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DOI
10.1088/1755-1315/57/1/012050

Publication date
2017

Document Version
Final published version

Published in
IOP Conference Series: Earth and Environmental Science

Citation (APA)
Zheng, C., Jia, L., Hu, G., Menenti, M., Lu, J., Zhou, J., Wang, K., & Li, Z. (2017). Assessment of Water Use in Pan-Eurasian and African Continents by ETMonitor with Multi-Source Satellite Data. *IOP Conference Series: Earth and Environmental Science*, *57*(1), Article 012050. https://doi.org/10.1088/1755-1315/57/1/012050

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To cite this article: Chaolei Zheng *et al* 2017 *IOP Conf. Ser.: Earth Environ. Sci.* **57** 012050

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Assessment of Water Use in Pan-Eurasian and African Continents by ETMonitor with Multi-Source Satellite Data

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Abstract. The Pan-Eurasian and African Continents are characterized by large ranges of climates varying from humid, semi-humid, semi-arid and arid regions, and great challenges exist in water allocation for different sectors that related to water resource and food security, which depends strongly on the water use information. Quantitative information on water use is also important to understand the effectiveness of water allocation and further to prevent from water stress resulted by drought in water-scarce regions. Explosive development of satellite remote sensing observations provide great chance to provide useful spatiotemporal information for quantifying the water use at regional to global scales. In this paper, a process-based model ETMonitor was used in combination with biophysical and hydrological parameters retrieved from earth observations to estimate the actual evapotranspiration, i.e. the agricultural and ecological water use. The total water use is also partitioned into beneficial part, e.g. plant transpiration, and non-beneficial part, e.g. soil evaporation and canopy rainfall interception, according to the water accounting framework. The estimated water use show good agreements with the ground observation, indicating the ability of ETMonitor for global and continental scale water use estimation. The spatial and temporal patterns of the water use in the Pan-Eurasian and African Continents were further analysed, while large spatial variation of water use was convinced. Current study also highlights the great capability of satellite observations in studying the regional water resource and continental water cycle.

1. Introduction

Water is an important resource required for the daily sustenance and survival of human beings, and it is crucial to facilitate livelihoods and economic growth. As a result of climate change and population development pressures, water is becoming an increasingly scarce resource worldwide [1]. Coping with water scarcity and growing competition for water among different sectors requires proper water management strategies and decision processes. A prerequisite is crucial to understand the basin hydrological processes, manageable and unmanageable water flows, the interaction with land use and opportunities to mitigate the negative effects and increase the benefits of water depletion on society [2-4].

At global and continental scales, precipitation is the largest components of the terrestrial water budget which presents the water availability, while evapotranspiration (ET) is the second largest component presenting the water use [5]. Remote sensing has great potential but remains underutilized

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by practicing water resource managers. Accurately estimating consumptive water use using remotely sensed data helps water managers in planning, allocation, and management of water resources. Thanks to the continuous advanced hardware and data processing technologies, the open-access precipitation datasets based on satellite earth observation have a long heritage and are rapidly increasing, e.g. Tropical Rainfall Measuring Mission (TRMM), CPC MORPHing technique (CMORPH) product, which could be utilized for land surface modelling and global water budget study [6-7]. However, the generation of similar datasets for actual ET is in its infancy due to the complex water and energy transfer process. ET is limited by soil moisture supply and atmospheric moisture demand [8-9]. The former is largely linked to precipitation, while the latter relates to net radiation and advection which are impacted by surface and atmospheric temperature. A quantitative knowledge of the loss of water by actual ET (latent heat flux) is crucial in hydrological studies and water resource management, because it serves as a link between the land surface and the atmosphere [10-11]. Therefore, it is crucial to develop methods or tools to quantify water availability and water use (i.e. ET) over large spatial scales in order to inform decision makers on sustainable utilization and management of water resource.

The most popular remote sensing algorithms for continental or global scale ET estimation include surface energy balance models based on visible and infrared observations, and the micro-meteorological models based on the optical and microwave remote sensing data [12-18]. The first type algorithm was developed with the thermal infrared remote sensing, and was recognized to be able to generate accurate ET. However, it was restricted in cloud free conditions and difficult to provide continuous ET information at high temporal resolution since it relied heavily on the land surface temperature retrieved from thermal infrared bands. The land surface temperature was either assumed to be the aerodynamic temperature for surface sensible heat estimation, or believed to somehow reflect the surface moisture condition under the assumption that high temperature occurred over dry surface with low ET, while low temperature occurred over wet surface with high ET [19-20]. These assumptions were convinced in most cases, however failed in some cases, e.g. over the heterogeneous and non-isothermal surfaces, thermal infrared surface temperature cannot be directly used as the aerodynamic temperature in estimating surface fluxes [21]. Thus, the second one has grown up to the most attractive approach with the increasing earth observation dataset available [11, 16-17, 22-24].

