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ESTIMATING IN-SEASON ACTUAL EVAPOTRANSPIRATION OVER A LARGE-SCALE IRRIGATION SCHEME IN RESOURCE-LIMITED CONDITIONS

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Abstract

Reliable and readily available data on actual evapotranspiration (ET_a) over large-scale areas throughout the crop growing season are critical for improved agricultural irrigation and water resource management. On-site data collection is costly, labour-intensive, and very challenging in resource-limited conditions. Thus, open-source satellite-based approaches might be adopted as cost-effective alternatives. In this study, the performance of a cost-effective and open source satellite-based approach for estimating ET_a over a large-scale (1200 ha) irrigation system, the Kou Valley Irrigation Scheme (KVIS), in Burkina Faso was assessed. ET_a values over the critical irrigation period during the 2014 dry season (January-April) were estimated using the Python module for Surface Energy Balance Algorithm for Land model (PySEBAL). Then, they were compared against the Water Productivity Open-access (FAO-WaPOR), and United States Geological Survey-Famine Early Warning Systems Network Operational Simplified Surface Energy Balance (USGS-FEWS NET's SSEBop) ET_a over the same period at different temporal scales. Overall, ET_a values were satisfactorily estimated throughout the crop growth season across the Kou Valley irrigation scheme using PySEBAL. They spatially varied depending on the soil type and crop, with daily values ranging from 4.09 mm day^{-1} to 7.7 mm day^{-1}, for a seasonal average of 619 mm. The finer spatial resolution (30 m) of

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PySEBAL outputs allowed better estimations compared to the FAO-WaPOR and SSEBop-based approaches. Our findings help ascertain the use of the PySEBAL model in semi-arid environment in Burkina Faso, and could serve as a basis for developing strategies for improved irrigation water management in countries experiencing similar conditions such as Burkina Faso.

Key words: water management, remote sensing, Landsat, semi-arid environment, Sub-Sahara

Introduction. Evapotranspiration (ET) plays an essential role in determining the exchanges of energy and mass between the hydrosphere, atmosphere, and biosphere [1]. With a more variable and changing climate, water resources for irrigation are becoming increasingly scarce in several Sub-Saharan African countries [2]. Reliable and timely information on the actual evapotranspiration (ET_a) over large-scale regions is critical to the optimum management of agricultural irrigation water. In countries where funds are limited to maintain continuous on-site monitoring, and few historical objective information is available, developing cost-effective approaches for improved irrigation water management strategies is vital to sustainable farming activities and the livelihoods of individuals.

Several methods with various levels of complexity and data requirements exist for estimating ET. They range from air temperature-based methods [3] to methods involving several climate variables (e.g. relative humidity, wind speed, solar radiation and air temperature) [4], or remote sensing satellite-based methods [5]. Among the methods used for measuring ET, weighing lysimeters are considered standard for field scale applications [6]. Their use over large-scale areas is limited due to their costly implementation and the values obtained can fail to represent the spatial variability across a given irrigation scheme [7]. To overcome these limits remote sensing-based methods are employed. An example is the Surface Energy Balance Algorithm for Land (SEBAL) model [5], which uses such data, in addition to climate data. One of the main advantages of remote sensing-based methods is their cost-effectiveness and their ability to cover various scales (from field to catchment to region). Nevertheless, advection effects and complex biophysical dynamics across these heterogeneous agro-ecosystems that characterize large-scale regions constitute non-negligible sources of errors while applying these approaches [8].

To overcome the negative impacts of increased rainfall variability on crop yields in Burkina Faso, efforts have been increased to set up irrigation systems and promote small-scale irrigation over the past decades [9]. Smallholder farmers are thus relying on irrigation to maintain or increase their productivity. The main objective of this study was to assess the performance of a cost-effective and open source satellite-based approach for estimating ET_a over a large-scale (1200 ha) irrigation system, the Kou Valley Irrigation Scheme (KVIS), in Burkina Faso. ET_a values over the critical period for irrigation during the 2014 dry season (January-April) were first estimated using the Python module for Surface Energy Balance

Algorithm for Land (PySEBAL) model. Then, they were compared against the FAO-WaPOR (Water Productivity Open-access) and United States Geological Survey-Famine Early Warning Systems Network Operational Simplified Surface Energy Balance (USGS-FEWS NET's SSEBop) ET_a over the same period. The KVIS was established to increase the national rice production, and help surrounding populations diversify and increase their incomes [10]. The results of this study will help ascertain the use of the PySEBAL model in semi-arid environment, and will provide a basis for developing strategies for improved irrigation water management in countries experiencing similar conditions such as Burkina Faso.

