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Assessing potential land suitable for surface irrigation using groundwater in Ethiopia

Abeyou W. Worqlul [a, *], Jaehak Jeong [a], Yihun T. Dile [b], Javier Osorio [a], Petra Schmitter [c], Thomas Gerik [a], R. Srinivasan [b], Neville Clark [d]

[a] Texas AgriLife Research, Temple, TX, USA
[b] Texas A&M University, College Station, TX, USA
[c] The International Water Management Institute, Nile Basin and East Africa Office, Addis Ababa, Ethiopia
[d] The Norman Borlaug Institute for International Agriculture, Texas A&M AgriLife Research, College Station, TX, USA

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ABSTRACT

Although Ethiopia has abundant land for irrigation, only a fraction of its potential land is being utilized. This study evaluates suitability of lands for irrigation using groundwater in Ethiopia using GIS-based Multi-Criteria Evaluation (MCE) techniques in order to enhance the country's agricultural industry. Key factors that significantly affect irrigation suitability evaluated in this study include physical land features (land use, soil, and slope), climate (rainfall and evapotranspiration), and market access (proximity to roads and access to market). These factors were weighted using a pair-wise comparison matrix, then reclassified and overlaid to identify suitable areas for groundwater irrigation using a 1-km grid. Groundwater data from the British Geological Survey were used to estimate the groundwater potential, which indicates the corresponding irrigation potential for major crops. Results indicated that more than 6 million ha of land are suitable for irrigation in Ethiopia. A large portion of the irrigable land is located in the Abbay, Rift Valley, Omo Ghibe, and Awash River basins. These basins have access to shallow groundwater (i.e., depth of groundwater less than 20 m from the surface) making it easier to extract. The comparison between available groundwater and total crop water requirements indicate that groundwater alone may not be sufficient to supply all suitable land. The study estimates that only 8% of the suitable land can be irrigated with the available shallow groundwater. However, groundwater is a viable option for supplementing surface water resources for irrigation in several basins in the country.

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1. Introduction

Agriculture plays a key role in the economies of most African countries (IFAD, 2011). For example, Ethiopia's agricultural sector employs about 80% of the labor force on a formal and informal basis, and accounts for approximately 45–50% of the gross domestic product (GDP) and 85% of export earnings (Araya & Stroosnijder, 2011; Berry, 2003; Bewket & Conway, 2007; Worqlul, Collick, Rossiter, Langan, & Steenhuis, 2015). However, the agriculture industry in Ethiopia is traditionally subsistence based and rainfed, which frequently suffers from rainfall variability (Seleshi & Camberlin, 2006). Rainfall variability compounded with lack of appropriate soil fertility management contribute to lower crop yield. For example, the country receives 70–90% of its rainfall in a short rainfall season, mainly from June to September. Moreover, approximately 90–95% of the total annual food production in the country is produced during the rainy season (Funk et al., 2003; Mario, James, & Prisca, 2010). Reliance on rainfed agriculture systems contributes to major food shortages throughout the country (Pankhurst & Johnson, 1988).

Various studies (Awulachew et al., 2007; You et al., 2011) have indicated that the country has a large potential of arable land. However, less than 5% of this potential is irrigated, due to lack of water storage facilities and infrastructure systems (e.g., pumps, water conveyance structures, etc.). Recently, the agriculture sector has received a particular emphasis to transition towards a more comprehensive agricultural production system known as Agriculture Development Led Industrialization. Use of irrigation could substantially transform the agriculture sector, which is currently

* Corresponding author. Tel.: +1 254 774 6020.
E-mail address: abeyou_wale@yahoo.com (A.W. Worqlul).

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dominated by single cropping rainfed crops (Awulachew & Ayana, 2011).

The Ethiopian Ministry of Water Resources MoWR (1999) and Awulachew et al. (2007) reported that the country has significant surface water potential from its twelve major river basins, but there is high spatial and temporal variability (Worqlul et al., 2015). Although there is no detailed study on groundwater resources potential in Ethiopia, a recent study by MacDonald, Bonsor, Dochartaigh, and Taylor (2012) indicates that Africa has substantial groundwater storage. They estimate that the annual groundwater storage in Africa has 100 times more than the annual renewable freshwater resources. As Ethiopia is described as the "water-tower" of Africa (Birkett, Murtugudde, & Allan, 1999; Hammond, 2013; Swain, 1997), it may be fair to assume that Ethiopia may have the lion's share of this groundwater potential.

Groundwater will remain the ultimate source of freshwater while surface water sources has been depleted. Groundwater is more suitable for irrigation than surface water since it has a slow response to climate variability and requires less treatment (Siebert et al., 2010). Much progress is achieved in using groundwater for cultivation in Asia (Siebert et al. (2010). Use of groundwater for irrigation has significantly affected agricultural growth in Asia, for example, especially after the green revolution. Groundwater played a critical role to support the agriculture industry (Altchenko & Villholth, 2014; Giordano, 2006). However, in Africa groundwater is less utilized resource. For example, in Ethiopia, groundwater is not adequately used due to higher development and operational cost and lack of understanding of the resource dynamics (Awulachew, Erkossa, & Namara, 2010). The groundwater in Ethiopia is mainly used for domestic water use. There may be limited cases where the groundwater is used for irrigation and other purposes. Despite some gross estimates (MoWR, 1999) and large-scale assessments of groundwater irrigation potential (MacDonald et al., 2012), there is little quantitative study on the groundwater resource potential for irrigation and other none domestic water uses. The aim of this study is, therefore, to estimate the potential suitable land for groundwater irrigation using a multi-criteria evaluation technique in a GIS environment.

