Scientific Research Publishing

Spatio-Temporal Determination of Irrigated Paddy Rice Pixels Using Evapotranspiration and Vegetation Indices: A Case Study for Ca River Basin in Vietnam

Chung N. Luong[1], Lan T. Ha[1*], Thanh C. Pham[2], Hung X. Dinh[3], Thanh T. Hoang[3], Hoan N. Nguyen[2], Tuan V. Nguyen[1], Phung X. Nguyen[4]

[1]Institute of Water Resources Planning, Hoan Kiem, Hanoi, Vietnam
[2]Division of Water Resources Planning in Northern Central Region, Institute of Water Resources Planning, Hoan Kiem, Hanoi, Vietnam
[3]Department of Training and International Cooperation, Institute of Water Resources Planning, Hoan Kiem, Hanoi, Vietnam
[4]Division of Hydro-Meteorology, Institute of Water Resources Planning, Hoan Kiem, Hanoi, Vietnam
Email: *htqt@iwrp.gov.vn

Abstract

Improving irrigation monitoring and efficiency is a current priority of the Government of Vietnam, focusing primarily on the agricultural sector which consumes most of the available surface and groundwater. This paper presents how remote sensing can be used in an integrated manner to achieve better understanding of key eco-hydrological processes including precipitation, evapotranspiration, irrigation and crop growth. The results indicated that Normalized Difference Vegetation Index derived from Moderate Resolution Imaging Spectroradiometer (MODIS) can be applied to determine irrigated pixels on a spatial and temporal basis. The validation using measured water level showed a Pearson correlation of 0.7 proving the high accuracy of this method. The inclusion of these technologies is deemed necessary to improve water resources monitoring and management and hence, ensure long-term drought resilience and water and food security. Ca River Basin in the central Vietnam was selected as a case study to test this approach.

Keywords

Remote Sensing, Drought Management, Irrigated Paddy

1. Introduction

River basins play a key role in water management, as it defines the area where all

waters related processes are interlinked (Rebelo et al., 2014). Basin-wide sustainable management approaches are required to maintain the key functions of a watershed, including agriculture, biodiversity, energy, health and leisure (Falkenmark & Rockström, 2006). As such, it is imperative to have insight in water management strategies, consumption and demand patterns for all users and functions within a river basin (Hoekstra, 2014; Karimi et al., 2013; Shilpakar et al., 2012). Conventional methods to calculate basin wide water balances often use interpolated weather data including land-use to estimate the total amount of rainfall and evaporation. Since most basins in Vietnam are poorly gauged and data is often difficult to obtain, this is not a viable option (Bastiaanssen & Steduto, 2015).

Several papers indicated that remote sensing technology is suitable for monitoring of hydrology (Neale & Cosh, 2010; Pietroniro & Leconte, 2000; Bastiaanssen & Harshadeep, 2007; Karimi et al., 2013) and water resources (Melesse et al., 2016; Dembele & Zwart, 2016). Remotely sensed precipitation (Serrat-Capdevila et al., 2014), evaporation, water storage has been used worldwide for water management purposes (van Eekelen et al., 2015; Jia et al., 2009; Mirales et al., 2013). Evaporation derived from energy balance approach was used to monitor water consumption and use from local field level to global scale (Templeton et al., 2014; Anderson et al., 2011). Vegetation indices calculated from spectral reflectance provided information on crop growth, water deficit and drought (Hu et al., 2020; Nanzad et al., 2019). These data are especially valuable for policy makers in data scarce areas, as they can be linked to land-use, hydrology and all other water related issues within a river basin. This information is vital to achieve sustainable land management practices.

In addition to climatic and flow data, mapping of irrigated area also required information on crop growth. Traditional assessment involves locally collected data at field level and from census sources. The fieldwork became extensive and often impossible for large or transboundary basin (Sruthi & Aslam, 2015). Determination of vegetation growth from satellite imagery for basin-wide cultivation is a modern and appropriate method of mapping and assessing irrigation. The Moderate Resolution Imaging Spectroradiometer (MODIS) presents a considerably accurate and operational dataset to classify irrigated area at reasonable resolution (Wardlow & Egbert, 2010; Shahriar Pervez et al., 2014). Usman et al. (2015) applied MODIS NDVI to detect temporal changes for irrigated cropland in Pakistan. Biggs et al. (2006) utilized MODIS to map land cover and irrigated pixels for small scale farming in India using MODIS and Landsat time series. Ambika et al. (2016) published irrigated maps for India from 2000-2015 using similar approaches.

In Vietnam, the quality and quantity of the available water resources is already affected by over exploitation and unsustainable land management practices. In the highlands, water induced soil erosion is considered as a threat as it reduces crop yield and pollutes water resources. Heavy rain showers cause floods in the lowlands during the tropical monsoon season, whereas the lowlands are plagued by drought in the dry season (Poortinga et al., 2019). Low river levels in the dry season also cause saline water to enter the river mouth, causing contamination

of the ground and surface water. Mismanagement of the natural resources has declined the forest carbon stock, degraded the forest and led to dangerous levels of toxins in the groundwater.

In this paper, we apply the remote sensing approach for mapping irrigated paddy rice in the Ca river basin in Central Vietnam. The Ca river basin is a poorly gauged basin which experiences all of the above mentioned problems of floods, droughts, salinity, water quality deterioration and overlapping mandates.