Materials and methods. ***The python module for Surface Energy Balance model (PySEBAL).*** The PySEBAL model, developed by the UNESCO-IHE Institute for Water Education, is the python module for the SEBAL model (`https://pypi.org/project/SEBAL/`). The model calculates the energy balance at the land surface at the satellite overpass time to obtain the latent heat flux. For more details on the SEBAL model, reference is made to [5] and [11].

Study area. The KVIS is a 1200 ha irrigation scheme located in the Kou watershed (Fig. 1). The watershed area is drained by the Kou River and its tributaries and is characterized by a sub-humid climate: a dry season from October to May, followed by a rainy season from June to September. Monthly temperatures vary between 18 and 37 °C on average; relative humidity ranges from 20 to 80%; the average wind speed is approximately 2.6 m s^{-1} [12]. Annual ET_0 is up to 1700 mm, with daily values ranging from 4 mm (August-December) to 7 mm in March [13]. The KVIS diverts water from the Kou river into its irrigation canals. From the headwork water is gravitationally conveyed across the KVIS (Fig. 1A) by 11-km long feeder canals at an average flow rate of 3.5 m^3 s^{-1} and 1.4 m^3 s^{-1} in rainy and dry seasons, respectively [13]. Six different soil groups are identified across the KVIS: clay, clay loam, sandy clay, sandy clay loam, loam, and sandy loam (Fig. 1B). A hierarchical irrigation canal system from the primary to the quaternary canal allocates the water over the scheme area to irrigate an average plot size of 0.5 ha with a basin irrigation system. The study period of this study spanned from January 1 to April 30, 2014, and corresponded to the critical irrigation period of the dry season 2014. During that season, rice, maize, and sweet potato are the main crops produced in the KVIS. The respective production areas were 317, 232, and 175 ha.

Landsat images. Seven clear-sky Landsat 8 Operational Land Imager and Thermal Infrared Sensor images encompassing the study period were used in this study. Landsat 8 OLI/TRIS bands 2–7, 10 and 11 (spatial resolution being 30 or 100 m, depending on the band) were used in the PySEBAL model [11]. They were downloaded from the USGS Earth Explorer website (`https://earthexplorer.usgs.gov/`).

Weather and digital elevation model data. Three-hourly data of air temperature, wind speed, relative humidity, and solar radiation over the study period were used. They were obtained from the Bobo-Dioulasso weather station located about 25 km southeast of the KVIS (air temperature, wind speed, and relative humidity), and from the website `http://www.soda-pro.com` (solar radiation). The weather data were used in PySEBAL for calculating ET_a. Digital elevation model [14] data at 30 m spatial resolution were used in the surface temperature correction within PySEBAL given the changes in temperatures according to elevation and slope. DEM data were sourced from the U.S.A. National Aeronautics and Space Administration's (NASA) Shuttle Radar Topography Mission (SRTM).

FAO-WaPOR and USGS-FEWS NET's ET_a data. Dekadal (10-day period) ET_a data at 250 m spatial resolution for the study period from the FAO-WaPOR's data portal (`https://wapor.apps.fao.org`) were used in this study. FAO-WaPOR (version 1.0; `https://wapor.apps.fao.org/home/WAPOR_2/1`) uses satellite data to produce agricultural land and water productivity data at three spatial levels: continental (250 m spatial resolution), country and river basin (100 m spatial resolution) and sub-national (30 m spatial resolution). Evapotranspiration values at different spatial and temporal scales are determined using the Penman–Monteith equation and satellite-derived data through the ETLook model. The satellite data are from the MODIS (Moderate Resolution Imaging Spectroradiometer) and AMSRE (Advanced Microwave Scanning Radiometer) sensors. A description of the ETLook model is provided in [15]. FAO-WaPOR data have been qualitatively assessed by checking the consistency of the different layers using various independent data sources [16]. Likewise, dekadal ET_a data from the USGS-FEWS NET's SSEBop for the study area were retrieved from the data portal `https://earlywarning.usgs.gov/fews`. MODIS thermal imagery data at 1 km pixel resolution are used through the SSEBop approach [17] to generate ET_a values. Given the details provided in the SSEBop approach, the reader is referred to [17] for its description.

