areas the depth to groundwater is shallow, which would allow domestic wells to be dug for irrigation. A first and crude estimation indicates that possibly 30,000 m<sup>3</sup>/day of groundwater can be abstracted in the Geba basin in a sustainable way.

## References

- Alene Y (2006) GIS and remote sensing assisted water balance computation of the Geba basin, Tigray, Ethiopia. MSc thesis, Water Resources Engineering, KULeuven–VUB, Belgium, 122 pp
- Arkin Y, Beyth M, Dow DB, Levitte M, Haile T, Hailu T (1971) Geological map of Mekelle sheet area ND 37-11, Tigre Province. Geological Survey, Ministry of Mines, Energy and Water Resources, Addis Ababa
- Batelaan O, De Smedt F (2001) WetSpa: a flexible, GIS based, distributed recharge methodology for groundwater modelling. In: Impact of human activity on groundwater dynamics, IAHS publ 269, pp 11–17
- Batelaan O, De Smedt F (2004) SEEPAGE, a new MODFLOW DRAIN package. *Ground Water* 42:576–588
- Beyth M (1972) Palaeozoic-Mesozoic sedimentary basin of Mekelle outlier, Northern Ethiopia. *Am Ass Petrol Geol Bull* 56:2426–2439
- Chiang WH, Kinzelbach W (2005) 3D-groundwater modelling with PMWIN, a simulation system for modelling groundwater flow and transport. Springer, New York, 346 pp
- COSAERT (Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray) (2001) Suluh valley integrated rural, agriculture and water resources development study. Identification and reconnaissance report, Mekelle, Ethiopia
- DEVECON (1992) Five towns water supply and sanitation study. Ministry of Water Resources, Addis Ababa
- Gebregziabher B (2003) Integrated geophysical methods to investigate the geological structures and hydrostratigraphic unit of the Aynalem area, Southeast Mekelle. MSc thesis, Addis Ababa University, Ethiopia
- Gemechu A (2006) Sustainable irrigation in the Tigray highlands of Northern Ethiopia. MSc thesis, Water Resources Engineering, KULeuven–VUB, Belgium, 80 pp
- Getaneh W, Valera R (2002) Rare earth element geochemistry of the Antalo Supersequence in the Mekele Outlier (Tigray region, northern Ethiopia). *Chem Geol* 182:395–407
- Getnet M (2005) Groundwater recharge and water balance assessment in Geba basin, Tigray, Ethiopia. MSc thesis, Water Resources Engineering, KULeuven–VUB, Belgium, 78 pp
- Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model—user guide to modularization concepts and the ground-water flow process. US Geological Survey Open-File Report 00-92, 121 pp
- Hussein (2000) Hydrogeology of the Aynalem wellfield, Tigray, Northern Ethiopia. Unpublished MSc thesis, Addis Ababa University
- Leul K (1994) Need, potentials and limitations for irrigation development in Tigray. Commission for Sustainable Agricultural and Environmental Rehabilitation in Tigray, Mekelle, 30 pp
- Merla G, Abbate E, Azzaroli A, Bruni P, Canuti P, Fazzuoli M, Sagri M, Tacconi P (1979) Comments to the geological map of Ethiopia and Somalia. Consiglio Nazionale delle Ricerche, Firenze, 95 pp
- Miles JC, Chambet PD (1995) Safe yield of aquifers. *J Water Resour Plan Manag* 121:1–8
- MoWR (Ministry of Water Resources of Ethiopia) (2002) Ethiopian water resources management policy. Addis Ababa, 56 pp
- NEDECO (Netherlands Engineering Consultants) (1997) Tekeze river basin integrated development master plan project. Ministry of Water Resources, Addis Ababa
- REST (Relief Society of Tigray) (1996) Raya valley development study project—reconnaissance phase report. US Agency for International Development DCHA/OFDA, Mekelle, 56 pp
- REST (Relief Society of Tigray) (2005) Drought emergency and rehabilitation program annual report (May 2004–April 2005). US Agency for International Development DCHA/OFDA, Mekelle
- Sifeta K, Roser BP, Kimura J (2005) Geochemistry, provenance, and tectonic setting of Neoproterozoic metavolcanic and metasedimentary units, Werri area, Northern Ethiopia. *Afr Earth Sci* 41:212–234
- Tesfaye C, Gebretsadik E (1982) Hydrogeology of Mekelle area. Ministry of Mines and Energy, Addis Ababa, 50 pp
- WWDSE (Water Works Design and Supervision Enterprise) (2006) Evaluation of Aynalem well field and selection of additional prospective boreholes for Mekelle Town water supply source. Report II, 140 pp
- Yazew E (2005) Development and management of irrigated lands in Tigray, Ethiopia. PhD thesis, UNESCO-IHE Institute for Water Education, Delft, the Netherlands, 265 pp