The Pan-Eurasian and African Continents are characterized by large ranges of climates varying from humid, semi-humid, semi-arid and arid regions. Practical problems related to water resource and food security depends strongly on the water availability and water use in the Pan-Eurasian and African Continents. In many agricultural areas, crop water consumption often accounts for major elements of regional water use, which competes with many other purposes of water uses (e.g. cities and industries) in particular in water-scarce regions. Therefore, current study aims to analyze the quantitatively water availability and water use in Pan-Eurasian and African Continents to understand the effectiveness of water use and further to mitigate from water stress resulted by drought in water-scarce regions.

2. Study area and material

2.1 Study area

The Pan-Eurasian and African Continents characterized by large ranges of climates varying from humid, semi-humid, semi-arid and arid regions, account over half of the global land area. It is the area with the largest population density with its population account for about 85% of the world. This area is also characterized by uneven development, including the most developed region, e.g. west Europe, underdeveloped regions, e.g. Africa, and fast developing regions, e.g. China and India. The large amount of population and development of economy in recent year have great pressure on its water resources management. Practical problems related to water resource and food security depends strongly on the water availability and water use in the Pan-Eurasian and African Continents.

2.2 Methodology and Dataset

2.2.1 Water use estimation. The water use was estimated as the total actual evapotranspiration from the land surface to the atmosphere. A process-based ET estimation model named ETMonitor based on remotely sensed data was developed to estimate the daily actual evapotranspiration from 2008 to 2013 with spatial resolution of 1km. The ETMonitor model combined different ET parameterizations for the following land cover types: (1) water body; (2) snow/ice surface; and (3) soil–vegetation canopy. The details about ETMonitor were given in previous work [11, 25].

In current study, the biophysical variables derived from the Global LAnd Surface Satellite (GLASS) products including albedo and LAI were adopted [26]. The standard MODIS land cover product (MCD12) was used to infer information on different land cover classes, and 17 land cover types were identified based on the IGBP classification. The Advanced Scatterometer (ASCAT) soil moisture products estimated from the ERS scatterometer and soil data [27-28] was used. The near-surface meteorological forcing data, including air temperature, air pressure, dew point temperature, wind speed, precipitation, downward short-wave and long-wave radiation fluxes are essential to drive the ETMonitor, which were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) meteorological product (http://www.ecmwf.int).

2.2.2 Statistical analysis for validation. The water use estimated by ETMonitor was validated according to the *in situ* observation from 10 observation sites (Table 1), with land cover types of forest, shrubland, grassland, and cropland, after careful quality evaluation. We do not intend to validate the precipitation data since it has been well validated in other studies [7, 29].

Table 1. Information of selected sites for validation

Site	Latitude	Longitude	Land cover	period
BE-Bra	51.30	4.52	Mixed Forest	2008-2011
CH-Oe2	47.28	7.7343	Croplands	2008-2011
IT-Ren	46.58	11.43	Evergreen Needleleaf forest	2009-2011
RU-Cok	70.82	147.49	Open Shrublands	2008-2009
Yingke	38.85	100.42	Croplands	2009-2011
Arou	38.05	100.45	Grasslands	2009-2011
Guantan	38.53	100.25	Evergreen Needleleaf Forest	2009-2011
Daxing	39.62	116.42	Croplands	2009-2011
Guantao	36.51	115.12	Croplands	2009-2011
Miyun	40.63	117.32	Mixed Forest	2009-2011

The statistical indices, including coefficient of determination (R^2) and root mean square error (RMSE), were calculated in this study to illustrate the difference between model outputs and ground measurement.

