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Irrigation water management in arid regions of Middle East: Assessing spatio-temporal variation of actual evapotranspiration through remote sensing techniques and meteorological data

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ABSTRACT

Spatial and temporal distribution of reference (ETo) and actual evapotranspiration (AET) over the central region of Saudi Arabia during 1950–2013 are estimated using remote sensing and GIS techniques. Firstly, the FAO Penman-Monteith method was used to model the spatial distribution of ETo on a grid-by-grid basis using data collected from meteorological stations and GIS techniques. Then, crop coefficients (Kc) were modeled as a function of 16-day time-series MODIS normalized difference vegetation index (NDVI). Next, using Kc maps and ETo as input, daily AET was simulated by the soil water balance (SWB) model and aggregated to monthly and annual AET. From empirical NDVI-Kc relationships developed and applicable at pixel level, Kc derived from the NDVI-Kc relationships agree well with Kc recommended by FAO over various crop growth stages in the field. The monthly AET maps for 1950–2013 show a gradual increase in AET during the crop-growing season in January to May but a subsequent decline as the season progresses from June to December. The AET estimated for January to June are arranged in descending order, which are May (3.67–44.7 mm/day), April (5.99–36.8 mm/day), March (2.96–32.7 mm/day), February (0.68–20 mm/day), June (2.42–17.7 mm/day) and January (1–11 mm/day), respectively. Statistical analysis shows that statistically significant change point in daily AET generally occurred in 1990, such that the long-term average daily AET of 1950–1990 at 3.6 mm/day increased to about 5.3 mm/day between 1990 and 2016 with a positive trend of 1.5 mm/decade. The annual AET estimated for irrigated cropland in northern and central regions of Riyadh, Al-Qassim province and Hail province range from 1200 to 2900 mm/year. In these regions, low AET values are found in shrubland, grassland, and other natural vegetation. The annual AET estimated by the SWB model are about 9–11% higher than modeled AET in the study area, where the long-term average daily AET estimated for 1950–2013 range from 2 mm/day to 30 mm/day. Representative AET maps derived from applying the NDVI-Kc relationships to the SWB model will be useful to achieve the planning and management of sustainable water use in arid regions of Middle East.

1. Introduction

The Kingdom of Saudi Arabia (KSA) (24°N, 45°E) is the largest Arab country located in Western Asia. The kingdom has an area of 2.15 million square kilometers, but its mean annual rainfall is only about 112 mm/year (Mahmoud, 2014 and Mahmoud et al., 2014). The agricultural sector of KSA equipped with modern irrigation technology has more than 1.1 million hectares of irrigated land (Department of Statistics and Information, 2008). Because of its arid climate, almost all agricultural lands are dependent on groundwater as the main source of water supply, which, however, is costly to withdraw (Mahmoud, 2014). Major crops grown in Saudi Arabia include cereals (wheat, sorghum, barley, and millet), vegetables (tomato, watermelon, eggplant, potato, cucumber, and onions), fruits (dates, citrus, and grapes), and the forage crop of alfalfa. Agricultural water demand in KSA is very high, ranging between 83–90% of the total water demands during 1990–2009 (Chowdhury and Al-Zahrani, 2015). Therefore, evapotranspiration (ET) loss from irrigated lands is a key factor to consider for water supply to the agriculture sector (for example, as part of an early warning system). As large amount of irrigated water are lost through ET partly dependent on irrigation methods employed (Mahmoud and Alazba, 2016), accurate regional estimation of ET will be helpful for effective management of irrigation water.

Actual evapotranspiration (AET) reflects the crop's water need which consists of transpiration and evaporation (Alberto et al., 2014; Senay et al., 2017; Olivera-Guerra et al., 2018). AET can be estimated

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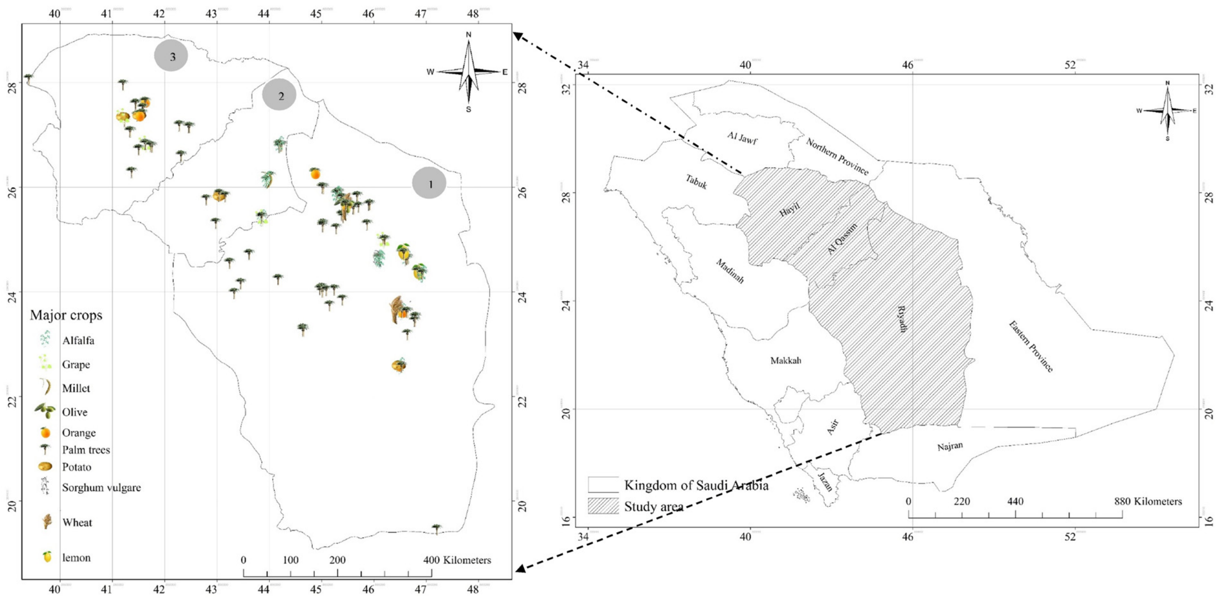