Data analyses. Spatial and temporal statistical comparisons between the ET_a from PySEBAL model, and ET_a from FAO-WaPOR and USGS-FEWS NET's SSEBop were performed. For the spatial analysis, PySEBAL-derived ET_a data were resampled to 250 m and 1 km spatial resolutions to match the spatial resolutions of FAO-WaPOR and USGS-FEWS NET's SSEBop, respectively, using the nearest neighbour algorithm implemented in the QGIS software (version 2.18.27). The temporal analysis was done using decadal data from the three sources (PySEBAL, FAO-WaPOR and USGS-FEWS NET's SSEBop). The quality of the comparisons was assessed using the root mean square error (RMSE) and the coefficient of determination (R^2). All data analyses and mapping were carried out using the QGIS software (`https://qgis.org/`) and Microsoft® Office Excel (Redmond, WA, USA).

Results and discussion. ***Spatial distribution of seasonal actual evapotranspiration.*** Different ranges of ET_a values were found depending on the

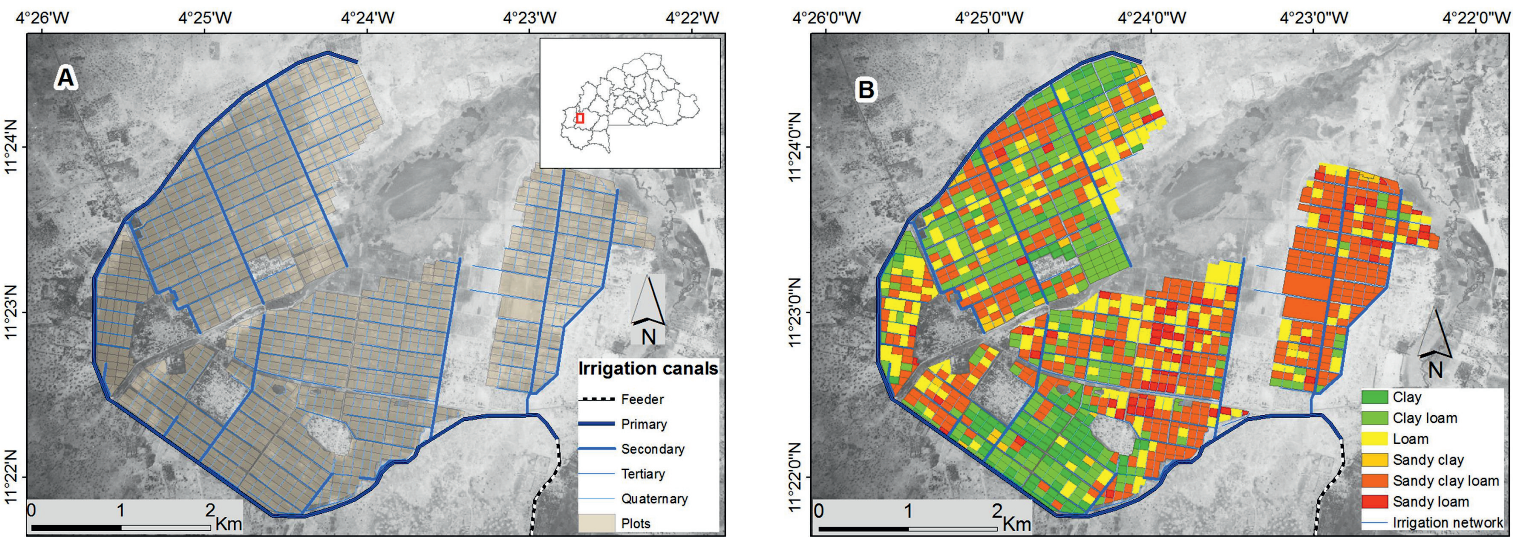

Fig. 1. Distribution of irrigation canals (A) and soil types (B) at the Kou Valley irrigation scheme, Burkina Faso

