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Application of a spatially distributed water balance model for assessing surface water and groundwater resources in the Geba basin, Tigray, Ethiopia

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SUMMARY

The Geba basin is one of the most water-stressed areas of Ethiopia, with only a short rainy period from mid-June to mid-September. Because rainfall in this region has been consistently erratic in the last decades, both in time and space, rain-fed agriculture has become problematic. Hence, in order to supplement rain-fed agriculture by irrigation, a detailed understanding of local and regional surface water and groundwater resources is important. The main objective of this study is to assess the available water resources in the Geba basin using a spatially distributed water balance model (WetSpass). Relevant input data for the model is prepared in the form of digital maps using remote sensing images, GIS tools, FAO and NASA databases, field reconnaissance and processing of meteorological and hydrological observations. The model produces digital maps of long-term average, seasonal and annual surface runoff, evapotranspiration and groundwater recharge. Results of the model show that 76% of the precipitation in the basin is lost through evapotranspiration, 18% becomes surface runoff and only 6% recharges the groundwater system. Model predictions are verified against river flow observations and are shown to be reliable. Additional maps are derived of accumulated surface runoff, safe yield for groundwater abstraction and water deficit for crop growth. Comparison of existing reservoirs with the accumulated runoff map shows that many reservoirs have failed because their design capacity is much higher than the actual inflow. Comparison of the safe yield map with the crop water deficit map shows that in most areas groundwater can be safely abstracted to supplement the water deficit for crop growth during the wet summer season. However, in the dry winter season the crop water deficit is too high to be supplemented by groundwater abstraction in a sustainable way.

1. Introduction

Ethiopia is commonly referred to as "the water tower of Africa", because of the huge amount of surface runoff from the Ethiopian highlands that make up over 86% of the flow of the Nile River (Yacob and Imeru, 2005). However, the country is constantly affected by shortage of water for rain-fed agriculture, mainly because of lack of proper water resources utilization and management practices. Of the total land area of Ethiopia (about 113 million ha) only 14.8% is under cultivation (EPA, 1998). About 3.8 million ha of the cultivable land area is potentially irrigable but, so far, only about 289,000 ha has been irrigated (Frenken, 2005). According to the Ethiopian Ministry of Water Resources report (2001), the total renewable freshwater (mean annual flow) of the country is estimated at 122 billion m^3, and 54.4 billion m^3 of surface water and 2.6 billion m^3 of groundwater could be developed for utilization. Currently less than 5% of the surface water potential is used for consumptive purposes while groundwater is virtually untouched.

The Geba basin is one of most food insecure areas of the Tigray Regional State, in Northern Ethiopia (Eyasu, 2005). The climate is mainly semi-arid, such that rainfall is limited and erratic and usually insufficient for optimal crop production. The regional government and several non-governmental agencies have been investing in water harvesting activities to supplement subsistence agriculture with small to medium scale irrigation through the construction of micro-dams and hand-dug wells. The principal objectives are to change the agrarian system to widespread small-scale irrigated agriculture and to gradually attain self-sufficiency in food

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production. However, the success of these initiatives has been very limited due to various reasons, among which the absence of adequate surface and groundwater knowledge is considered to be the main factor.

Although existing regional studies (e.g. Yilma and Zanke, 2004; Yilma and Camberlin, 2006) and meteorological records in the basin show that the total rainfall remained more or less constant since the 1950s, the spatial and temporal variation resulted in recurrent draught and continuous impoverishment of the farmers. Hence, it is becoming clear that food self-sufficiency can only be attained by adopting a strategy which encourages conjunctive groundwater and surface water management. In this respect, a better understanding of the availability and distribution of groundwater resources for supplementary irrigation could help to ease the water stress and thereby improving crop production, but groundwater studies in the region have been limited. Chernet and Eshete (1978) undertook a regional scale (1:250,000) hydrogeological mapping of the region around the regional capital Mekelle. DevCon (1992) investigated the water resources potential of the Mekelle area as part of the Five Towns Water Supply and Sanitation project, by the Ministry of Water Resources. NEDECO (1997) conducted drillings up to 300 m deep in the Mekelle area to identify exploitable groundwater resources. Hussein (2000) investigated the hydrogeology of the Aynalem valley south of Mekelle. CoSAERT (2001) presented a hydrogeological study of the Suluh valley in the north of the Geba basin. WWDSE (2006) made a comprehensive investigation of the Aynalem well field, which supplies drinking water for Mekelle. Walraevens et al. (2009) and Vandecasteele et al. (2011) studied a small perched aquifer near Hagere Selam in the west part of the basin during the rainy season of 2006, and estimated the soil water budget for the period 1995–2006, showing that there is a water deficit for on average 10 months per year due to the strong seasonal variation in rainfall. Kibrewossen et al. (2011) made an assessment of the groundwater resources in the Geba basin using a simplified 2D groundwater model, and concluded that possibly 30,000 m^3/d of groundwater could be abstracted in the Geba basin in a sustainable way.