2. Materials and Methods

2.1. Study Area

Ca River Basin is a basin cover Laos and Vietnam. The total area is approximately 27,000 km³ with an estimated population of 5 million inhabitants (Figure 1). About two third of the basin area and the most downstream is located in Vietnam. The high mountains in Laos reach up to 2200 - 2600 m amsl. with spare population while the lowland located mostly in Vietnam with highly dense population. Paddy rice is the dominant crops in the delta and cultivated in two seasons: Winter-Spring from January to May and Summer-Autumn from June-November. The Winter-Spring crop is also the driest period in the basin.
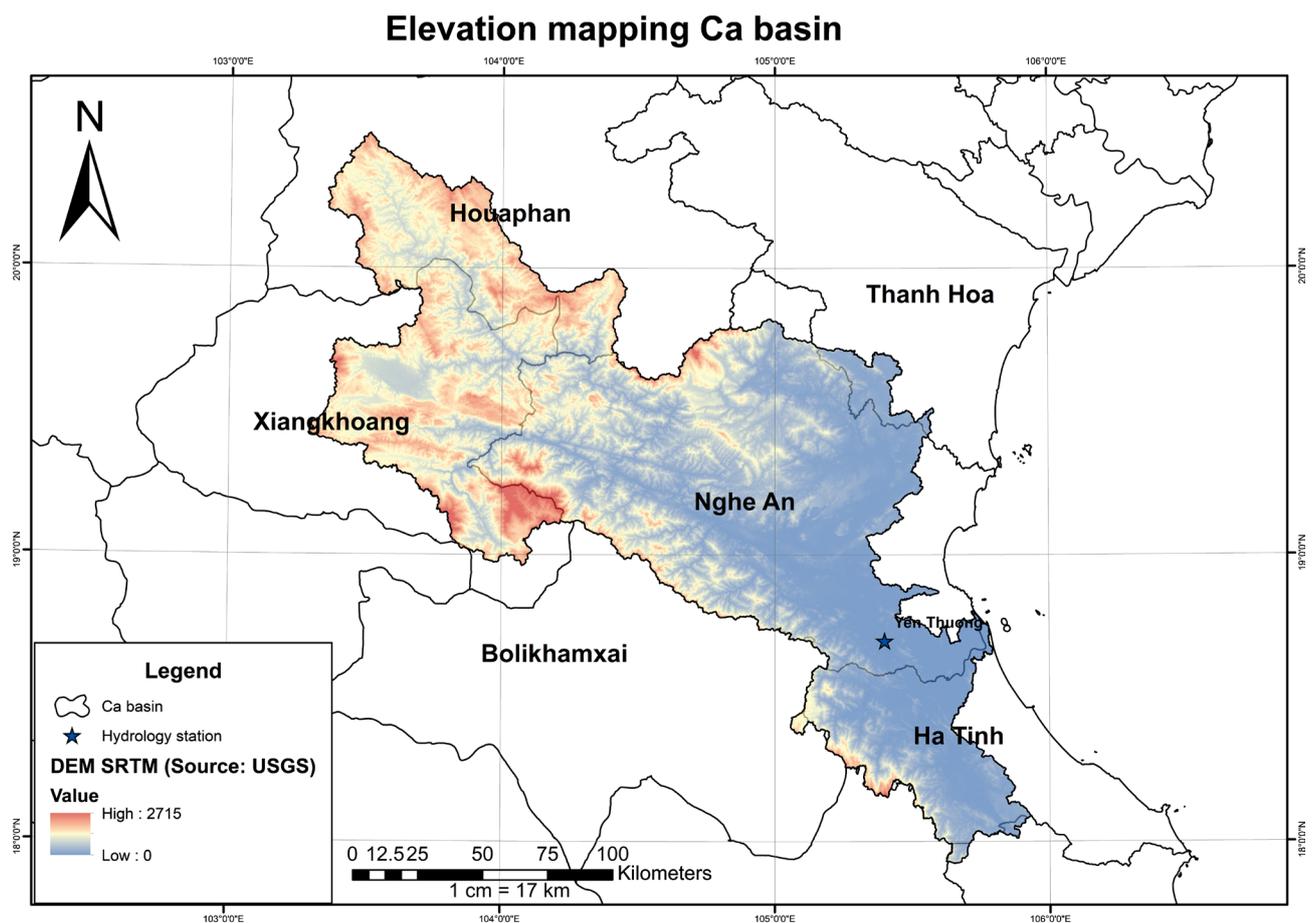
Figure 1. Ca river basin and digital elevation map.

The increasing need for electricity by the growing population and water resources in the dry season has led to the development of a series of mainstream and tributary dams. The total effective storage capacity of the medium and larger size dams is 2.2 km³/yr. An additional volume of 126 mm³/yr is under construction in Ban Mong. With the annual rainfall being 53.8 km³/yr, only 4% of the rainfall can be stored (or 8% of the exploitable water resources). This is low for a mountainous catchment, and the potential for small dams for rainwater collection and sustainable hydropower production is great.

There are three large irrigation systems in place, which supply water to the agricultural areas but also supply water for industrial and domestic purposes. The system consists of 3486 water supply infrastructures in Ca River Basin, including 1602 reservoirs, 600 weirs, 1266 pumping stations, 18 sluices supplying water for 170,030 ha (135,000 ha paddy rice; 35,030 ha vegetables and subsistence crops) in Nghe An and Ha Tinh province.

Hydropower dams and reservoirs: There are 14 hydropower stations constructed in the basin. The installed capacity is 695 MW and annual generated electricity of 2686.106 kwh. In the mainstream of Ca River Basin there are 3 major hydropower dams: Ban Ve, Khe Bo and Chi Khe. Ngan Truoi Reservoir operated since 2019 with a total capacity of 775 mil m³ and irrigated an area of 32,585 ha. Ban Mong reservoir has a total capacity of 224.78 mil m³ irrigating 18,871 ha with average discharge of 22 m³/s and installed capacity for hydropower generation of 42 MW.

Downstream area has a condensed system of sluice, pumping stations and weirs, e.g. Do Luong Barrage, Nam Dan sluice.

The water resources supplied to the downstream delta is mostly controlled by two regulation sluices, i.e. Nam Dan 1 and 2. In the recent years, the observed water level at these sluices is decreasing. In 2015, water level at Nam Dan 1 and 2 reached only −0.22 m compared to the design water level of +1.15 m amsl. It led to a severe water shortage in the downstream delta for both irrigation and domestic water supply. Hence, drought occurred in a large areas and severe salinity intrusion happened further to the downstream.

The drought statistics in recent year at the downstream of Ca River basin from 2014-2017 peaked was 16,010 ha (2014), 18,027 (2015), 18,262 ha (2016) and 17,040 (2017).

2.2. Elevation and Landuse

A Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) map was retrieved from USGS. The resolution of 1 arc-second or 30 m (Figure 1) is deemed sufficient to determine irrigated pixels.

The landuse data was collected from SERVIR Mekong Regional Land Cover Monitoring System. This landuse for Ca river basin was studied including Poortinga et al. (2019). The landuse map was constructed for the period from 1988 until 2019 using Landsat time series, machine learning algorithm and ground-truth

data from the member countries. The procedural steps were described in Saah et al. (2019).