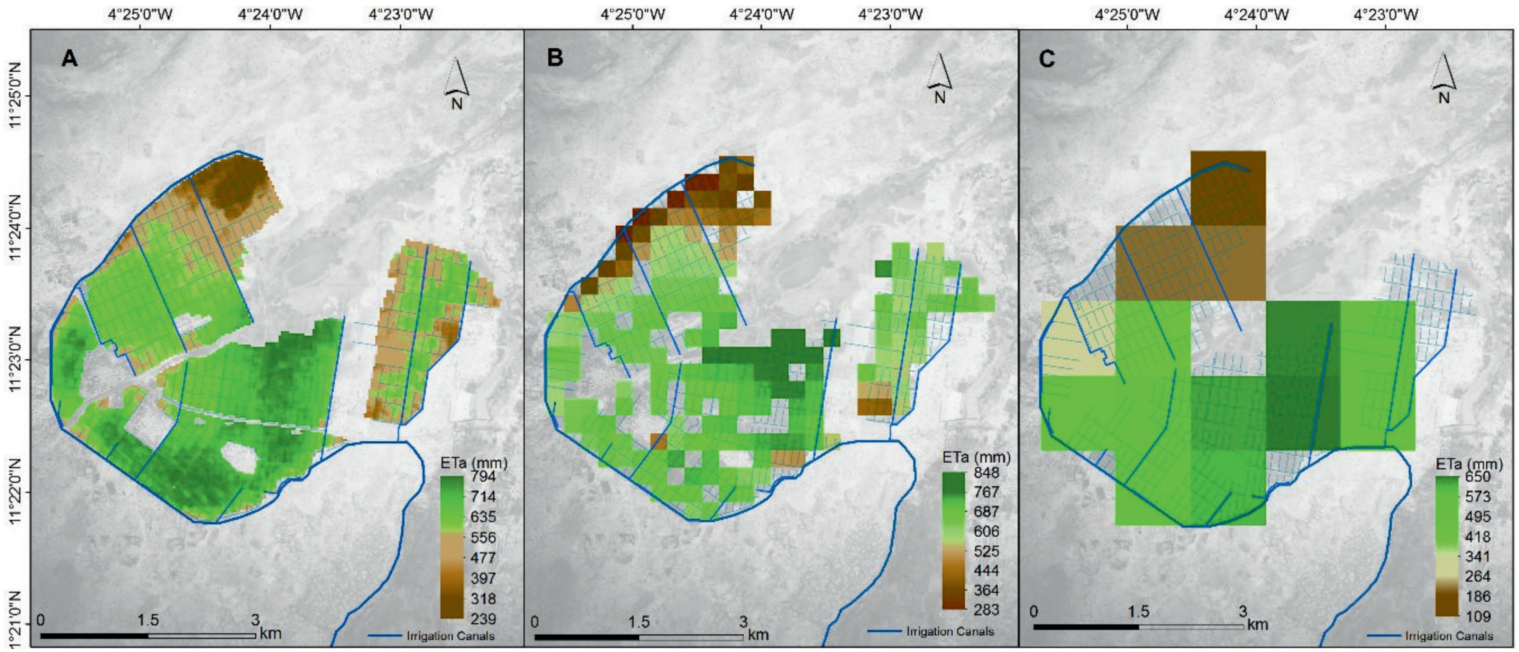

Fig. 2. Spatial distribution of seasonal ET_a in the Kou valley irrigation scheme during January-April 2014. ET_a estimated using three satellite-based approaches: (A) PySEBAL (30 m spatial resolution), (B) FAO-WaPOR (250 m spatial resolution), and (C) USGS-FEWS NET's SSEBop (1 km spatial resolution)