3. Results and discussion

3.1 Validation of water use estimated by ETMonitor

The result of water use validation is listed in Table 2. ETMonitor performs the best at RU-Cok site with very high R^2 of 0.93 and low bias and RMSE of 0.03 mm d^{-1} and 0.19 mm d^{-1}, respectively. The water use estimated by ETMonitor differ from observation mostly occurs in Guantao site, however its bias is still less than 1 mm d^{-1} and RMSE is less than 1.5 mm d^{-1}, which is acceptable in current large scale water flux estimation model. Overall, the ETMonitor based on mainly remote sensing datasets shows good accuracy in estimating water use.

Table 2. Statistics of estimated water use validation results.

Site	Bias (mm d^{-1})	R^2	RMSE(mm d^{-1})
BE-Bra	0.11	0.86	0.34
CH-Oe2	-0.74	0.61	1.14
IT-Ren	-0.50	0.65	0.86
RU-Cok	0.03	0.93	0.19
Yingke	-0.07	0.86	0.90
Arou	-0.30	0.86	0.51
Guantan	0.29	0.68	0.79
Daxing	0.09	0.36	1.34
Guantao	0.88	0.80	1.40
Miyun	0.72	0.78	1.20

3.2 Spatial variation of water availability and water use

CMORPH precipitation data was collected to present the water availability in current study, which showed clear spatial variations (Figure 1A). Extreme large amount precipitation was found near the equator area in Africa and Asia, with maximum value reaches 5000mm/yr. Extreme small amount precipitation was found near the desert area in Africa and Asia (e.g. the Sahara desert), with the minimum value less than 100 mm/yr. The water use, estimated by ETMonitor, also showed clear spatial variation (Figure 1B). Extreme large amount ET was found near the equator area in Africa and Asia, with the maximum value reaches 1500mm/yr. Extreme small amount ET was found near the desert area in Africa and Asia, with the minimum value less than 100 mm/yr. Regions with high precipitation are usually accompanied with high water use, most due to the limit of water available for water use is low in these regions, which is especially true in the equator region.

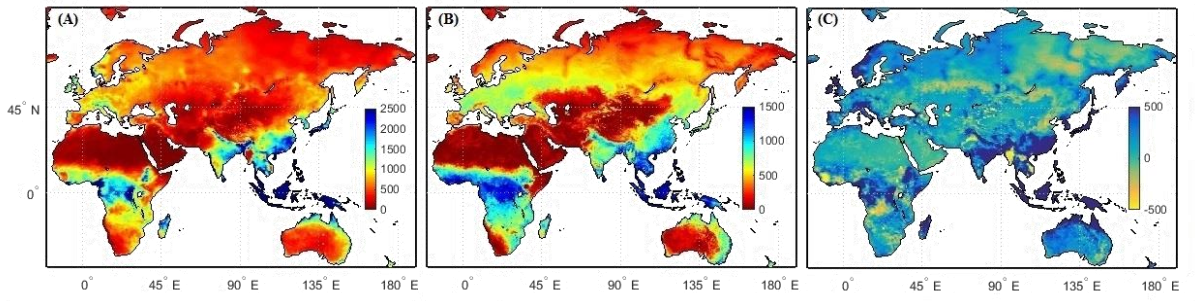

Figure 1. Spatial variation of water availability (A), water use (B), and the precipitation – evapotranspiration deficit (C). Annual mean value from 2008 to 2013 with the unit of mm yr^{-1}.

3.3 Spatial variation of precipitation – evapotranspiration deficit

The deficit between precipitation and evapotranspiration (P-ET) represents the degree of water availability to meet the water use, and its annual spatial variation is shown in Figure 1C. Regions with high precipitation were found to have high positive value of P-ET, including the forest area around the equator in Africa and Asia, west Europe, and monsoon impact area in east and southeast Asia, indicating the water availability could meet the water use and there exist water storage gaining potentially in these regions. These regions will generate surface runoff, interflow, drainage, groundwater recharge, seepage and base flow. Agro-ecosystems where P > ET are referred to as net

producers of water and are typically present in the forested upstream end of river basins. Such excess water moves downgradient in a given tributary to be used by other agro-ecosystems [30]. For the regions with limited precipitation amount, negative values of P-ET were found, mainly located in the agricultural area with irrigation, e.g. the north China plain, the Indus basin, and the Nile basin, which could be found in previous studies based on different datasets [31]. Agro-ecosystems that are net water consumers have an incremental ET that cannot be attributed to precipitation only, but also to other water sources with a natural origin, such as groundwater seepage, shallow water tables, interflow or inundations during annual wet seasons with high river flow levels.