Figure 2 shows that the lowlands along the coast are mostly used for human settlements and irrigated rice cultivation, but also forest plantations, fruits, and annual or perennial crops. Paddy rice can be grown up to three seasons a year in summer, autumn and winter. Rice cultivation in Summer-Autumn (May - September) is most common, but roughly 70% of the farmers grow also rice in Winter-Spring (January - May), about 30% grows rice year round. Farmers with three rotations are more common in Nghe An (45%) as compared to Ha Tinh (13%). Uplands are dominated by secondary, broadleaved medium forest and rich forest. Most parts of the uplands actually consist of a mosaic of forests and farmlands, where primary forests have been degraded to support goods and services for the local livelihoods. Dry or upland rice cultivation can be found throughout the highlands, whereas the plains are used for more intensive forms rice cultivation. Slash and burn techniques are applied in the uplands for rice or annual crop cultivation, dependent on the market demand. Logging can be found along the main roads, supplying wood for the national and international market. Broadleaved rich forests are associated with national protected areas.
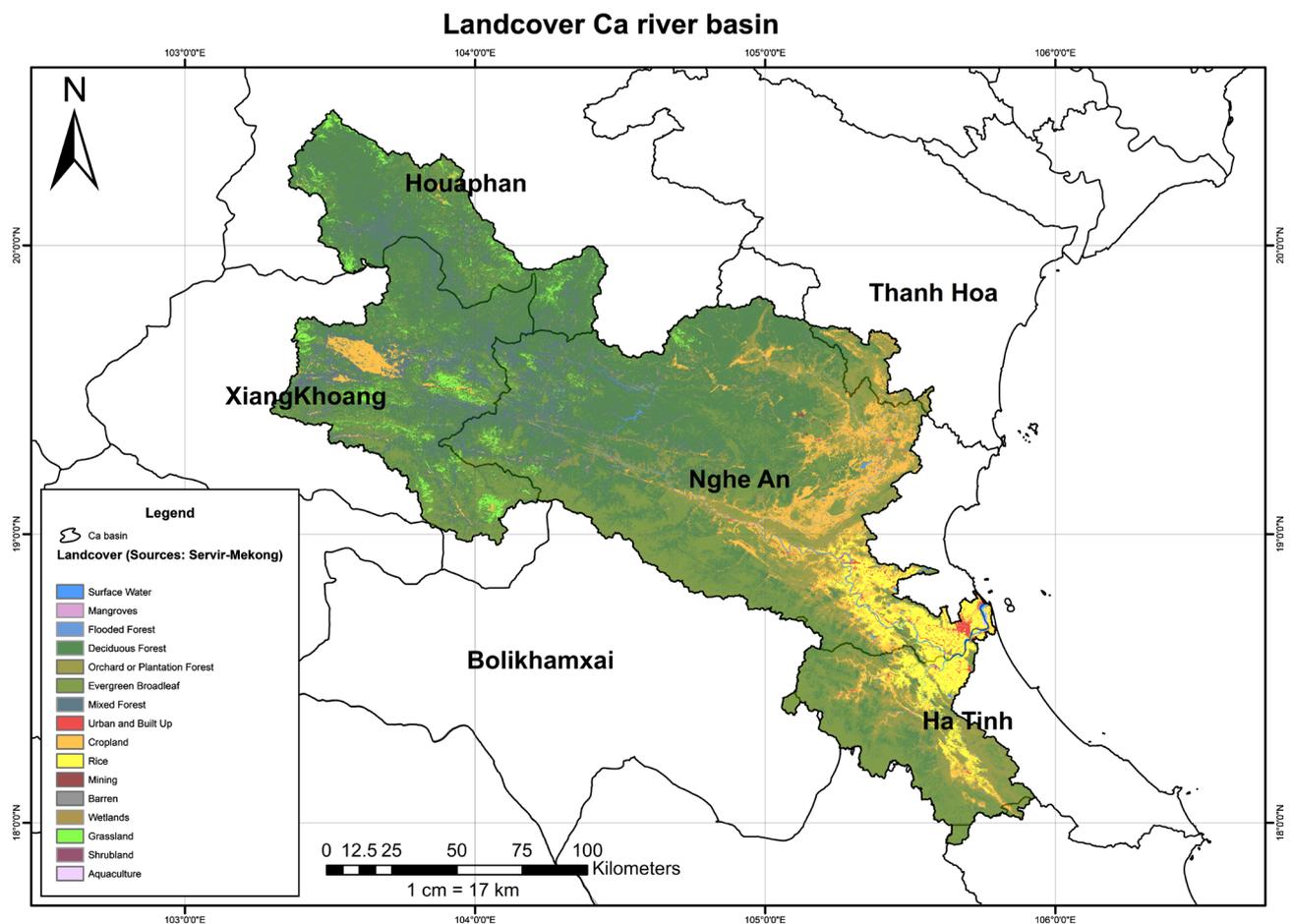
Figure 2. Landuse map of Ca river basin.

2.3. Meteorological and Hydrological Data

Precipitation (P) is the sole input of water into the river basin. To achieve optimal results in terms of water input estimations, Ha et al. (2018) reviewed various satellite-based precipitation products, i.e. Tropical Rainfall Measurement Mission (TRMM), Climate Hazards Group InfraRed Precipitation Station (CHIRPS), Climate Prediction Center Morphing Technique (CMORPH) and Climate Research Unit (CRU) for climatic conditions in Vietnamese river basins and concluded that CHIRPS performance yielded good correlation with station measurements. CHIRPS came with a better resolution of 0.05˚ × 0.05˚ as compared with other products. In this study we used the precipitation data from CHIRPS (Funk et al., 2014).

Rainfall provides 53.8 km^3/yr (or 1985 mm/yr). The spatial distribution of rainfall is shown in Figure 3. Many areas in the downstream part receive more (2300 mm/yr) than the upstream end in Lao PDR (1250 mm/yr). Flood risk is thus not only caused by runoff from the upstream mountains, but to a large extent influenced by local rainfall.

