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Evaluation and calibration of alternative methods for estimating reference evapotranspiration in the main hydrosystems of Senegal: Senegal, Gambia and Casamance River Basins

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Abstract. Reference evapotranspiration (ET_0) is an essential parameter for hydrological modeling, irrigation planning and for studying the impacts of climate change on water resources. The Penman–Monteith method is recommended for estimating ET_0 under all climatic conditions, but its application is limited in regions where data is difficult to access. The alternative is to use methods that incorporate fewer climatic parameters. The objective of this work is to evaluate twenty alternative methods using few climate parameters of estimating ET_0 and to calibrate/validate the best ones in order to adapt them to the climatic context of the main hydrosystems of Senegal: Senegal, Gambia and Casamance river basins. The KGE and the PBIAS were used to evaluate the performance of the methods. The results show that after calibration/validation the methods of Trabert, Hargreaves, Hargreaves & Samani, Trajkovic and Oudin are the best on for the estimation of the reference evapotranspiration in the Senegal, Gambia and Casamance River Basins.

Keywords. UPH1; SDG6; Reference evapotranspiration; Senegal; Gambia; Casamance River Basins

1 Introduction

The estimation of evapotranspiration is a major difficulty in the context of developing countries. This is generally explained by the difficulty of accessing the climatic data necessary for its estimation and the low density of measurement stations. To overcome this, reanalysis data can be an alterna-

tive to often incomplete observed data. These data give the opportunity to calculate the evapotranspiration with several methods. The latter vary according to the climatic parameters that they integrate. A distinction is made between aerodynamic methods according to which evapotranspiration is proportional to wind speed and saturation deficit (Dalton, 1802), methods based on temperature (Hargreaves, 1975) and solar radiation (Makking, 1957) and those based on which combine several climatic variables (Penman, 1948; Monteith, 1965). These methods make it possible to estimate the refer-

ence evapotranspiration (ET_0) and their performance varies according to the geographical areas (Djaman et al., 2015). Therefore, it is important to evaluate them before using them in a specific context. Moreover, even after evaluation, these methods must be calibrated in order to adapt them to the local climatic context other than the original climates under which these models were developed. Several studies around the world (Bogawski and Bednorz, 2014; Valipour, 2015; Djaman et al., 2015; Ndiaye et al., 2020) have focused on the evaluation of different ET_0 estimation methods. In the Senegal River Basin, Ndiaye et al. (2020) evaluated the performance of twenty alternative methods for estimating ET_0 . Their results showed that the best methods retained after calibration/validation: Valiantzas 2, Trabert, Valiantzas 3 and Hargreaves and Samani. This work aims to expand the study by Ndiaye et al. (2020) on the other watersheds of Senegal (Gambia and Casamance) in order to evaluate alternative methods using few climate parameters of estimating ET_0 on the main hydrosystems of Senegal.

2 Material and methods

2.1 Study area

The Senegal, Gambia and Casamance river basin constitute the main hydrosystems of the Senegalese territory (Fig. 1). The Senegal and Gambia rivers have their source in the Fouta Djallon at an altitude of 1150 m and drain respective areas of more than 300 000 and 77 100 km², respectively (Ndiaye et al., 2020). The Senegal river basin extends into Senegal, Guinea, Mauritania and Mali and is managed by the Organization for the Development of the Senegal River. The Gambia river covers parts of Senegal, Gambia and Guinea together with Guinea-Bissau which constitute the Organization for the Development of the Gambia River. The Casamance basin extends over an area of 20 150 km² and is located almost entirely in Senegalese territory (Dacosta, 1989). From a climatic point of view, these three hydrosystems extend over three climatic zones: Guinean (average annual rainfall > 1500 mm); South Soudanian (1000 < rainfall < 1500 mm); North Sudanian (500 < rainfall < 1000 mm) and Sahelian (rainfall < 500 mm). The water resources of these three hydrosystems are used for the development of agriculture, hydroelectric production, drinking water supply, navigation and the maintenance of ecosystems.