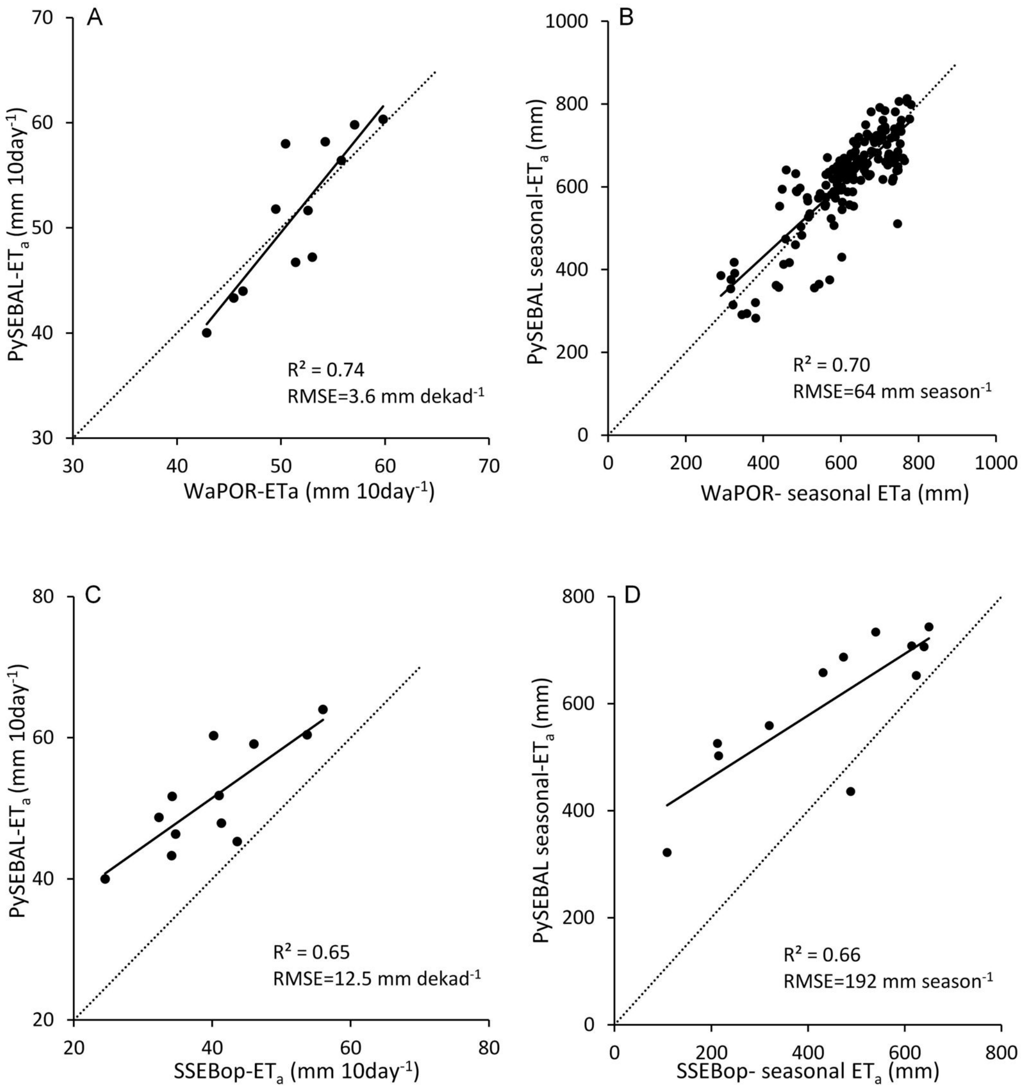

Fig. 3. Scatterplots of ET_a values obtained using three satellite-based approaches, PySEBAL, FAO-WaPOR and USGS-FEWS NET's SSEBop: comparisons between values at dekadal (A, C) and seasonal (B, D) scales. Dashed lines on the sub-figures represent the 1:1 lines

method of estimation: 239 to 794 mm (average value = 619 mm), 283 to 848 mm (average value = 618 mm), and 109 to 650 mm (average value = 482 mm) for PySEBAL-derived, FAO-WaPOR and USGS-FEWS NET's SSEBop, respectively (Fig. 2). The variability of ET_a in the KVIS can be related to the soil type and the different crops grown during the study period. Water scarcity and poor water management practices, including reduced maintenance works and increase in upstream water use are potential reasons [12,13]. Although satellite remote sensing cannot provide the underlying reasons for explaining such spatial variations, it can, however, be used to identify areas with good and poor water management practices [18]. The finer spatial resolution from the PySEBAL-derived approach would allow better and targeted monitoring of crop water components across the KVIS compared to data derived from the two other approaches.

Comparisons of ET_a values between the three satellite-based methods. Overall, good agreements between dekadal and seasonal ET_a from PySEBAL and FAO-WaPOR were found: RMSE of 3.6 mm and 64 mm for the dekadal and seasonal estimations, respectively (Fig. 3A, B). The average ET_a were similar, 619 mm for PySEBAL and 618 mm for FAO-WaPOR. Not surprisingly, the agreement between ET_a values from PySEBAL and USGS-FEWS NET's SSEBop were relatively weak, compared to those of FAO-WaPOR, because of the coarser spatial resolution in the USGS-FEWS NET's SSEBop-based approach [17,19]. RMSE were 12.5 mm and 192 mm for the dekadal and seasonal estimations, respectively (Fig. 3C, D). The average ET_a were 619 mm and 482 mm for the PySEBAL and SSEBop models, respectively. Good correlation between the flux tower and FAO-WaPOR ET_a with R^2 of 0.70 was reported in Senegal [16]. In the Nile basin [20] reported ET_a values 668 and 633 mm year^{-1} for FAO-WaPOR and USGS-FEWS NET's SSEBop, respectively. The results found in this study indicate good skill of the PySEBAL model for estimating ET_a in the KVIS.

Conclusion. We evaluated the performance of the PySEBAL model for estimating ET_a in the KVIS in Burkina Faso. Compared to the two independent remote sensing satellite-based approaches, at different temporal and spatial scales, ET_a was satisfactorily estimated throughout the crop growth season using PySEBAL. This analysis is part of a series of studies dealing with the improvement of irrigation water management in the KVIS. Our results highlight the effectiveness of the PySEBAL model for estimating ET_a and could be used for identifying in a cost-effective manner poorly-performing areas across the KVIS and could serve as a basis for developing targeted strategies for improved irrigation water use.

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