For evapotranspiration, various efforts are underway to develop estimates of global evapotranspiration using surface energy balance models being fed by remote sensing input data. Most common global scale ET datasets are MOD16 (Mu et al., 2007), Surface Energy Balance System (SEBS) (Su, 2002), Operational Simplified Surface Energy Balance SSEBop (SSEBop) (Senay et al., 2013). Ha et al. (2018) compared the accuracy of several ET products, i.e. CMRSET (Guerschman et al., 2009), MOD16, SEBS, SSEBop and an ensemble of these 4 products and concluded that SSEBop and Ensemble ET has the best performance. Poortinga et al. (2017) evaluated the performance of global ET products against Budyko curve and concluded that evapotranspiration estimated using SSEBop algorithm showed a good agreement with theory. In this study, evapotranspiration from SSEBop (Figure 4) was used to assess water yield and potential
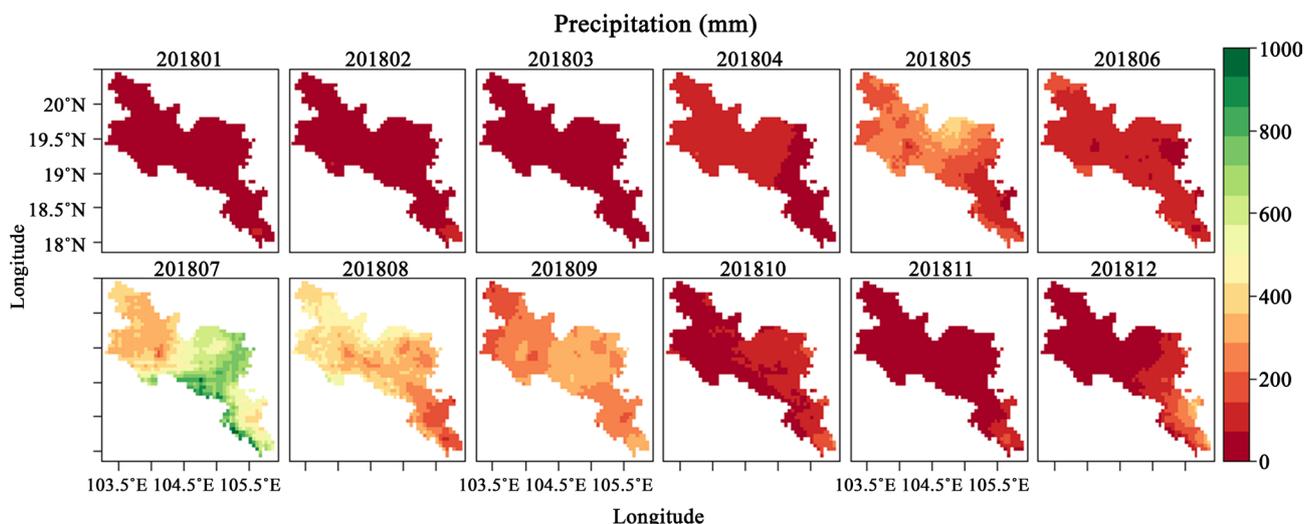
Figure 3. Monthly precipitation data from CHIRPS for 2018.

in irrigation mapping.

The difference between precipitation and evapotranspiration (water yield) was calculated as precipitation minus evapotranspiration. Figure 5 presents the water yield calculated for 2018. As presented P-ET peaks at approximately 300 - 500 mm during July and August when precipitation surplus evapotranspiration. This P-ET can be negative during dry season (between November to June).

The flow measurement for 11 years at Yen Thuong station (Figure 1) was collected to validate the accuracy of irrigated area mapping. The location of Yen Thuong station determines the amount of water flowing into the large irrigation schemes downstream.
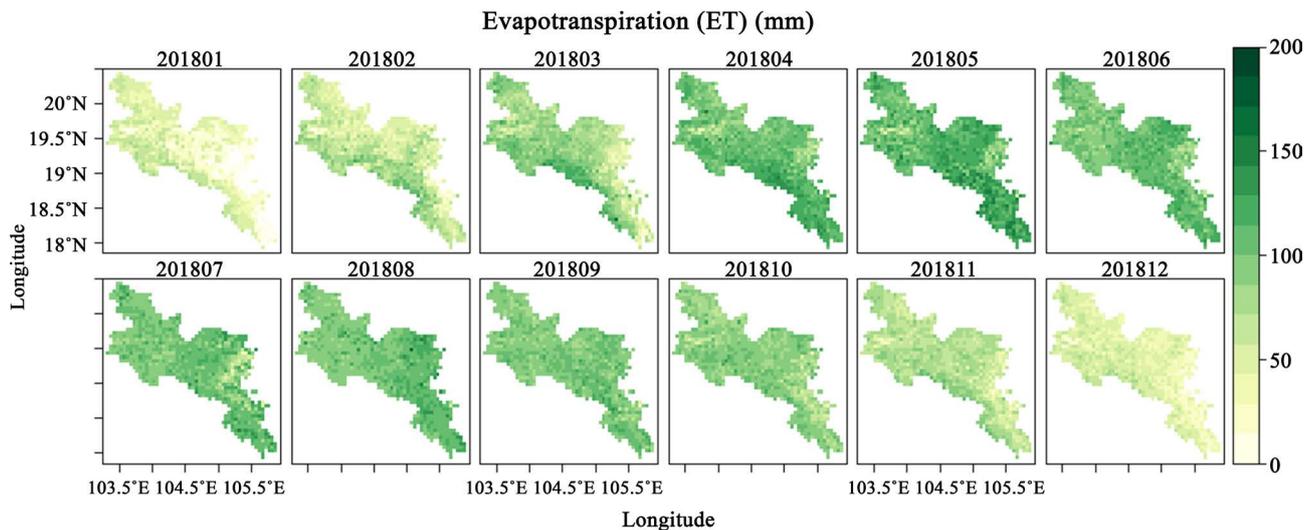
Figure 4. Evapotranspiration data from SSEBop for 2018.
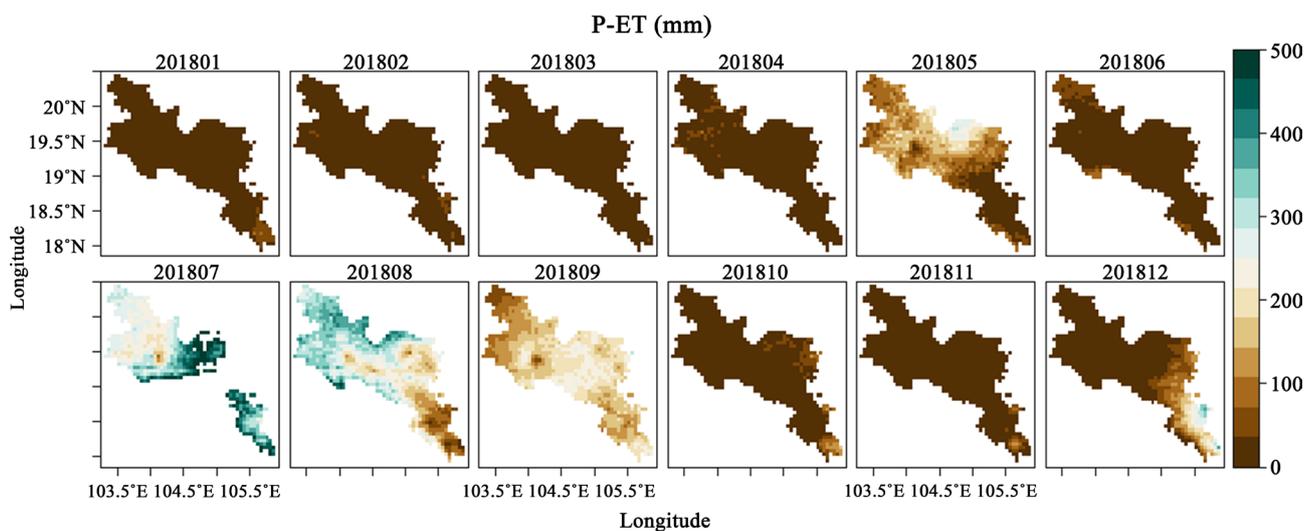
Figure 5. Precipitation minus evapotranspiration taken from CHIRPS và SSEBop for the year 2018.