2.2 Data

In West Africa, meteorological data managed by national meteorological services are difficult to access due to their high acquisition costs (Bodian et al., 2020). Additionally, the low density of the observation networks limits their spatial representativeness at the scale of the catchment area (Ndiaye et al., 2020). For this reason, reanalyses from the NASA Langley Research Center (LaRC) POWER Project funded

through the NASA Earth Science/Applied Science Program (<https://power.larc.nasa.gov>, last access: February 2022) are used as an alternative (Ndiaye et al., 2020). The coordinates of 160 (64, 58 and 38 for Senegal, Gambia and Casamance river basins, respectively) stations distributed across the three basins (Fig. 1) are used to extract climate variables on a daily scale over the period 1984–2019. The climatic variables collected are: maximum and minimum air temperatures, solar radiation, air relative humidity and wind speed at 2 m above ground.

2.3 Methods

2.3.1 Estimation method of reference evapotranspiration

The reference method used is that of FAO56-PM which is given by the following formula:

$$ET_{0\text{FAO56-PM}} = \frac{0.408\Delta(R_n - G) + \frac{\gamma C_n}{T+273.3}u_2(es - ea)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

Where $ET_{0\text{FAO56-PM}}$ is the reference evapotranspiration (mm d^{-1}), R_n : net radiation on the crop surface ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the heat flux density of the soil ($\text{MJ m}^{-2} \text{d}^{-1}$) which is ignored on a daily scale, T is the average daily air temperature at a height of 2 m ($^{\circ}\text{C}$), C_n and C_d are constant values which change according to the scale of time used (on a daily scale C_n and C_d are 900 and 0.34 respectively), u_2 is the wind speed at a height of 2 m (m s^{-1}), es is the saturated vapor pressure (kPa), ea is real vapor pressure (kPa), $(es - ea)$ is the saturation deficit (in kPa) Δ is the vapor pressure slope curve ($\text{kPa } ^{\circ}\text{C}^{-1}$) and γ is the psychrometric constant psychrometric ($\text{kPa } ^{\circ}\text{C}^{-1}$).

The list of the twenty alternative methods used in this work as well as their mathematical formulations are detailed in Ndiaye et al. (2020). The Table 1 give only the names of methods used and their categories.

The calibration of the best methods was done by the gradient reduction method (Bogawski and Bednorz, 2014). This seeks to change the constant values of the original methods to minimize estimation errors. For this, the series is divided into two part as recommended by Xu and Singh (2001): 2/3 of the series (1984–2005) for calibration and 1/3 (2006–2019) for validation. The calibrated methods were re-evaluated using the same criteria as for the evaluation with different time-frame dataset.

2.3.2 Evaluation criteria

Kling Gupta Efficiency (KGE, Gupta et al., 2009) and percentage bias (PBIAS) are used (Table 2) to assess the performance of alternative methods. The KGE includes both the correlation coefficient (r), the biases (β) and the variability (γ) and makes it possible to determine the degree of concordance between the reference ET_0 and that of the alternative methods. The PBIAS indicates errors as a percentage. A