Fig. 1. Location map of the study area.

by: (i) in situ measurements using lysimeters or flux towers, (ii) crop coefficients approach (Allen et al., 1998), and (iii) remotely sensed data (Kalma et al., 2008) and models, which are either based on empirical / statistical or energy balance approaches. Using a spline model and a linear sub-model dependent on elevation, McVicar et al. (2007) interpolated maximum (Tmax) and minimum (Tmin) air temperatures, wind speed (u) and vapor pressure (ea) to estimate the radiative energy affected by the topography (i.e., elevation, slope and aspect), to calculate ETo for each grid-cell of the Yellow River basin of China. The crop evapotranspiration (*ETc*), defined as Kc x ETo, is commonly used to estimate crop water requirements (Doorenbos and Pruitt, 1977; Allen et al., 1998). Tables of Kc have been developed for crops of various growth stages, soil, and climate characteristics (Doorenbos and Pruitt, 1977; Allen et al., 1998). From the strength and weaknesses of some potential evapotranspiration (PET) models developed for land covers commonly found in southwestern United States, Douglas et al. (2009) selected a PET model for Florida.

Recent studies that applied remotely sensed (RS) data to estimate spatio-temporally estimated AET and crop-water consumption are such as Duchemin et al. (2006), Er-Raki et al. (2007), González-Dugo and Mateos (2008), Er-Raki et al. (2010), Sánchez et al. (2010), Cruz-Blanco et al. (2014), Senay et al. (2017), and Parka et al. (2017). Similar seasonal patterns of vegetation indices and evapotranspiration have been found over annual crops (Bausch, 1995; Duchemin et al., 2006; Er-Raki et al., 2007). Agrometeorological monitoring of crop production is often done on a large spatial scale and small temporal resolutions using RS vegetation indices of visible and near-infrared wavelengths, such as normalized difference vegetation index (NDVI) to assess the leaf area index, LAI, biomass, or the absorbed photosynthetically active radiation/ soil-adjusted vegetation index. NDVI can be used to estimate real-time Kc given the high correlation between NDVI and Kc (Ray and Dadhwal, 2001; Er-Raki et al., 2007; González-Dugo et al., 2013; Mateos et al., 2013; Kullberg et al., 2017; Campos et al., 2017). Because of this close relationship between NDVI and Kc, NDVI has been widely used for vegetation monitoring, crop yield assessment and drought detection (Justice and Townshend, 2002). High NDVI values generally indicate more photosynthetic activity. On the other hand, higher Kc due to higher temperature results in less soil water and therefore a decline in NDVI, while denser vegetation indices mean more ET losses which lower the land surface temperature (Boegh et al., 1999).

Integrating remote sensing data into soil water balance models are one of the most commonly used methods for estimating crop water requirements (Bodner et al., 2007). For instance, Campos et al. (2016a) estimated the total soil moisture in soil layers of southwestern Spain based on AET and time series of multispectral imageries of (vegetation cover). They developed a simple linear relationship between the NDVI and Kc. Such a relationship has been shown to be effective in mapping AET of crops (Campos et al.,2016a, b; Toureiro et al., 2017). Senay et al. (2017) developed historical ET maps for major irrigation districts in California, USA using Landsat images. Parka et al. (2017) estimated AET in northeast Asia using Kc, ETo, and surface soil moisture data from satellite images. They found that Kc estimated from NDVI data correspond well with observed Kc. Consoli and Vanella (2014) mapped crop ET in southern Italy using a soil-water balance model driven with vegetation indices and climate data. The authors reported that this method has the potential to estimate crop water requirements and water management over large agricultural areas. Many earlier studies tend to estimate field scale crop coefficient and crop water requirements only for a specific crop, such as maize, soybean, cotton, and wheat (Duchemin et al., 2006; Irmak et al., 2013; Campos et al., 2017; Drerup et al., 2017; Rozenstein et al., 2018).

The development of models to estimate AET based on remotely sensed data applicable over large areas in arid regions of Middle East can be challenging because irrigation water requirements are essential but available water resources are limited. The objectives of the present study are: (1) To estimate Reference Evapotranspiration using data collected from meteorological stations and Geographic information system techniques on a grid-by-grid basis (2) Modeling Kc as a function of 16-day time-series of MODIS-NDVI, (3) To estimate AET based on soil water balance, Kc, and ETo, and (4) To detect change points and trends in long-term average daily AET.

2. Material and methods

2.1. Description of the study area

The study area is in three provinces of central Saudi Arabia: (1) Al-Riyadh, (2) Al-Qassim and (3) Hail Province (Fig. 1). The Al-Riyadh Province has an area of 380,497.8 km^2 and a population of 6,777,146 (2010), making it the second largest province of Saudi Arabia in terms of both area and population. It is located at the center of the Arabian Peninsula (24° 38′ N and 46° 43′ E) on a large plateau, with an arid