2.4. Vegetation Index

The Normalized Difference Vegetation Index (NDVI) can be used to monitor

the growth of vegetation cover. NDVI value reflects the concentration of green biome in vegetation leaf and hence, indicates vegetation health and dynamics.

It can give indication on the impact of water shortage and water scarcity to vegetation cover, including crop. NDVI is calculated using the following formula:

$$NDVI = \frac{(\varphi_{NIR} - \varphi_{red})}{(\varphi_{NIR} \mp \varphi_{red})}$$

In which: φ_{NIR} is reflectance from near thermal infrared; φ_{red} is reflectance from red band.

Regional and global spatially determination of irrigated lands conducted earlier using MODIS dataset (Reed et al., 1994). In this study, NDVI dataset was downloaded from MODIS Global MOD13C2. MOD13C2 is cloud-free spatial composites of the gridded monthly 1-km geographic (lat/lon) Climate Modeling Grid (CMG). Cloud-free global coverage is achieved by replacing clouds with the historical MODIS time series climatology record.

NDVI at resolution of 1 km is sufficient to map paddy rice for the 27,000 km^2 basin. Popular rice plants cultivated in Nghe An and Thanh Hoa need approximately 3 - 5 months to complete its grow cycle from seeds to matured rice. Hence, a monthly time step of NDVI maps can capture this growth. There are two rice seasons per year in the basin, namely Winter-Spring and Summer-Autumn. The total annual artificial water withdrawals are 4.6 km^3/yr (2.0 and 2.6 in dry and wet season respectively). The largest portion of the withdrawals is from three large scale irrigation schemes. These irrigation schemes have an intake capacity of about 35 m^3/s and supply water for irrigation, industry and domestic use. Most of the water is allocated to for irrigation (2.7 km^3).

Figure 6 illustrated the NDVI dynamics from January to December in 2018. The irrigated mapping was conducted for the period from 2008-2018. NDVI time series can be used to capture discrepancy during growing period and hence, helps separate irrigated and non-irrigated pixels. The information on NDVI was
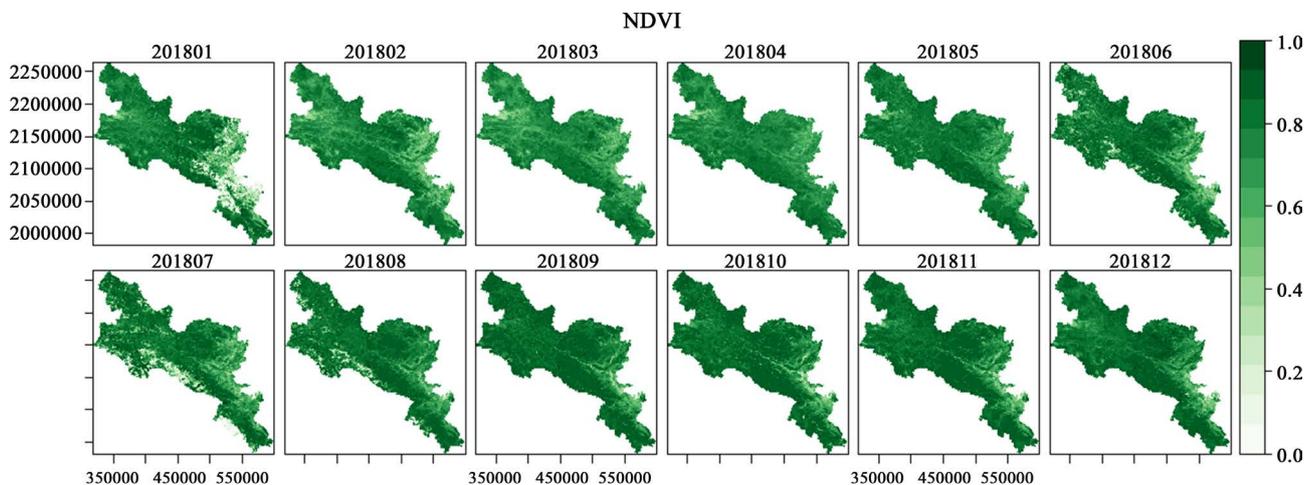
Figure 6. NDVI in Ca River basin calculated for 2018.

used in combination with data on slope derived from SRTM DEM map. Since paddy rice in Ca River Basin was cultivated in rather flat land (<5% slope), this filter was applied to classify irrigated and non-irrigated pixels.

3. Results and Discussions

A comparison of monthly NDVI time series for different landuse classes and precipitation are shown in Figure 7. For each landuse class, a monthly average time series was plotted against precipitation. Since higher photosynthesis level yielded higher biome and thus, NDVI values, it can be seen that forest classes shown higher NDVI values throughout the year.

The NDVI time series show two distinguished peaks in April-May and August-September respectively. These two peaks are in coincident with the crop calendars when paddy rice matures during these two months before being harvested in June and September (depending on the lunar calendar). In contrast, NDVI for other forest and fruit tree classes show a consistent development from January (middle of dry season) until September when precipitation reaches its peak during monsoonal season. By distinguishing this feature, irrigated paddy rice can be identified from other land use classes or from rain-fed paddies.

More precisely, Figure 8 shows NDVI for paddy rice for an 11-year period from 2008 until 2018. The peaks of NDVI during Winter-Spring crop (February-June) are mostly in April while in several years it was in May, e.g. in 2010 when there is a drought event. Paddy rice is normally harvested in June. The next season Summer-Autumn normally starts during June-July.

