Responses to reviewers' comments point by point

Journal: HESS
Title: Revisiting the Hydrological Basis of the Budyko Framework with the Hydrologically Similar Groups Principle
MS No.: hess-2022-290
MS Type: Research article

Dear Prof. Roger Moussa and reviewers,

We are very grateful to you and the reviewers for the time and constructive comments on our manuscript "Revisiting the hydrological basis of the Budyko framework with the hydrologically similar groups principle" (MS No.: hess-2022-290). The comments have helped improve the paper quite tremendously.

We have carefully studied these comments by Reviewer#1, Reviewer#2, and Dr. Vazken Andréassian, and revised our manuscript accordingly. The point-to-point responses are listed below. Please note that the comments from the reviewers are in **bold** followed by our responses in regular text. The changes in our manuscript are underlined with red.

In the revised manuscript, we added Wenping Yuan as co-author because he provided important guidance on the seasonal indices (SI) as well as the revisions and editorial for the manuscript. The change of authorship as listed below,

the previous authorship:

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the new authorship:

Yuchan Chen[1], Xiuzhi Chen[1], Meimei Xue[1], Chuanxun Yang[2,3], Wei Zheng[1], Jun Cao[4], Wenting Yan[1], Wenping Yuan[1]

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Among the authors in the list: XC designed the study and proposed the scientific hypothesis; YC implemented the experiments, conducted the analysis and wrote the paper; MX helped with data collection, and checked the technical adequacy of the experiment; CY and WZ helped with data processing; WPY provided the guidance on the seasonal indices (SI); CY, WZ, CJ, WTY and WPY reviewed and edited the manuscript; XC oversaw the study and conducted manuscript revision as a mentor. After consultations, all the authors agreed with the addition of authors in this paper.

We believe the quality of the manuscript can now meet the high standard of HESS and deeply appreciate your consideration of our manuscript.

Sincerely,
Yuchan Chen, Xiuzhi Chen
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Response to Reviewer#1:

General Comments:

The authors used global data sets to analyze an impressive number of catchments in order to calculate their position on the Budyko curve. They use the results to establish correlation between the single parameter of a parametric expression of the Budyko curve and various catchment characteristics. In the discussion, the results are analyzed to provide physical explanations for some of these correlations.

Overall, the paper is sound and the analysis provides new insights, making this an interesting paper that I enjoyed reading.

Response:

Thank you for your positive comments. Your suggestions are very useful for us to improve our research. We revised our manuscript according to your comments. The changes in our manuscript are underlined with red. We believe our manuscript improved a lot after the modification. Please see the response below.

Comment 1:

I would like the Introduction to clarify better the role of the parameter.

Response:

Thanks for the good suggestion. We added more description of the role of the parameter as follows,

"From the hydrological point of view, the Pw controls the fraction of precipitation diverted into the runoff for a given aridity index (Caracciolo et al., 2018). Watersheds with larger Pw values converts larger parts of precipitation to evapotranspiration and consequently less part to runoff than those with smaller Pw value; and some studies defined the Pw as the water retention capacities of watersheds (Fu, 1981; Zhou et al., 2015). Overall, the Pw denotes the adjustment of water-energy partitioning by watershed characteristics (Yao et al., 2017; Li et al., 2013)." (Lines 50-54 in the revised manuscript)

Comment 2:

The results indicate there is a temporal trend in the quality of the runoff reconstruction. I would like to see some examples of this for individual catchments, and if possible some more discussion of this.

Response:

Thank you. We have added Supplement 3 in the revised manuscript to show the simulation results of average annual runoff and validation results of time series runoff reconstruction for each GRDC watershed. At the same time, we have added the analysis of individual typical watersheds, as follows,

"The reconstructed time-series runoffs in the Milk River watershed (GRDC station number: 4220501) and Near Lethbridge watershed (GRDC station number: 4213111) both show an underestimation of annual runoff in the arid areas. The Milk River and the Near Lethbridge are two adjacent watersheds with similar drainage areas located on the border of the United States and Canada. However, the underestimation is more serious in the Milk River watershed (RelBIAS=-0.32, annual mean P/PET=0.52) than in the Near Lethbridge watershed (RelBIAS=-0.27, annual mean P/PET=0.55)." (Lines 285-290 in the revised manuscript)

Comment 3:

The readability of the figures is poor because too much information is jammed in many panels comprising a single figure. Trying to read Fig. 7, I had to enlarge it so such a degree that the resolution became too coarse. At times, the English is a bit hard to comprehend.

Response:

Thank you for pointing out this. In the revised manuscript, for the Fig. 7 of the original manuscript, we have separated the line plot into Fig. 8 and the scatter plot into Fig. 9 to make them easier to understand. In addition, we have modified the English expressions to make them easier to read.

