Remote Sensing of Environment 149 (2014) 155–165

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Mapping irrigated areas in Afghanistan over the past decade using MODIS NDVI

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ARTICLE INFO

Article history:
Received 19 August 2013
Received in revised form 8 March 2014
Accepted 9 April 2014
Available online 3 May 2014

Keywords:
Irrigated areas
Afghanistan
Food security
MODIS NDVI
Landsat

ABSTRACT

Agricultural production capacity contributes to food security in Afghanistan and is largely dependent on irrigated farming, mostly utilizing surface water fed by snowmelt. Because of the high contribution of irrigated crops (>80%) to total agricultural production, knowing the spatial distribution and year-to-year variability in irrigated areas is imperative to monitoring food security for the country. We used 16-day composites of the Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to create 23-point time series for each year from 2000 through 2013. Seasonal peak values and time series were used in a threshold-dependent decision tree algorithm to map irrigated areas in Afghanistan for the last 14 years. In the absence of ground reference irrigated area information, we evaluated these maps with the irrigated areas classified from multiple snapshots of the landscape during the growing season from Landsat 5 optical and thermal sensor images. We were able to identify irrigated areas using Landsat imagery by selecting as irrigated those areas with Landsat-derived NDVI greater than 0.30–0.45, depending on the date of the Landsat image and surface temperature less than or equal to 310 Kelvin (36.9 ° C). Due to the availability of Landsat images, we were able to compare with the MODIS-derived maps for four years: 2000, 2009, 2010, and 2011. The irrigated areas derived from Landsat agreed well $r^2 = 0.91$ with the irrigated areas derived from MODIS, providing confidence in the MODIS NDVI threshold approach. The maps portrayed a highly dynamic irrigated agriculture practice in Afghanistan, where the amount of irrigated area was largely determined by the availability of surface water, especially snowmelt, and varied by as much as 30% between water surplus and water deficit years. During the past 14 years, 2001, 2004, and 2008 showed the lowest levels of irrigated area (~1.5 million hectares), attesting to the severe drought conditions in those years, whereas 2009, 2012 and 2013 registered the largest irrigated area (~2.5 million hectares) due to record snowpack and snowmelt in the region. The model holds promise the ability to provide near-real-time (by the end of the growing seasons) estimates of irrigated area, which are beneficial for food security monitoring as well as subsequent decision making for the country. While the model is developed for Afghanistan, it can be adopted with appropriate adjustments in the derived threshold values to map irrigated areas elsewhere.

1. Introduction

With three decades of war, civil unrest, recurring natural disasters (such as flooding, droughts, earthquakes, landslides, and avalanches), and widespread food vulnerability, monitoring food security for the people of Afghanistan has never been more important in the recovery of their livelihoods. Approximately 30% of the total population of 31 million (Banks & Soldal, 2002; WHO, 2009) in Afghanistan are food insecure to some degree (NRVA, 2009; Viola, Najimi, & Bacon, 2007). The country's economy is highly dependent on the agriculture sector, which contributes one-third of the country's Gross Domestic Product (USDA-FAS, 2011) and employs approximately 80% of the total population (ICARDA, 2002; USDA-FAS, 2011). Only 12% (7.9 million hectares) of the total land area (65 million hectares) is arable, of which about half (3.7 million hectares) is cultivated annually, leaving the other half (4.2 million hectares) mostly as fallow land (USDA-FAS, 2011). The annual average precipitation in Afghanistan varies between 50 mm in the southwest to over 1000 mm in the east (Banks & Soldal, 2002). Also, the annual potential evapotranspiration is about six times higher than the annual average precipitation, implying that the direct recharge of precipitation to groundwater is likely to be extremely low (Banks & Soldal, 2002). As a result, 55–70% of total cultivated land is irrigated

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http://dx.doi.org/10.1016/j.rse.2014.04.008
0034-4257/

for successful production(Qureshi, 2002; USDA-FAS, 2011), and 85% of that irrigation comes from surface water, mostly in the form of snowmelt (Reeling, Lee, Mitchell, Halimi, & Carver, 2012).

The landscape of Afghanistan is characterized by high mountains with snow-covered peaks, fertile valleys, and desert plains. The lowland fertile valleys and desert plains are located in the northern, western, southwestern, and southeastern areas, while the highlands are located in the central, eastern, and northeastern parts of the country. In general, irrigated areas are found throughout Afghanistan, especially along flood plains of rivers. However, their greatest concentrations are found in the lowlands of the northern, western, and southwestern parts of the country. Agriculture in Afghanistan is primarily smallholder farming using non-mechanized skills and techniques. The median size of an irrigated farm is 1.4 hectares compared to 6–7 hectares for rainfed farms (Qureshi, 2002), which makes irrigated agriculture production vulnerable to wide fluctuations depending on available water resources. Although dependence on annual rainfall regimes makes variability in rainfed systems even more vulnerable, in this study we have concentrated on irrigated area estimation since rainfed production accounts for a much smaller portion of overall production. Climate change is believed to be impacting water availability, since renewable freshwater (the sum of mean annual surface runoff and groundwater recharge) resources are expected to be below the calculated demand threshold of 1500 cubic meters annually per capita by 2030 (Yang, Reichert, Abbaspour, & Zehnder, 2003).