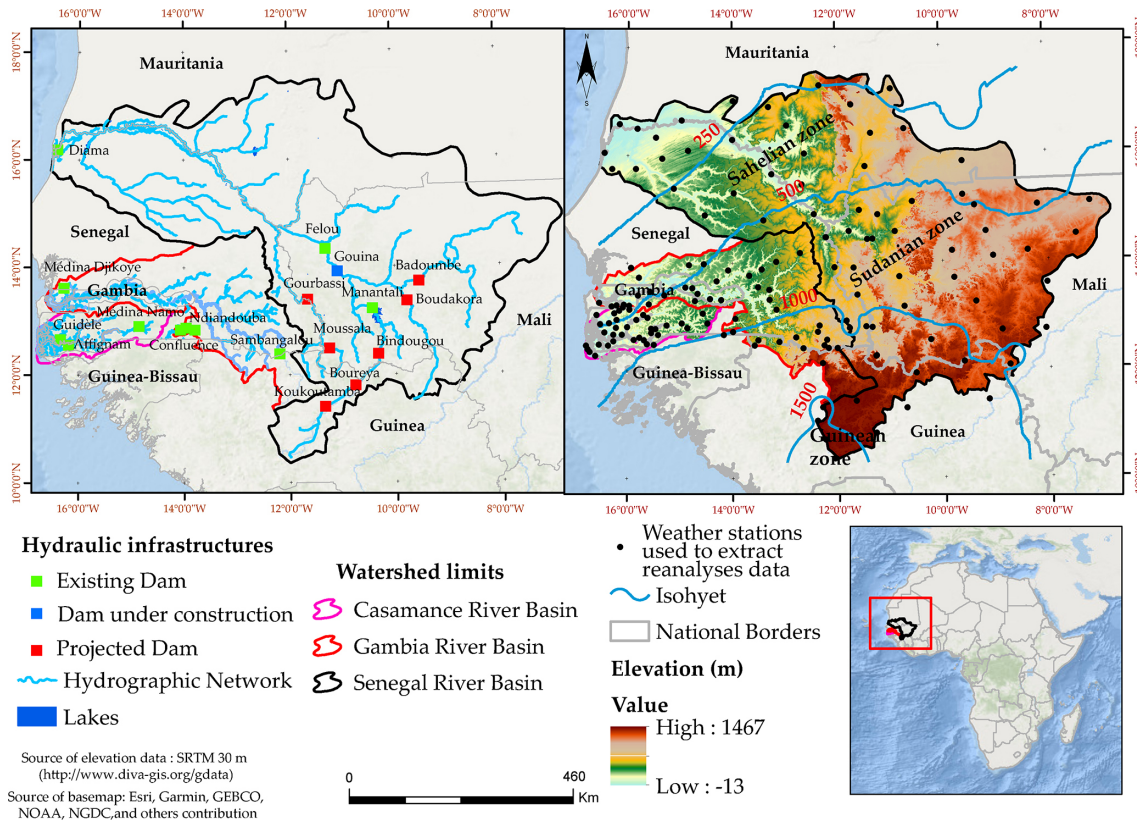


Figure 1. Location of the three Senegalese hydrosystems, hydraulic infrastructures, climate zones, hydrographic network and weather stations used to extract reanalyses data.

Table 1. List of the twenty alternative methods evaluated against FAO56-PM.

Categories	References	Abbreviation	Categories	References	Abbreviation
Aerodynamic	Dalton (1802)	DN (2)	Radiation	Makking (1957)	MK (12)
	Trabert (1896)	TRB (3)		Jensen et Haise (1963)	JH (13)
	Penman (1948)	PNM (4)		Priestley and Taylor (1972)	PT (14)
	Rohwer (1931)	RW (5)		Abtew (1996)	AB (15)
	Mahringer (1970)	MHR (6)		Oudin (2005)	OD (16)
Temperature	Hargreaves (1975)	HG (7)	Combinatory	Penman (1963)	PNM (17)
	Hargreaves and Samani (1985)	HS (8)		Doorenbos and Pruitt (1977)	DP (18)
	Trajkovic and Stojnic (2007)	TRA (9)		Valiantzas 1 (Valiantzas, 2013)	Val 1 (19)
	Droogers and Allen (2012)	DA (10)		Valiantzas 2 (Valiantzas, 2013)	Val 2 (20)
	Heydari and Heydari (2014)	HH (11)		Valiantzas 3 (Valiantzas, 2013)	Val 3 (21)

positive/negative PBIAS indicates an overestimation/underestimation of ET_0 by the alternative method.

3 Results and discussion

3.1 Evaluation of twenty alternative methods against FAO56-PM

Figure 2 gives the synthesis of the KGE of the twenty alternative methods compared to the FAO56-PM (Penman–

Monteith). Because of the objective of this work, only the results of methods integrating few climatic variables are presented. The performance of these methods varies slightly depending on the river basins. For the Senegal River basin, the five best methods are those of Trabert, Valiantzas 3, Jensen & Haise and Hargreaves & Samani. For the Gambia River basin, in addition to the methods of Valiantzas (2 and 3), those of Oudin, Droogers & Allen and Hargreaves & Samani are the most robust for estimating ET_0 . The KGE values of these methods are generally greater than 0.60 and estima-

Table 2. Evaluation criteria, range, optimal values.

Criteria	Formula	Range	Optimal values
PBIAS	$\left[\frac{\frac{1}{n} \sum_{i=1}^n (ET_{0alt} - ET_{0FAO56-PM})}{\frac{1}{n} \sum_{i=1}^n (ET_{0alt})} \right] \cdot 100$	$-\infty, +\infty$	0 (22)
KGE	$1 - \sqrt{(r - 1)^2 + (\beta - 1)^2 + (\alpha - 1)^2}$	$-\infty, 1$	1 (23)