The P-ET value also showed large differences among different land cover types (Figure 2). Evergreen broadleaf forest showed the highest P-ET value, since it is mainly located in the tropical rainforest regions with large amount of precipitation. Cropland show low value of P-ET, but larger than grassland, mostly due to some cropland locate in the tropical area with high precipitation, while grassland mainly locate in the high latitude area with less precipitation. We notice that the averaged P-ET value for each land cover types shows a positive value, which is mainly caused by the averaged effect that large precipitation contribute too much to P-ET and blends the negative P-ET.

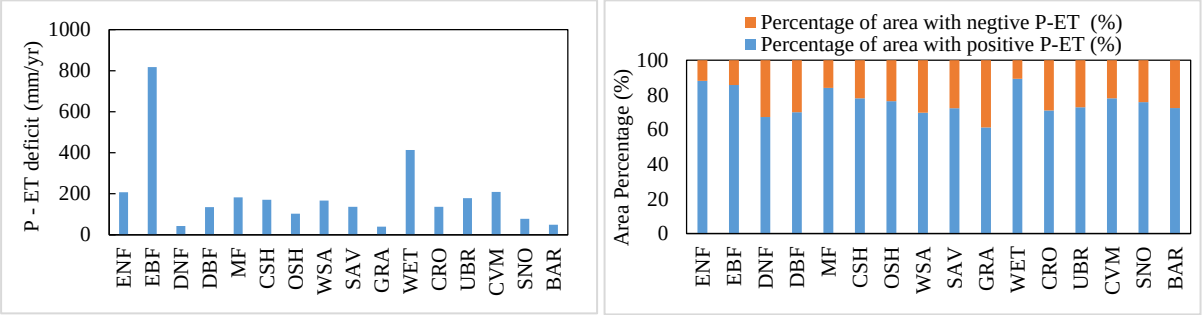

Figure 2. Variation of P-ET among different land cover types. (left panel: averaged P-ET in each land cover type; right panel: percentage of water gain and loss area for each land cover type)
ENF: Evergreen Needleleaf forest; EBF: Evergreen Broadleaf forest; DNF: Deciduous Needleleaf forest; DBF: Deciduous Broadleaf forest; MF: Mixed forest; CSH: Closed shrublands; OSH: Open shrublands; WSA: Woody savannas; SAV: Savannas; GRA: Grasslands; WET: Permanent wetlands; CRO: Croplands; URB: Urban and built-up; CVM: Cropland/Natural vegetation mosaic; SNO: Snow and ice; BAR: Barren or sparsely vegetated

In Figure 2, we also show the percentage of area with positive P-ET and negative P-ET for each land cover type. Evergreen broadleaf forest showed the highest percentage of positive P-ET since it mainly located in the tropical area with high precipitation. Deciduous forest, woody savannah, grassland, cropland, are among the land cover types showed the highest percentage of negative P-ET, about 30%.

Combing with the uneven spatial distribution as illustrated in Figure 2, it could be found that the cropland in the tropical area gain much water from precipitation than water loss by ET and thus irrigation is unnecessary. However, for the cropland in the temperate or arid area, many regions are found to be with negative P-ET since the ET is higher than precipitation, indicating the potential large amount of irrigation in these areas [31-32]. It also highlights the ability of groundwater management, since about 43% of irrigated water is pumped from groundwater globally [33]. Even large efforts have been done, the water-table in many areas, like the north China plain, are keeping declining, and potential solutions are urgently to be in action, including reducing the irrigated area, reintroducing fallow periods, and shifting water from agriculture to other less consumptive uses [34].

3.4 Spatial variation of water use components

The different water use components are also estimated in ETMonitor, including plant transpiration (Tr), soil evaporation (Es), canopy rainfall interception (EI), open water body evaporation, and snow

sublimation (Figure 3). Plant transpiration is the largest water use components, accounting for 54.83% of total water use, while soil evaporation is the second largest accounting for 33.33%. The canopy rainfall interception is much less than the plant transpiration and soil evaporation, only accounting for 9.01% of the total water use. The rest of the water use, about 2.83%, is lost through open water body evaporation, and snow sublimation.