The monthly NDVI for different landuse classes so that NDVI for paddy rice peaks twice a year during March-April and August-September. It agrees with a fact that in Ca River basin, most of the downstream paddy rice farm grow two seasons a year. The highest NDVI for paddy rice is 0.65 - 0.7 when the rice reaches its highest biome. The harvesting period for Winter-Spring crop season is during end
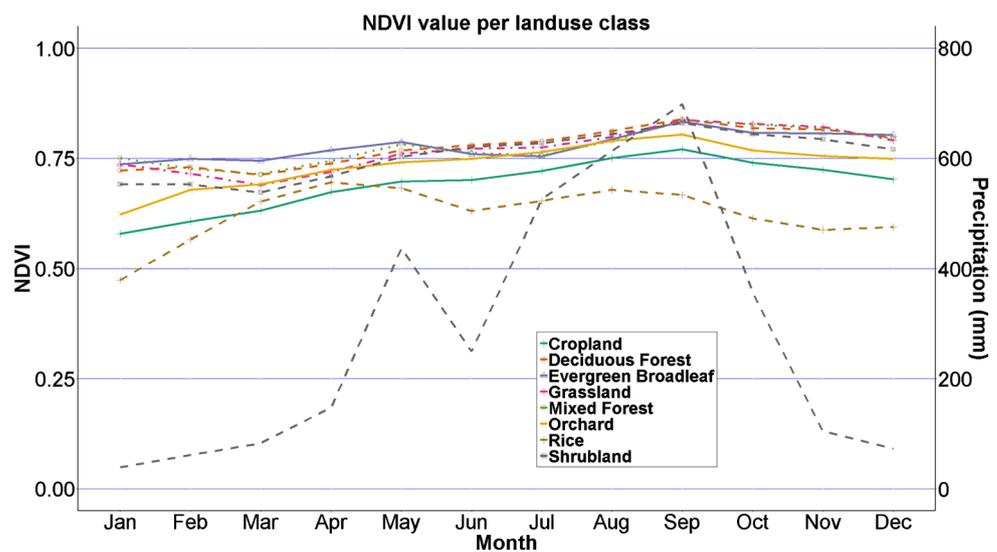
Figure 7. Monthly NDVI for landuse classes in Ca river basin.

of May to beginning of June and for Summer-Autumn is during September.

These values also match with previous studies, for example FAO recommended NDVI between 0.6 and 0.7. Other landuse classes such as cropland (e.g. maize), forest, grassland or orchard only have one peak per year during September, agreeable with the rainy season.

Figure 9 shows that irrigated area and water level in Yen Thuong are highly correlated. Basin evapotranspiration also adds to this consistency. For instance, the year 2010 observes both irrigated area and ET in March drops to its lowest in the observation timeline, at 89,660 ha and 59.74 mm/month. Meanwhile, water level at Yen Thuong station reduces to only 98 cm. Similar results were observed in 2015 when total irrigated area dropped to 102,000 ha and water level was at 86 cm. ET in that year reached 77.68 mm/month.
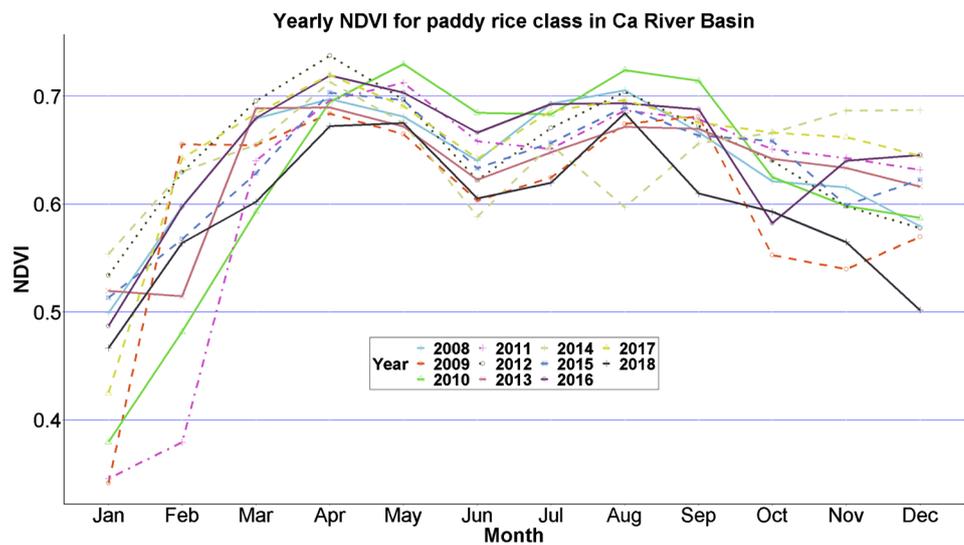
Figure 8. Monthly NDVI for paddy rice class in Ca river basin.
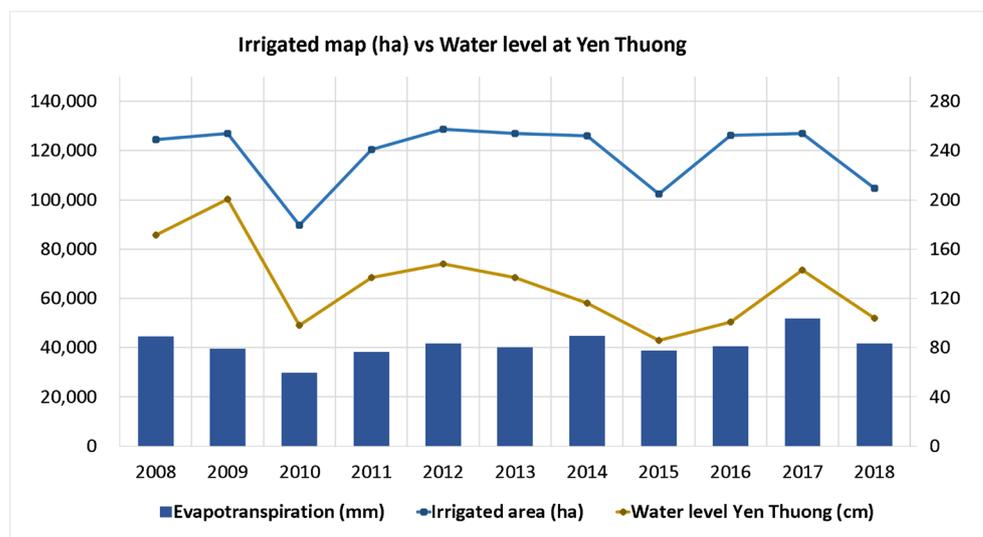
Figure 9. Yearly irrigated area (ha) versus evapotranspiration (mm) and water level at Yen Thuong (cm).

Table 1. Pearson correlation between irrigated area (ha), evapotranspiration (mm) and water level (cm) for the period from 2008-2018.