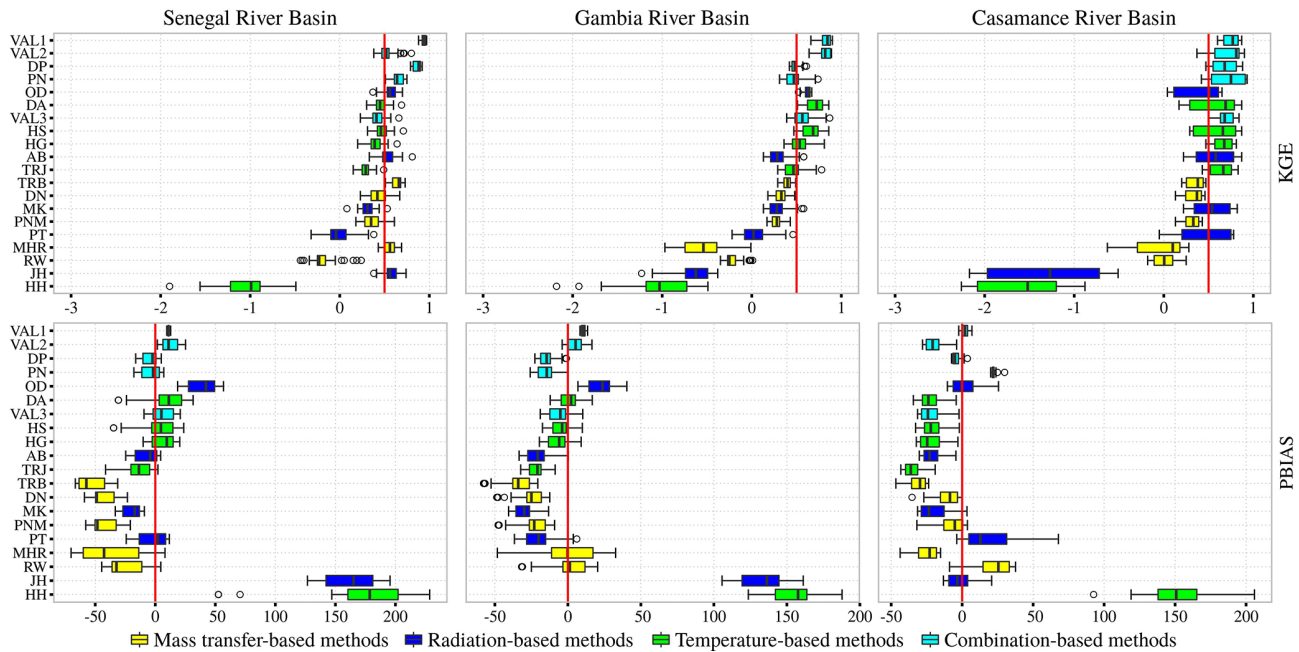


Figure 2. Performance of the methods according to the KGE (The red line in each figure represents the mean values of each KGE).

tion errors of -4% to 23% . In the Casamance River basin, the temperature-based methods of Hargreaves (HG) and Trajkovic give the best results with KGE of nearly 0.88 and low estimation errors ranging from -4.6% to 11% .

3.2 Calibration and validation of the best methods

The choice of methods to be calibrated is guided by the performance criteria and the number of climatic variables they include. On the basis of these criteria, five methods were selected in each basin for calibration. In the Senegal River basin, the mean KGE values of Trabert and Hargreaves & Samani methods increased globally by 24% to 40%. Trabert estimation errors were reduced by 97% after calibration. In the Gambia River basin, the KGE values of the calibrated methods increased by 12% to 28%. The estimation errors of the VAL2 and DA methods decreased by 37% and 23%, respectively, after calibration in the basin. In the Casamance River basin, calibration slightly improved the performance of the methods. For example, the KGE values of the VAL2, HG and TRJ methods increased by 7%, 5% and 2% respectively (Fig. 3 and Table 3). Figure 4 gives the spatial

distribution of the PBIAS, which shows that the calibrated methods are effective in all the river basins. The Trabert method overestimates ET_0 over almost the entire Senegal River basin while the combinatory (VAL2, VAL3), radiation-based (Oudin) and temperature-based (Hargreaves) methods underestimate it in the Gambia basin. In the Casamance River basin, ET_0 is overestimated on the coastal fringe and underestimated on the mainland. Given the similarity of certain results and based on the number of climatic variables, the best methods retained in this study are summarized in Table 2. Thus, the calibration has improved the performance of the methods for estimating ET_0 in the three basins. The performance of these methods was noted by Ndiaye et al. (2020) in the Senegal River Basin and Djaman et al. (2015) in the Senegal River Valley and Delta.

