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Implications of non-sustainable agricultural water policies for the water-food nexus in large-scale irrigation systems: A remote sensing approach

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ABSTRACT

This study proposes a novel monitoring tool based on Satellite Remote Sensing (SRS) data to examine the status of water distribution and Water Use Efficiency (WUE) under changing water policies in large-scale and complex irrigation schemes. The aim is to improve our understanding of the water-food nexus in such schemes. With a special reference to the Gezira Irrigation Scheme (GeIS) in Sudan during the period 2000–2014, the tool devised herein is well suited for cases where validation data are absent. First, it introduces an index, referred to as the Crop Water Consumption Index (CWCI), to assess the efficiency of water policies. The index is defined as the ratio of actual evapotranspiration (ET_a) over agricultural areas to total ET_a for the whole scheme where ET_a is estimated using the Simplified Surface Energy Balance model (SSEB). Second, the tool uses integrated Normalized Difference Vegetation Index (iNDVI), as a proxy for crop productivity, and ET_a to assess the WUE. Third, the tool uses SSEB ET_a and NDVI in an attempt to detect wastage of water. Four key results emerged from this research as follows: 1) the WUE has not improved despite the changing agricultural and water policies, 2) the seasonal ET_a can be used to detect the drier areas of GeIS, i.e. areas with poor irrigation water supply, 3) the decreasing trends of CWCI, slope of iNDVI-ET_a linear regression and iNDVI are indicative of inefficient utilization of irrigation water in the scheme, and 4) it is possible to use SSEB ET_a and NDVI to identify channels with spillover problems and detect wastage of rainwater that is not used as a source for irrigation. In conclusion, the innovative tool developed herein has provided important information on the efficiency of a large-scale irrigation scheme to help rationalize laborious water management processes and increase productivity.

1. Introduction

Though the coupling of water and agriculture systems has for long been practiced, knowledge on the connection between water availability and food security is particularly important given the already high withdrawal of water for irrigated agriculture worldwide (Ringler et al., 2013), especially in view of the global change that is characterized by water and food crises. These resource crises have been among the main drivers for the emergence of the water-energy-food security nexus (Al-Saidi and Elagib, 2017). Extensive irrigation without adequate vision on agricultural water management may reveal unsustainable agricultural production in the future due to increasing water scarcity. Many developing countries, especially those located in arid and semi-arid regions, may have already been practicing non-sustainable irrigation techniques. The Nile Basin in Africa emerges as a region where agriculture is a predominant activity, but is characterized by high water-food-poverty because of high vulnerability to water-related hazards, loss of livelihood, inequitable access to water and low water productivity (Kemp-Benedict et al., 2011). Since the concept of sustainability should carry with it combined elements, such as resource use, efficiency of utilization, conservation and social, economic, and cultural characteristics (Kennedy, 2007), it is believed that the understanding of the concept of water-food nexus in the context of irrigated agriculture in this basin faces the challenge of considering the aforementioned elements in order for the joint water-agriculture sectors to become sustainable.

There are approximately five million hectares of irrigated land in the Nile Basin (Bastiaanssen and Perry, 2009). Although the basin has fascinating irrigation network systems, there are areas with very poor irrigation performance (Karimi et al., 2012). For

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instance, traditional irrigation agriculture in Sudan is now facing a big challenge, and irrigation managers ought to develop water-saving irrigation practices for sustainable water use. During the last 20 years, the interest of the Sudanese government has shifted from agriculture-based economy first to oil production (Nour, 2013) and later to mining; thus, the irrigated agriculture sector has been economically unattractive. Most of the irrigated agricultural schemes have experienced the least concern about their rehabilitation and maintenance (Hamid et al., 2011).

The Sudanese large-scale Gezira Irrigation Scheme (GeIS) is fundamental for the food security and economy of Sudan. Nevertheless, the government had conducted several conservation water policies and handled responsibility of management to the farmers. Most policies focused on supplying more irrigation water through the scheme's irrigation system while some adapted the crop management systems to reduce the need for irrigation water. Poor performance of GeIS has manifested in forms of significant wastage of water and adverse effect on crop production (Ibrahim et al., 2002; Adeeb, 2006; Elamin et al., 2011). In addition to inefficient irrigation infrastructure, low crop productivity from GeIS is also attributable to frequent drought and ineffective agricultural policies (Mahgoub, 2014). As a result of these policies, cotton cultivation area, for instance, has declined recently in GeIS (Al Zayed et al., 2015). It is believed that these water policies have exacerbated the problems reported for GeIS. Inappropriate operation and maintenance of the irrigation and drainage networks (FAO, 2011) have induced water distribution problems across GeIS (Ahmed, 2009). Improvement of network functionality by means of rehabilitation or upgrading of channels is, thus, needed and has been recommended by many investigators (World Bank, 2000; Ahmed and Ismail, 2008; FAO, 2011). Developing an effective monitoring tool is essential for decision making (Anderson et al., 2012). This helps assess the changing water use strategies for better irrigation management (Yang et al., 2012) and to prioritize the rehabilitation and the upgrading of the irrigation channels. However, GeIS is exceptionally large with a complex system, thus constituting a major constraint to data acquirement. These factors in turn render the operation and management of GeIS problematic. Hence, an effective monitoring tool using Geographic Information System (GIS) and Satellite Remote Sensing (SRS) should be sought.