Table Head	Pearson correalation		
	Irrigated area (ha)	ET (mm)	Water level (cm)
Irrigated area (ha)	1.0	0.3	0.6
ET (mm)	0.3	1.0	0.7
Water level (cm)	0.6	0.7	1.0

While in 2017, a wet year, both irrigated area and ET in March peak at 126,944 ha and 103.6 mm/month. Water level at Yen Thuong in March maintained at 142.8 cm showing its capability to secure enough water for irrigation.

Table 1 described the correlation calculated using Pearson formula for three datasets: Irrigated area (ha), evapotranspiration—ET (mm) and water level at Yen Thuong (cm). The result indicated that irrigated area and water level has high correlation at 0.6 while irrigated area and ET only yielded at 0.3. On the other hand, ET and water level has a correlation result of 0.7, reflecting that high water level in the river basin resulted in higher plant water intake and hence, higher evapotranspiration. This analysis proved that the methodology applied in this study can improve the accuracy of irrigated area mapping using remote sensing, as compared to field measurement.

4. Conclusion

This study presents a comprehensive overview of water resources and irrigated area mapping in the Ca river basin using remote sensing. It was demonstrated that remote sensing-derived irrigated area using NDVI has a good agreement with theory and field observation.

While this study provides very specific numbers on irrigated paddy rice pixels, they should be considered as a best estimate rather than absolute figures. More elaborate in-situ information on river flows and water extractions can further refine the numbers presented. Furthermore, it should be noted that all analyses strongly rely on the quality of the land use map. Nevertheless, the data offers exciting insights for policy makers to promote more effective water resource management strategies in the Ca river basin. This mapping of irrigated land provides more insights that allow policy makers and planners to identify alternative approaches such as improving water use efficiency, land management, cultivation of more water efficient crops, crop-rotations and inter-cropping etc.

Acknowledgements

number ĐTĐL.CN-38/18.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Ambika, A., Wardlow, B., & Mishra, V. (2016). Remotely Sensed High Resolution Irrigated Area Mapping in India for 2000 to 2015. *Scientific Data, 3,* Article ID: 160118. https://doi.org/10.1038/sdata.2016.118

Anderson, M. C., Kustas, W. P., Norman, J. M., Hain, C. R., Mecikalski, J. R., Schultz, L., González-Dugo, M. P., Cammalleri, C., d'Urso, G., Pimstein, A., & Gao, F. (2011). Mapping Daily Evapotranspiration at Field to Continental Scales Using Geostationary and Polar Orbiting Satellite Imagery. *Hydrology and Earth System Sciences, 15,* 223-239. https://doi.org/10.5194/hess-15-223-2011

Bastiaanssen, W. G. M., & Harshadeep, N. R. (2007). Managing Scarce Water Resources in Asia: The Nature of the Problem and Can Remote Sensing Help? *Irrigation and Drainage Systems, 19,* 269-284. https://doi.org/10.1007/s10795-005-5188-y

Bastiaanssen, W. G. M., & Steduto, P. (2015). The Water Productivity Score (WPS) at Global and Regional Level: Methodology and First Results from Remote Sensing Measurements of Wheat, Rice and Maize. *Agriculture, Ecosystems and Environment* (Submitted).

Biggs, T. W., Thenkabail, P. S., Gumma, M. K., Scott, C. A., Parthasaradhi, G. R., & Turral, H. N. (2006). Irrigated Area Mapping in Heterogeneous Landscapes with MODIS Time Series, Ground Truth and Census Data, Krishna Basin, India. *International Journal of Remote Sensing, 27,* 4245-4266. https://doi.org/10.1080/01431160600851801

Dembele, M., & Zwart, J. Z. (2016). Evaluation and Comparison of Satellite-Based Rainfall Products in Burkina Faso, West Africa. *International Journal of Remote Sensing, 37,* 3995-4014. https://doi.org/10.1080/01431161.2016.1207258

Falkenmark, M., & Rockström, J. (2006). The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management, 132,* 129-132. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129)

Funk, C. C., Peterson, P. J., Landsfeld, M. F., Pedreros, D. H., Verdin, J. P., Rowland, J. D., Romero, B. E., Husak, G. J., Michaelsen, J. C., & Verdin, A. P. (2014). *A Quasi-Global Precipitation Time Series for Drought Monitoring* (4 p.). U.S. Geological Survey Data Series 832. https://doi.org/10.3133/ds832

Guerschman, J. P., Van Dijk, A. I. J. M., Mattersdorf, G., Beringer, J., Hutley, L. B., Leuning, R., Pipunic, R. C., & Sherman, B. S. (2009). Scaling of Potential Evapotranspiration with MODIS Data Reproduces Flux Observations and Catchment Water Balance Observations across Australia. *Journal of Hydrology, 369,* 107-119. https://doi.org/10.1016/j.jhydrol.2009.02.013

Ha, L. T., Bastiaanssen, W. G. M., Van Griensven, A., Van Dijk, A. I. J. M., & Senay, G. B. (2018). Calibration of Spatially Distributed Hydrological Processes and Model Parameters in SWAT Using Remote Sensing Data and an Auto-Calibration Procedure: A Case Study in a Vietnamese River Basin. *Water, 10,* 212. https://doi.org/10.3390/w10020212

Hoekstra, A. Y. (2014). *The Water Footprint of Modern Consumer Society* (204 p.). London: Earthscan Publications Ltd.

Hu, T., van Dijkb, A. I. J. M., Renzullo, L. J., Xu, Z. H., He, J., Tian, S. Y., Zhou, J., & Li, H. (2020). On Agricultural Drought Monitoring in Australia Using Himawari-8 Geostationary Thermal Infrared Observations. *International Journal of Applied Earth Observation and Geoinformation, 91,* Article ID: 102153. https://doi.org/10.1016/j.jag.2020.102153

Jia, L., Xi, G., Liu, S., Huang, C., Yan, Y., & Liu, G. (2009). Regional Estimation of Daily to Annual Regional Evapotranspiration with MODIS Data in the Yellow River Delta Wetland. *Hydrology and Earth System Sciences, 13,* 1775-1787. https://doi.org/10.5194/hess-13-1775-2009

Karimi, P., Bastiaanssen, W. G. M., & Molden, D. (2013). Water Accounting plus (WA+): A Water Accounting Procedure for Complex River Basins Based on Satellite Measurements. *Hydrology and Earth System Sciences, 17,* 2459-2472. https://doi.org/10.5194/hess-17-2459-2013

Melesse, A. M., Weng, Q., Thenkabail, P. S., & Senay, G. B. (2016). Remote Sensing Sensors and Applications in Environmental Resources Mapping and Modelling. *Sensors, 7,* 3209-3241. https://doi.org/10.3390/s7123209