4 Conclusion

This study provides information on the choice of simple methods for estimating reference evapotranspiration in the main hydrosystems of Senegal. The results show that the Trabert method can be used in the Senegal River basin

Table 3. Formula of methods before and after calibration.

Reference	Before calibration	After calibration
Senegal River Basin		
Hargreaves and Samani (1985)	$ET_{0HS} = 0.408 \times 0.0023 (T + 17.8) \times (T_{max} - T_{min})^{0.5} \times Ra$	$ET_{0HS_{cal}} = 0.408 \times 00031 (T + 17.8) \times (T_{max} - T_{min})^{0.5} \times Ra$
Trabert (1896)	$ET_{0TRB} = 0.3075 \sqrt{u2} (es - ea)$	$ET_{0TRB_{cal}} = 2770 \sqrt{u2} (es - ea)$
Valiantzas-2 (Valiantzas, 2013)	$ET_{0VAL2} = 0.0393 R_s \sqrt{T + 9.5} - 0.19 R_s^{0.6} \times \phi^{0.15} + 0.078 (T + 20) \times (1 - Hr/100)$	$ET_{0VAL2_{cal}} = 0027 R_s \sqrt{T + 9.5} - 0.19 R_s^{0.6} \times \phi^{0.15} + 0159 (T + 20) \times (1 - Hr/100)$
Gambia River Basin		
Hargreaves and Samani (1985)	$ET_{0HS} = 0.408 \times 0.0023 (T + 17.8) \times (T_{max} - T_{min})^{0.5} \times Ra$	$ET_{0HS_{cal}} = 0.408 \times 000299 (T + 2.22) \times (T_{max} - T_{min})^{0.577} \times Ra$
Oudin (2005)	$ET_{0OD} = R_s (T + 5) / 100$	$ET_{0OD_{cal}} = R_s (T - 10) / 676$
Casamance River Basin		
Hargreaves (1975)	$ET_{0HG} = 0.0135 \times 0.408 R_s (T + 17.8)$	$ET_{0HG_{cal}} = 0024 \times 0.408 R_s (T - 3)$
Trajkovic and Stojnic (2007)	$ET_{0TRJ} = 0.0023 \times 0.408 \times (T + 17.8) \times (T_{max} - T_{min})^{0.424} \times Ra$	$ET_{0TRJ_{cal}} = 0.0035 \times 0.263 \times (T + 16.63) \times (T_{max} - T_{min})^{0.495} \times Ra$