Although the Modified Vegetation Condition Index (MVCI) proposed by Al Zayed et al. (2015) for GeIS is useful as a monitoring tool, the index does not account for detection of wasted water, for example in water accumulation areas. Therefore, understanding the spatial and temporal variability of actual evapotranspiration (ET_a) is important to assess the efficiency of water policies and to help in tackling the water wastage issues.

Estimation of ET_a for GeIS using SRS has been carried out only on a short-time scale, as for example the winter crop season of 2001 (Bashir et al., 2009a, b; Ahmed et al., 2010), the summer crop season of 2004 (Bashir et al., 2007, 2008; Al Zayed et al., 2016), and the whole year of 2006 (El Tahir et al., 2012) as well as 2007 (WaterWatch, 2009). These studies focused on specific farms or administrative units to determine the crop coefficient, and aimed to validate the ET_a estimates on the scheme scale. El Tahir et al. (2012) compared the estimated ET_a, using a SRS technique with a modified Thornthwaite water balance method, for the whole of the Blue Nile Basin including the GeIS. Despite these extensive works, scheme-wide and/or long-term analysis of ET_a has not yet been conducted. Furthermore, longer-period studies to overcome the limited availability of ground-truth data for validation have always been recommended by the above researchers.

Therefore, this study devises a novel approach for improving the monitoring and evaluation of irrigation performance on regional scales based on SRS. The aims are (1) to support strategic decision-making processes by presenting an evaluation approach of the efficiency of changing water policies of the past years and (2) to devise a monitoring tool to examine the status of water distribution in a cost-effective manner that helps ultimately better water allocation.

2. Study area

GeIS started in 1911 as a pilot project for growing cotton, and was officially inaugurated in 1925 (World Bank, 2010). As shown in Fig. 1, the irrigated area lies in the flat, central plains between the Blue Nile and the White Nile south of Khartoum, between latitudes 13°30′ N and 15°30′ N, and longitudes 32°15′ E and 33°45′ E. The elevation varies between 385 m and 415 m above mean sea level (average elevation 405 m). With a flat topography and a very gentle slope of 15 cm/km from south to north and from east to west, the area provides an ideal situation for gravity flow (Plusquellec, 1990). Covering an area of about 0.9 million ha (FAO, 2011), GeIS splits into two main areas, Gezira (0.5 million ha) and Managel (0.4 million ha). The width of GeIS from east to west is about 75 km, and its maximum length from north to south is approximately 245 km. A uniform soil with high clay content (50%–60%), known as vertisols soil, characterizes the area (Bashir et al., 2008).

The scheme is located in a typical hot arid region (Elagib, 2009a, 2010) with a 50-year average annual rainfall of 300 mm and a 50-year mean annual reference evapotranspiration (ET_o) of about 2221 mm for 1961–2010. Accordingly, irrigation is essential for agriculture, as rainfall is much lower than the crop water need. Though the GeIS is hydrologically part of the White Nile Basin, an average annual irrigation water of 6–7 billion cubic meters (BCM) based on data for 1970–2012 is diverted from the Blue Nile.

The irrigation system is infested with three main problems: siltation, weeds and improper drainage system. More silt is carried into the system every year, causing increasing silt deposits in the irrigation channel. The accumulation of silt has also created conducive conditions for abundant weed growth in the channel (Eldaw, 2004; Ahmed and Ismail, 2008). Siltation and prevalence of weed preclude the water flow from reaching the end of the minor channels (World Bank, 2000, 2010). The original design of the drainage network is limited to major and collector drains without field drainage (Plusquellec, 1990). The main purpose of the drainage network is to remove the surface runoff generated by rain or excess irrigation, but not the drained water, from the farm because of the nature of the soil and low groundwater table (World Bank, 2000). Plusquellec (1990) mentioned that the existing minor drains were completely silted up. The drained water is ponded in large local depressions unsuitable for cultivation, thus being lost to evaporation (Ahmed, 2009). Generally, there is no reuse of drainage water in the Sudanese irrigation system (Achamyeleh, 1993). Several field visits conducted as part of the present study during 2011–2013, including interviews with irrigation engineers and farmers, confirmed these observations. During a field visit in 2011, weed problem was deemed by farmers to be one of the reasons behind water shortage at the tail end of the system (Fig. 2a). Therefore, some farmers were seen using pumps to abstract water from the channels into their fields, as shown in Fig. 2b.

3. Agricultural water policies for the Gezira Irrigation Scheme

Water policies for the GeIS have evolved through nine distinct and changing phases, as summarized in Fig. 3. In the first phase, cotton was the only crop grown when the project was established (1925–1960). During this period, GeIS was fully managed and financed by the cotton company and the government, and farmers were just tenants (Adam et al., 2002). An efficient