Mirales, D. G., Holmes, T. R. H., De Jeu, R. A. M., Gash, J. H., Meesters, A. G. C. A., & Dolman, A. J. (2013). Global Land Surface Evaporation Estimated from Satellite-Based Observations. *Hydrology and Earth System Sciences, 15,* 453-469. https://doi.org/10.5194/hess-15-453-2011

Mu, Q., Heinsch, F. A., Zhao, M., & Running, S. W. (2007). Development of a Global Evapotranspiration Algorithm Based on MODIS and Global Meteorology Data. *Remote Sensing of Environment, 111,* 519-536. https://doi.org/10.1016/j.rse.2007.04.015

Nanzad, L., Zhang, J. H., Tuvdendorj, B., Nabil, M., Zhang, S., & Bai, Y. (2019). NDVI Anomaly for Drought Monitoring and Its Correlation with Climate Factors over Mongolia from 2000 to 2016. *Journal of Arid Environments, 164,* 69-77. https://doi.org/10.1016/j.jaridenv.2019.01.019

Neale, C. M. U., & Cosh, M. H. (2010). *Remote Sensing and Hydrology* (p. 482). IAHS Red Book Series Publ. 352, Wallingford: IAHS.

Pietroniro, A., & Leconte, R. (2000). A Review of Canadian Remote Sensing Applications in Hydrology, 1995-1999. *Hydrological Processes, 14,* 1641-1666. https://doi.org/10.1002/1099-1085(20000630)14:9<1641::AID-HYP75>3.0.CO;2-I

Poortinga, A., Bastiaanssen, W., Simons, G., Saah, D., Senay, G., Fenn, M., Bean, B., & Kadyszewski, J. (2017). A Self-Calibrating Runoff and Streamflow Remote Sensing Model for Ungauged Basins Using Open-Access Earth Observation Data. *Remote Sensing, 9,* 86. https://doi.org/10.3390/rs9010086

Poortinga, A., Nguyen, Q., Tenneson, K., Troy, A., Saah, D., Bhandari, B., Ellenburg, W. L., Aekakkararungroj, A., Ha, L., Pham, H., Nguyen, G., & Chishtie, F. (2019). Linking Earth Observations for Assessing the Food Security Situation in Vietnam: A Landscape Approach. *Frontiers in Environmental Science, 7,* 186. https://doi.org/10.3389/fenvs.2019.00186

Rebelo, L.-M., Johnston, R., Karimi, P., & McCornick, P. G. (2014). Determining the Dynamics of Agricultural Water Use: Cases from Asia and Africa. *Journal of Contemporary Water Research & Education, 153,* 79-90. https://doi.org/10.1111/j.1936-704X.2014.03182.x

Reed, B. C., Brown, J. F., VanderZee, D., Loveland, T. R., Merchant, J. W., & Ohlen, D. O. (1994). Measuring Phenological Variability from Satellite Imagery. *Journal of Vegetation Science, 5,* 703-714. https://doi.org/10.2307/3235884

Saah, D., Tenneson, K., Matin, M., Uddin, K., Cutter, P., Poortinga, A. et al. (2019). Land Cover Mapping in Data Scarce Environments: Challenges and Opportunities. *Frontiers in Environmental Science, 7,* 150. https://doi.org/10.3389/fenvs.2019.00150

Senay, G. B., Bohms, S., Singh, R. K., Gowda, P. H., Velpuri, N. M., Alemu, H., & Verdin, J. P. (2013). Operational Evapotranspiration Mapping Using Remote Sensing and Weather Data Sets: A New Parameterization for the SSEBOP Approach. *Journal of the American Water Resources Association, 49,* 577-591. https://doi.org/10.1111/jawr.12057

Serrat-Capdevila, A., Valdes, J. B., & Stakhiv, E. Z. (2014). Water Management Applications for Satellite Precipitation Products: Synthesis and Recommendations. *The Journal of the American Water Resources Association, 50,* 509-525. https://doi.org/10.1111/jawr.12140

Shahriar Pervez, M., Budde, M., & Rowland, J. (2014). Mapping Irrigated Areas in Afghanistan over the Past Decade Using MODIS NDVI. *Remote Sensing of Environment, 149,* 155-165. https://doi.org/10.1016/j.rse.2014.04.008

Shilpakar, R. L., Bastiaanssen, W. G. M., & Molden, D. J. (2012). A Remote Sensing-Based Approach for Water Accounting in the East Rapti River Basin, Nepal. *Himalayan Journal of Sciences, 7,* 15-30. https://doi.org/10.3126/hjs.v7i9.5785

Sruthi, S., & Aslam, M. A. (2015). Agricultural Drought Analysis Using the NDVI and Land Surface Temperature Data; a Case Study of Raichur District. *Aquatic Procedia, 4,* 1258-1264. https://doi.org/10.1016/j.aqpro.2015.02.164

Su, B. (2002). The Surface Energy Balance System (SEBS) for Estimation of Turbulent Heat Fluxes. *Hydrology and Earth System Sciences, 6,* 85-100. http://www.hydrol-earth-syst-sci.net/6/85/2002 https://doi.org/10.5194/hess-6-85-2002

Templeton, R. C., Vivoni, E. R., Méndez-Barroso, L. A., Pierini, N. A., Anderson, C. A., Rango, A., Laliberte, A. S., & Scott, R. L. (2014). High-Resolution Characterization of a Semiarid Watershed: Implications on Evapotranspiration Estimates. *Journal of Hydrology, 509,* 306-319. https://doi.org/10.1016/j.jhydrol.2013.11.047

Usman, M., Liedl, R., Shahid, M. A. et al. (2015). Land Use/Land Cover Classification and Its Change Detection Using Multi-Temporal MODIS NDVI Data. *Journal of Geographical Sciences, 25,* 1479-1506. https://doi.org/10.1007/s11442-015-1247-y

van Eekelen, M., Bastiaanssen, W. G. M., Jarmain, C., Jackson, B., Fereira, F., Bosch, J., Dye, P., Van der Zaag, P., Saraiva, A., Bastidas-Obando, E., Dost, R., & Luxemburg, W. (2015). A Novel Approach for Estimating Direct and Indirect Water Withdrawals Using Satellite Measurements: A Case Study from the Incomati Basin. *Agriculture, Ecosystems and Environment, 200,* 126-142. https://doi.org/10.1016/j.agee.2014.10.023

Wardlow, B. D., & Egbert, S. L. (2010). A Comparison of MODIS 250-m EVI and NDVI Data for Crop Mapping: A Case Study for Southwest Kansas. *International Journal of Remote Sensing, 31,* 805-830. https://doi.org/10.1080/01431160902897858