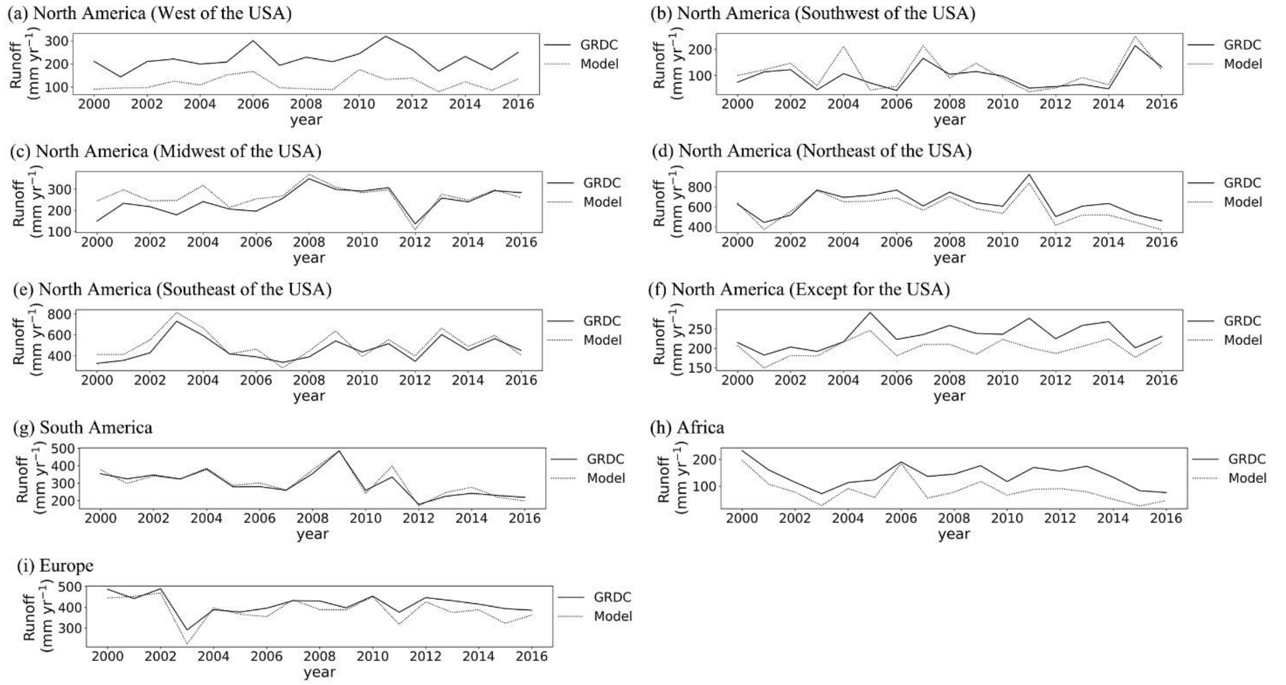


Figure 8. Observed time-series runoffs versus reconstructed time-series runoffs. Nine geographic sub-regions were in Fig. 1: North America ((a) west, (b) southwest, (c) midwest, (d) northeast, (e) southeast, (f) except of the USA), (g) South America, (h) Africa, and (i) Europe.