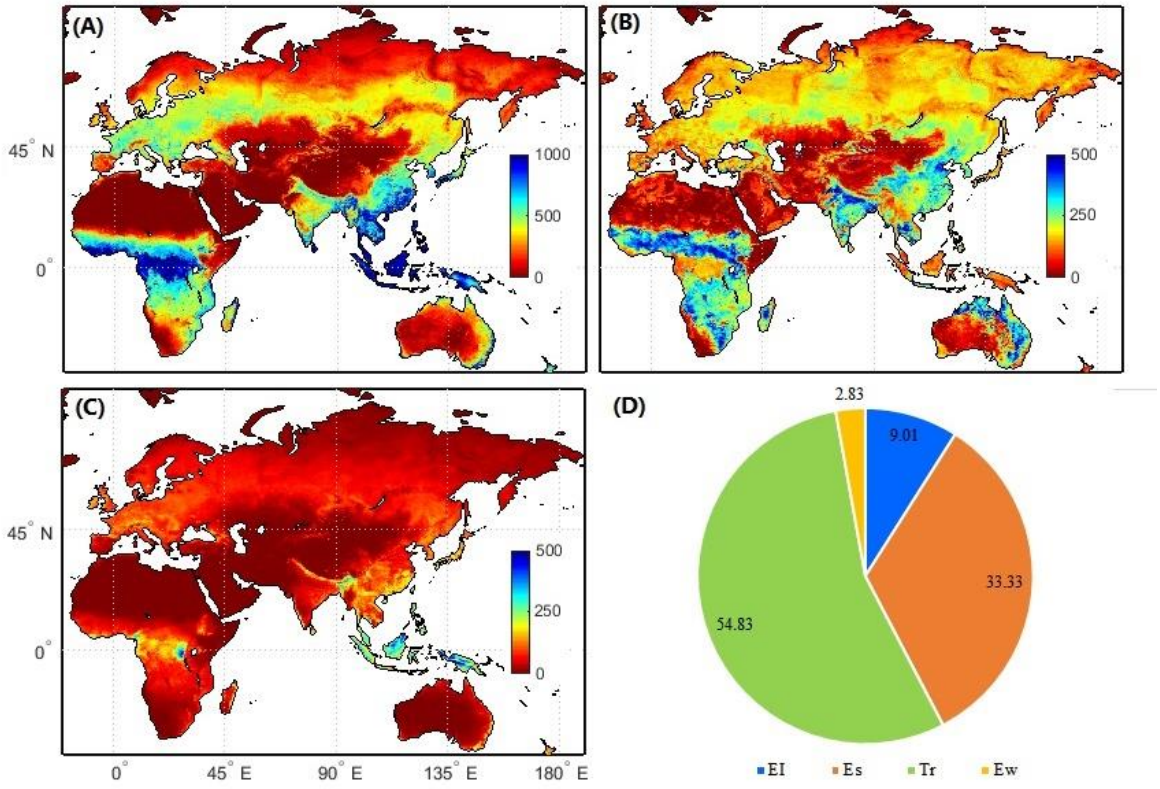

Figure 3. Spatial variation of plant transpiration (A), soil evaporation (B), canopy rainfall interception (C), and their percentage in % to total water use (D). Ew in (D) represent the water body evaporation and snow sublimation.

4. Conclusion

Agriculture is generally assumed to be the largest consumer of water in the Pan-Eurasian and African Continents, future increases in food production will be critical to ensure human wellbeing in both these regions and globally. The estimation of consumptive water use in the Pan-Eurasian and African Continents in current study is important for assessing and managing limited water resources. The estimated water use shows good agreements with the ground observations, indicating the ability of ETMonitor for global and continental scale evapotranspiration estimation. Large spatial variation of water availability and water use are convinced in the study area, and over a half of the total water use is by plant transpiration. The difference between precipitation and evapotranspiration (P-ET), is the difference between water availability and water use, also showed large spatial variations among different regions with different climate zones and different land cover types. The cropland is among the regions with low P-ET, highlighting its severe water scarce, especially in the temperate climate zones. Large amount of groundwater is used for irrigation in these areas, which threats its water security and leads to be severe problems in water management.

Acknowledgments

This work is supported by the National Key Basic Research Program of China (Grant no.

2015CB953702) and the National Natural Science Foundation of China (NSFC) (Grant no.91425303). We thank the Global LAnd Surface Satellite (GLASS) product generation system (http://glass-product.bnu.edu.cn/) for providing the input LAI and albedo datasets. We also thank HiWATER and EuroFlux providing the ground observation data for validation.

The authors declare no conflict of interest.

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