As is often the case in developing countries, Afghanistan does not possess adequate information on the spatiotemporal distribution of their irrigated agriculture. The first known classification of irrigated areas at the national scale was initiated by the Food and Agriculture Organization of the United Nations (FAO) in the early 1970s as part of an agricultural land cover database for the country. The 1972 land cover scheme included three classes of irrigated lands: a) orchards and gardens, b) intensively cultivated, and c) intermittently cultivated. The land cover classes were identified and hand-drawn based on visual interpretation of aerial photographs acquired between 1960 and 1970 (FAO, 1972). The quality and reliability of the 1972 land cover map were reported to be suspect (FAO, 1972) because the map identified only major irrigated areas in the northern and southwestern parts of the country with no validation.

During the 1990s, FAO updated the land cover maps through interpretation of Landsat Thematic Mapper satellite imagery acquired in 1990 and 1993 with the help of KFA-1000 (a film camera type) space photographs of various regions of Afghanistan, which were acquired between 1988 and 1992 (FAO, 1999). The 1993 land cover classification scheme included three classes of irrigated land: a) intensively cultivated (two crops per year, wheat followed by rice), b) intensively cultivated (one or two crops per year, wheat followed by other crops), and c) occasionally cultivated (every two or three years, generally wheat). About 3.2 million hectares of land were identified as irrigated in the 1993 land cover map. Recently, FAO released a 2010 land cover map of the country (FAO, 2013). The 2010 land cover classes were identified from high resolution (20 m, 10 m, and 5 m) Système Pour l'Observation de la Terre (SPOT) images, historical and recent Landsat images, and aerial photographs. The amount of identified irrigated areas in the 2010 map was 3.4 million hectares.

Apart from FAO initiatives, Afghanistan was included in several land cover mapping studies that were mostly optimized for global application. The Kassel digital Global Map of Irrigated Areas identified the percentage of each $0.5° \times 0.5°$ cell area that was equipped for irrigation in 1995 (Döll & Siebert, 1999). The map was subsequently improved and upgraded to $5' \times 5'$ cell size for 2000 (Siebert, Döll, Feick, Frenken, & Hoogeveen, 2007). The U.S. Geological Survey Global Land Cover Characterization (GLCC) dataset included four types of irrigated croplands from 1-km Advanced Very High Resolution Radiometer sensor data from 1992 to 1993 in a multi-temporal unsupervised classification method (Loveland et al., 2000). More recently, the International Water Management Institute produced a fractional global map of irrigated areas at 10-km resolution from a multi-resolution blend of satellite earth observations, topography, and climate data in an unsupervised classification method for 1999 (Thenkabail et al., 2009). The datasets were inconsistent in temporal frequency and nearly impossible to aggregate because of their differing classification systems.

The objective of this study is twofold. First, we develop a methodology capable of identifying irrigated areas consistently, annually, and at a national scale, as 80–85% of total crop production comes from irrigated land in Afghanistan (Qureshi, 2002). We primarily focus on mapping irrigated areas, although rainfed agriculture contributes one-third to overall cereal production (MAIL, 2012). Wheat (winter and spring) is the single most important crop grown on both irrigated and rainfed land. However, production from irrigated wheat contributes the most due to its 2.5 times higher yield than that of rainfed wheat (MAIL, 2012). The contribution of rainfed wheat to total cereal production varies between 5% and 26%, depending on the rainfall regime (MAIL, 2012). Due to the large contribution from irrigated lands, food security is affected by the availability of freshwater for irrigation, which in turn determines the extent of irrigated area for the country. In addition to the link between irrigated area and production, with increased irrigated area comes more need for agricultural labor, an important component of livelihoods in many parts of Afghanistan. Hence, identifying variability in the spatial extent of irrigated lands on an annual basis is important for food security monitoring. Second, we apply the method of mapping irrigated areas historically to establish a spatiotemporal irrigated area database for Afghanistan. The ability to apply such a method for mapping irrigated areas on an annual basis, with reference to a consistently mapped historical database, will aid in assessing potential food security scenarios for the country.

2. Data and methods

2.1. Definition of irrigated area

The irrigated area is defined as the agricultural area that receives full or partial application of water to the soil to meet water requirement by the standing crops at least once in a given year. Irrigated area only refers to extent of the physical area, meaning that agricultural area that is irrigated multiple times a year is counted once. The MODIS 250-m pixel spatial resolution equivalent to 6.25 hectares is kept as the mapping unit; however the lone identified single cell areas were removed from the irrigated area maps. Binary irrigated area maps are produced where 100% of the pixel area is considered irrigated. In Afghanistan, cereal crops (wheat, maize, barley, sorghum and rice), fruit trees, nuts, vineyards and other crops are commonly grown on irrigated land where irrigation is provided through formal and informal systems. Formal irrigation systems (large irrigation schemes developed with central government assistance with outside technical and financial support) account for only 10% of the irrigated areas while the rest (90%) of the irrigated areas draw upon informal systems (traditionally developed and managed by local communities e.g. karez, springs, wells, rivers and streams) mostly using surface water.

2.2. MODIS NDVI for mapping irrigated areas

The Normalized Difference Vegetation Index (NDVI) is a sufficiently good indicator of irrigation presence (Ozdogan, Woodcock, Salvucci, & Demir, 2006) because of its ability to measure green biomass (Tucker, 1979; Tucker, Newcomb, Los, & Prince, 1991) and its strong positive correlation with available moisture for vegetation (Pervez & Brown, 2010). Prior studies show that the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI dataset has the sufficient spatial, spectral, and temporal resolutions to capture quantitative vegetation dynamics over space and time (Wardlow & Egbert, 2008; Wardlow, Egbert, & Kastens, 2007), and can be used to identify irrigated areas