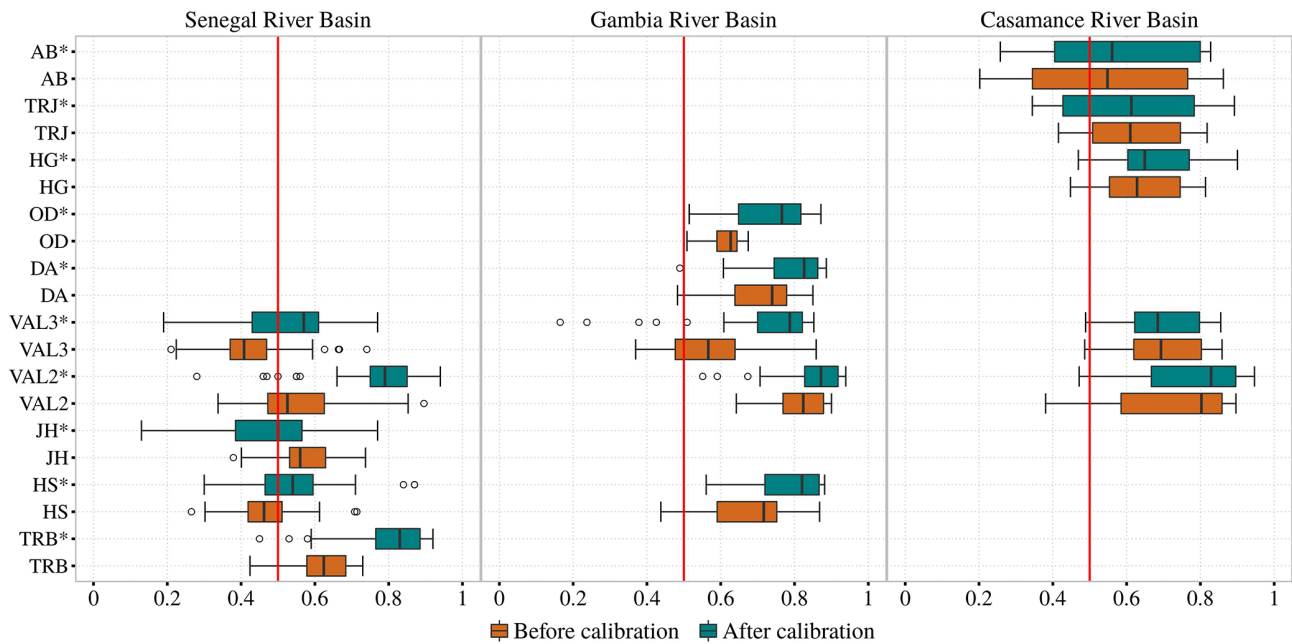


Figure 3. KGE values before and after calibration.

when temperature and wind speed data are available. The Valiantzas 2 method is applicable to all three basins. For the Gambia and Casamance river basins, temperature-based (Hargreaves, Hargreaves & Samani and Trajkovic) and radiation-based (Oudin) methods can be used when only temperature or solar radiation data is available. This information

can be useful for water managers and irrigation development. However, the reanalyses data used can constitute a limit of this work.

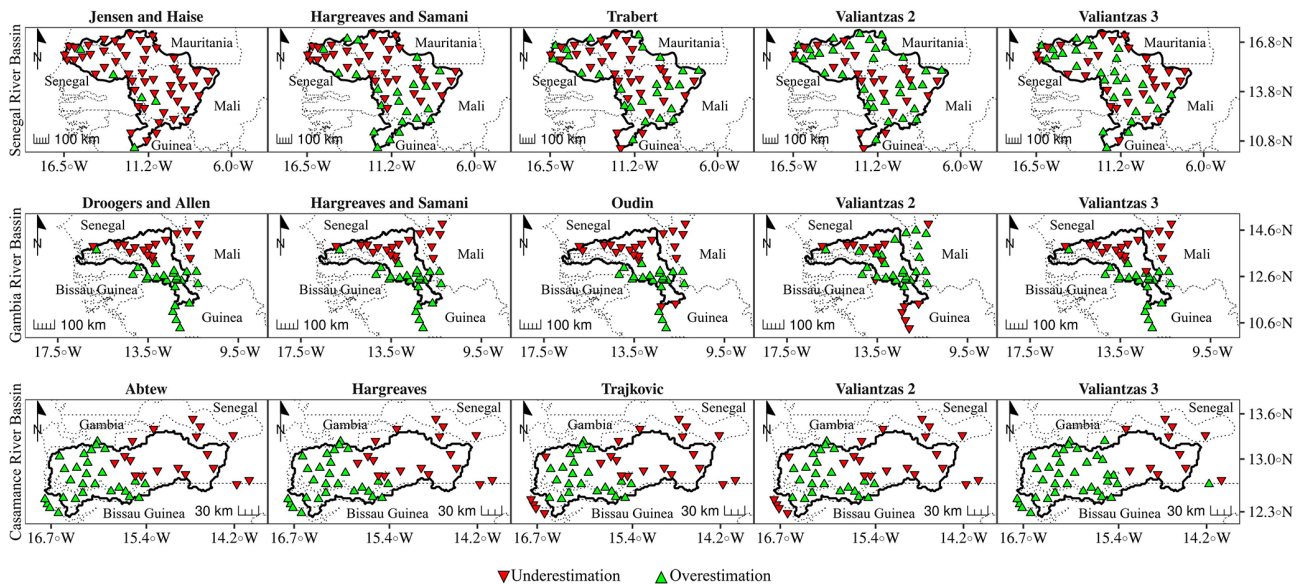


Figure 4. Spatial repartition of PBIAS according to calibrating methods.

Code availability. The software R used in this study is freely available (<https://www.r-project.org/>, last access: February 2022; R Development Team, 2022). The code is not publicly accessible. Please contact the authors if you are interested in this research code.

Data availability. The data of climate variables used in this study are available for public. They come from NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program (<https://power.larc.nasa.gov/data-access-viewer/>, last access: February 2022; NASA, 2022). Please contact the authors if you are interested in the evapotranspiration data used in this research.

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