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Analyses, calibration and validation of evapotranspiration models to predict grass-reference evapotranspiration in the Senegal river delta

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ABSTRACT

Study region: Grass-reference evapotranspiration estimation by the Penman-Monteith method (PM-ETo) requires a number of climate variables which are not always available at all weather stations. Different alternative ETo equations have been developed and their utilization for various local climate conditions requires analyses of their accuracy as compared to the standardized Penman-Monteith method. There is a significant lack of data and information on this topic in the Senegal River Delta (SRD).

Study focus: The objective of this study was to evaluate, calibrate and validate six ETo equations ((Trabert, Mahringer, Penman1948, Albrecht, Valiantzas1 and Valiantzas2) for the SRD. Although all six equations showed good agreement with the PM-ETo ($R^2 > 0.60$) for daily ETo estimates, the Valiantzas2 equation was the best model for the Senegal River Delta and had the lowest root mean squared difference (RMSE) of 0.45 mm/day and the lowest percent error of estimate (PE) about 7.1%.

New hydrological insights for the region: In the case of data limitations, the equations calibrated in this study are recommended for ETo estimation in the Senegal River Delta. The results of this study could be used by agricultural producers, crop consultants, university researchers, policy makers for the agricultural, hydrological, and environmental studies as well as proper allocation and use and forecasting in the SRD where lowland irrigated rice is predominant.

1. Introduction

Water resources for agriculture in the context of climate change are decreasing in time and space in different parts of the world with more emphasis in the arid and semi-arid Sahelian zones. Crop water use should be accurately evaluated to improve water management and increase water use efficiency of food and fiber production. Actual crop evapotranspiration (ETa) should be accurately estimated for better irrigation scheduling to minimize negative effects of over and under-irrigation

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on crop productivity and environment. Crop water use is estimated from direct and indirect methods. The maximum precision of ETa could be achieved with lysimeters (Jia et al., 2006; Benli et al., 2006; Miranda et al., 2006; Williams and Ayars 2005; Payero and Irmak 2007; Valipour, 2015), by Bowen Ratio Energy Balance System (Bowen 1926; Irmak and Irmak, 2008; Irmak et al., 2008, 2010, 2013; Irmak, 2010; Kabenge et al., 2013), and eddy covariance technique (Wilson et al., 2001; Baldocchi, 2003; Schume et al., 2005; Kosugi and Katsuyama, 2007; Sun et al., 2008; Novick et al., 2009; Scott, 2010). ETa can also be indirectly estimated by the water balance method in the absence of aforementioned advanced techniques (Xu and Singh, 2002; Azizi-Zohan et al., 2008; Senay et al., 2011; Djaman et al., 2013) and atmometers (ET gauges) (Chen and Robinson 2009; Irmak et al., 2005; Broner and Law, 1991). The two-step method is also used to estimate ETa and it necessitates accurate estimates of reference evapotranspiration (ETo) and locally developed crop coefficients (Kc). Thus, crop water use is estimated by multiplying the reference evapotranspiration by pre-determined crop-specific coefficient, which is dependent on many factors, including irrigation regimes and management (Djaman and Irmak, 2013).