Several studies have applied multi-criteria evaluation method for various applications including; potential land suitability mapping for irrigation using groundwater (Adhikary, Chandrasekharan, Trivedi, & Dash, 2015; Jha, Chowdary, & Chowdhury, 2010; Latinopoulos, Theodossiou, & Latinopoulos, 2011), irrigation area suitability mapping using surface water (Akıncı, Özalp, & Turgut, 2013; Worqlul et al., 2015), to identify solid waste disposal site (Ceballos-Silva & Lopez-Blanco, 2003; Şener, Şener, Nas, & Karagüzel, 2010), mapping of erosion-prone areas (Assefa et al., 2015; Rahman, Shi, & Chongfa, 2009; Setegn, Srinivasan, Dargahi, & Melesse, 2009), and for financial decision-making (Steuer & Na, 2003). Multi-criteria evaluation approach combines several factors to form a single indexed output. There are a number methods of combining factors which includes weighted linear combination (Miller, Collins, Steiner, & Cook, 1998), analytical network process (ANP) (Gencer & Gürpinar, 2007), multi-attribute utility theory (MAUT), weighted sum model (WSM) and analytical hierarchy process (AHP) (Saaty & Erdener, 1979; Saaty, 2008). This study applied the AHP method, which is widely used in the area of water resource management (Y. Chen, Yu, & Khan, 2010; Mendas & Delali, 2012; Steuer & Na, 2003).

2. Materials and methods

2.1. Study area

This study was carried out in the Federal Democratic Republic of Ethiopia, which is located between 3°00′ to 15°00′ N and 32°00′ to 48°00′ E in the eastern part of Africa (Fig. 1). The country has the second largest population in Africa after Nigeria, and is the most populated landlocked country in the world with a total area of 1.1 million km^2. The elevation of the study site ranges from 160 to 4530 m (i.e., meters above mean sea level); approximately 35% of the country is considered as a highland located at an altitude of 1500 m or above. Rainfall in Ethiopia is highly variable (Seleshi & Camberlin, 2005). Generally, there are three climate seasons in Ethiopia. These include *Kremt,* which is the main rainfall season from June to August; *Belg*, which is the small rainfall season from September to November; and *Bega*, which is the dry season from December through May. The highland receives moderate annual rainfall of about 1200 mm with minimal temperature variation, while the lowland (e.g., in the Afar and Somali region) receives an annual rainfall of less than 500 mm with a much greater temperature variation.

2.2. Factors used to map land suitability for irrigation

Factors that affect the suitability of an area for surface irrigation were identified based on literature and expert opinion (Akıncı et al., 2013; Y.; Chen et al., 2010; Mendas & Delali, 2012; Worqlul et al., 2015). Studied factors include biophysical (e.g., climate, soil characteristics, land use type, and topography) and socio-economic (e.g., market access such as proximity to a road and population density). Table 1 presents studied factors including the source of the data and their respective spatial resolutions.

2.2.1. Rainfall deficit

Climate factors such as rainfall and potential evapotranspiration are among the crucial factors that affect the suitability of an area for irrigation. Rainfall data from 509 weather stations (Fig. 1) were obtained from the Ethiopian National Meteorological Services Agency (ENMSA) for the period 2000 to 2010. ENMSA has divided the country into eight homogenous rainfall regimes (Diro, Grimes, Black, O'Neill, & Pardo-Iguzquiza, 2009; Gissila, Black, Grimes, & Slingo, 2004; Korecha & Sorteberg, 2013). The classification was based on typical rain producing system affecting the regional system in terms of spatial and temporal rainfall distribution. The lowland area, northern half and northeastern, receives small amount of rainfall with small rainfall variability. The long-term monthly rainfall data was aggregated to annual. The annual rainfall was interpolated using the Inverse Distance Weighting interpolation (IDW) method using standard neighborhood to estimate the spatial rainfall in the country (Fig. 2a). The interpolation provided spatial rainfall at 1 km resolution. Potential and actual evapotranspiration data were collected from MODIS global evapotranspiration (ET) products (Mu, Zhao, & Running, 2011). The MODIS ET dataset covers the period from 2000 to 2010 at an 8-day time step with a 1 km by 1 km resolution. The long-term average annual potential evapotranspiration was estimated by aggregating the 8-day MODIS ET (Fig. 2b).

2.2.2. Soil

Soil is a key factor in determining the suitability of an area for agriculture in general and irrigation in particular as is discussed in section 2.3.1. The soil data was obtained from the Africa Soil Information System (AfSIS, Vågen, et al., 2010). The AfSIS dataset was developed to bridge the soil information gap in Africa by collecting soil samples for over 28,000 locations distributed in 40 African countries from 2008 to 2014 (Hengl et al., 2015). The AfSIS soil data has a 250 m by 250 resolution for six layers (i.e., 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm and 100–200 cm); each layer contains soil texture, organic carbon content, bulk density and

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