Sustainable use of groundwater is largely determined by groundwater recharge, i.e. the downward flow of water reaching the water table, which is added to the groundwater storage (Freeze and Cherry, 1979; Lerner et al., 1990; Healy, 2010). Hence, knowledge of rates and locations of recharge is important for determining sustainable yields of groundwater systems (Sophocleous, 2000; Sophocleous and Devlin, 2004; Devlin and Sophocleous, 2005). Many methods have been proposed to determine the groundwater recharge, as described for instance by Lerner et al. (1990), Simmers (1997), Kinzelbach et al. (2002) and Healy (2010), but the largest class of techniques are water-budget methods and models (Healy, 2010).

The main objective of this study is to assess the regional surface and groundwater potential in the Geba basin to support crop growth by irrigation. Basically it focuses on understanding the hydrological processes in the basin that determine the water resources, i.e. the partitioning of the precipitation in runoff, evapotranspiration and groundwater recharge in relation to the spatial distribution of hydro-meteorological variables and soil, land-use and topographic conditions. To achieve these objectives various tools and techniques are applied, e.g. remote sensing and GIS for data gathering, and application of the WetSpass model (Batelaan and De Smedt, 2001) for assessment of runoff, evapotranspiration and groundwater recharge. The novelty of the work is to demonstrate how spatial distributed water resources can be assessed in a large, difficult to access, water-stressed region using existing modeling tools and popular global data by well-established methods.

2. Methodology

2.1. Description of the study area

The Geba River is a major tributary of the Tekeze River, which joins the river Nile at Atbara in Sudan. The Geba basin is situated in the Tigray regional state in north Ethiopia, between latitudes 13°16′ and 14°16′ north and longitudes 38°38′ and 39°49′ east. Fig. 1 shows the location map of the study area. The basin covers an area of about 5260 km^2 and is surrounded by the Ethiopian Rift escarpment in the east, by the Tekeze River basin in the south, the Mugulat Mountains in the north, and the Werii River basin in the west. The topographic elevation in the basin ranges from about 950 m at the basin outlet to 3300 m in the northern part (Fig. 1), and is characterized by steep volcanic mountains and sharp cliffs with plateaus of sandstones in the north, deep gorges of limestone in the centre and ragged metamorphic terrain in the southwest. The fault-controlled Mekelle, Wukro and Sinkata areas, and the Atsbi horst form the major plains of the Geba basin. The geology of the Geba basin is highly diversified and complicated, as described by Tesfagiorgis et al. (2010); a geological map and a cross-section taken from this publication is presented in Fig. 2. The geology of the basin comprises Precambrian, metamorphosed volcanics/volcanoclastics, intrusives and sediments in the north and southwest, Paleozoic and Mesozoic sediments in the centre, some patches of Tertiary volcanic and shallow intrusives (Dolerites) in the centre and north, and localized quaternary sediments along the valleys of the major rivers. More than half of the basin is covered by Mesozoic sediments, and about a quarter by Precambrian rocks, while the remaining consists of Tertiary volcanics and Dolerites, or alluvial sediments.

The climate in the Geba basin is semi-arid with a mean annual precipitation ranging from 400 mm in the eastern part of the basin up to 950 mm in the northern and western parts. The temperature varies from a minimum average of 6.5 °C in the northern highlands and the northeast plateau up to a maximum average of 32 °C in the western lowlands near the basin outlet. Precipitation mainly takes place during the summer, which lasts from mid June till mid September. The long-term annual average reference (potential) evaporation is about 1500 mm, such that the aridity index, i.e. the ratio between precipitation and potential evapotranspiration, is between 0.27 and 0.63, which according to the UNEP classification (Middleton and Thomas, 1992) corresponds to a semi-arid to dry sub-humid climate. The land cover is accordingly, with bare land or shrubs in the semi-arid eastern lowlands, and mostly cultivated land and occasionally forest in the dry sub-humid higher parts in the north and west of the basin. Because of the semi-arid climate, agricultural practice is hampered severely. Generally, there is only one harvest possible by dryland farming in the wet summer season from June to September. Farmers predominantly grow cereals, as wheat, sorghum and teff, which take about three to four months to mature. Cropping starts as soon as the rains arrive in May or June. The growing stage is often insecure due to the erratic nature of the rainfall and the high evaporative demand, which is usually much larger than the rainfall. Hence, harvests are often insufficient and certainly non-optimal. This could be improved by irrigation, as advocated by the authorities and relief agencies, who promoted the construction of small scale reservoirs and hand-dug wells, which however often do not meet expectations.

The drainage system of the Geba basin can generally be described as dendritic with some significant influence of major structures like folds and faults. The main tributaries of the Geba River are Suluh, Genfel, Agulae, Illala and Metere (Fig. 1). The east–west flow direction of the Illala in the central part of the basin and north–south orientation of the Genfel in the north are thought to