Number of models have been used to estimate reference evapotranspiration and range from direct measurement from a reference crop such as a perennial grass (Doorenbos and Pruitt, 1977; Watson and Burnett, 1995) or computed from weather data using: (a) temperature-based models (Thornthwaite, 1948; Doorenbos and Pruitt 1977), (b) radiation-based models (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985), and (c) combination-based energy balance models (FAO-56 PM) (Allen et al., 1998). The ASCE Penman-Monteith method has been adopted and recommended as a standardized method for most accurate reference evapotranspiration estimation (ASCE-EWRI 2005). However, it requires several parameters to estimate reference crop evapotranspiration. In most regions globally, especially in developing countries, since weather data are limited, it is not possible to use the standardized Penman-Monteith equation, which impose challenges to the agricultural professionals, water managers, researchers, and associated personnel as to which method to use in a given local region for reference ET estimations. Several studies have evaluated a number of ETo equations in different parts of the world against the standardized Penman-Monteith method for adaptability and accuracy of ETo estimates in comparison to the standardized Penman–Monteith equation (Yoder et al., 2005; Pedro et al., 2008; Trajkovic and Kolakovic, 2009; Tabari, 2010; Xystrakis and Matzarakis, 2011; Tabari and Hosseinzadeh-Talee, 2011; Ravazzani et al., 2012; Rojas and Sheffield 2013; Jia et al., 2013; Valiantzas, 2013; Kisi, 2013; Samaras Dimitrios et al., 2014; Bogawski and Bednorz, 2014; Shiri et al., 2014; Valipour, 2015; Djaman et al., 2015, 2016). In a recent comprehensive study in the Senegal River Valley, Djaman et al. (2015) reported that the Valiantzas, Trabert, Romanenko, Schendel and Mahringer equations are the most promising equations that could be used for reference evapotranspiration estimation. They showed that the Hargreaves, modified Hargreaves, Ravazzani and Tralkovic equations systematically overestimated ETo and the Makkink–Hansen, Oudin and Turc equations systematically underestimated ETo.

In the Sahel environment like the Senegal River Valley (SRV) and Senegal River Delta (SRD) where annual precipitation is less than 300 mm (Djaman et al., 2015), irrigation water is becoming increasingly scarce (Rijsberman, 2006) and costly. Rice production is the main activity in the Senegal River Valley and Delta with potential rice yields as high as 12 tons ha^{-1} under effective irrigation management (de Vries et al., 2010). Rice production covers approximately 60,000 ha in Mauritania and Senegal and has been playing a vital role in meeting the food demand of the region's population and also has critical economic implications to the area. In the Senegal River Valley, for a long time, water management was not considered as a critical management practice and irrigation schemes have been abandoned after few years of initial cultivation due to buildup of soil salinity in Senegal River Delta and Valley (OMVS-SOGREAH, 1998; Raes et al., 1995). Irrigation requirement is a major contributor to rice production cost, because the cost of pumping irrigation water is high, accounting for about 28% of the operational cost (Comas et al., 2012). Therefore, accurate determination of irrigation water requirement is critical for economics of rice production and environmental issues in the Senegal River Delta. While different equations have been calibrated for different regions and sub-regions under different climatic conditions including in Iran (Tabari and Hosseinzadeh-Talaee 2011; Tabari et al., 2014; Heydari and Heydari, 2014; Valipour 2015), in China (Zhai et al., 2010; Gao et al., 2015), in Poland (Bogawski and Bednorz, 2014), in Sub-Humid Region of Brazil (de Sousa Lima et al., 2013), in Florida (USA) (Thepadia and Martinez, 2012), in Southeast Australia (Azhar and Perera, 2011), and in Canada (Singh and Xu, 1997) extremely limited data and information existed in terms of proper ETo estimation model to be applied in this extremely climate data-limiting agricultural area.

Therefore, as a next step of the study conducted by Djaman et al. (2015), this study aims to calibrate and validate six ETo models (Trabert, Mahringer, Penman, (1948), Albrecht, Valiantzas 1 and Valiantzas 2) using long-term climatic data for accurate and reliable estimation of reference evapotranspiration in the Senegal River Delta.

2. Materials and methods

2.1. Site description and datasets

The Senegal River Basin is located in West Africa and covers a total area of 340,000 km^2 in North Senegal, West Mali, South Mauritania and the high plateaus of the Fouta Djallon massif in Guinea (Gaye et al., 2013). The basin is drained by the 1800 km long Senegal River, the second longest river of West Africa, and its main tributaries of the Bafing, Bakoye and Faleme Rivers, all three of which have their source in the Fouta Djallon Mountains in Guinea. The basin has mostly a sub-Saharan desert climate. Geographically the basin has three distinct parts including the mountainous upper basin, the valley and the delta which is a source of biological diversity and wetlands.