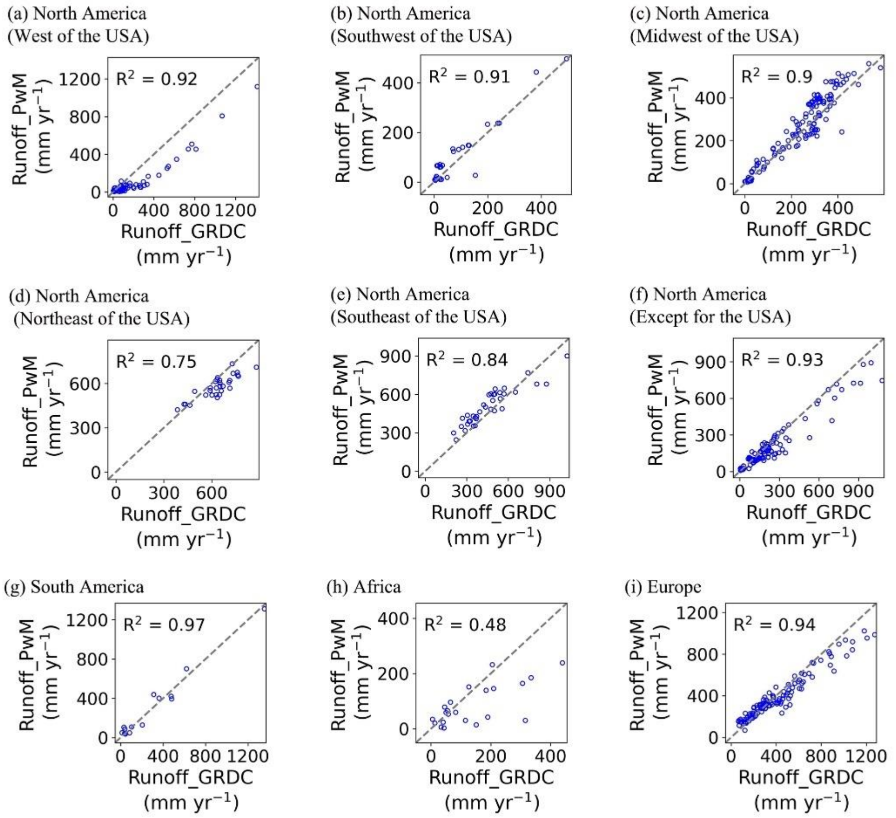


Figure 9. Scatterplots between observed annual mean runoffs and reconstructed annual mean runoffs. Nine geographic sub-regions were in Fig. 1: North America ((a) west, (b) southwest, (c) midwest, (d) northeast, (e) southeast, (f) except of the USA), (g) South America, (h) Africa, and (i) Europe.

Comment 4:

Carefully check the notation and explanation of all variables and make them consistent throughout. Two examples: PET and ET0 both denote the potential evapotranspiration, and Pw and m denote the watershed characteristic parameter.

Response:

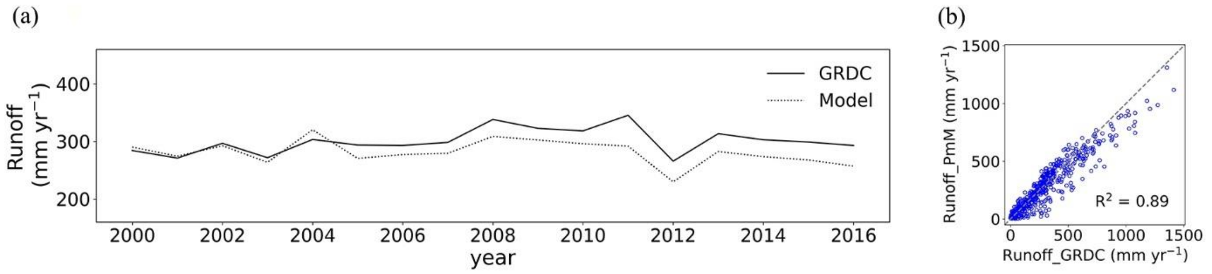
Thank you. As your suggestion, we have checked and revised the notation and explanation of all variables to make them consistent. In our revised manuscript, the abbreviation of the watershed characteristic parameter was unified as the Pw, the actual evaporation was unified as the ET, the runoff was unified as the R, the precipitation was unified as the P, and the potential evapotranspiration was unified as the PET.

Comment 5:

Figs. 5 and 6 present quantitative data in poorly readable color scales. But placing these in tables is not manageable because of the large number of catchments. Still, information for individual catchments would be useful. Perhaps add such a table as a supplement? Perhaps you can expand the table for annual data, so we can see the trend that you report in the aggregate in the main text for individual catchments.

Response:

Thank you for your suggestion. In the revised manuscript, we have revised the color of Fig.6 (i.e., Fig.5 in the original manuscript) and Fig.7 (i.e., Fig.6 in the original manuscript), and added Supplement 3 to show the simulation results of average annual runoff and validation results of time series runoff reconstruction for each GRDC watershed.



(c) North America (d) South America (e) Africa (f) Europe

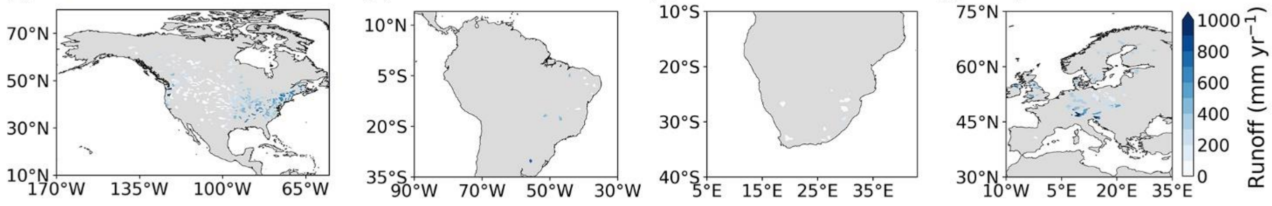


Figure 6. Time-series runoff reconstruction results in the selected GRDC stations. (a) Time-series annual mean runoff of the selected 545 GRDC watersheds; (b) Scatterplot between the modeled runoff and observed runoff; The spatial distribution of annual mean runoff in (c) North America, (d) South America, (e) Africa, and (f) Europe.

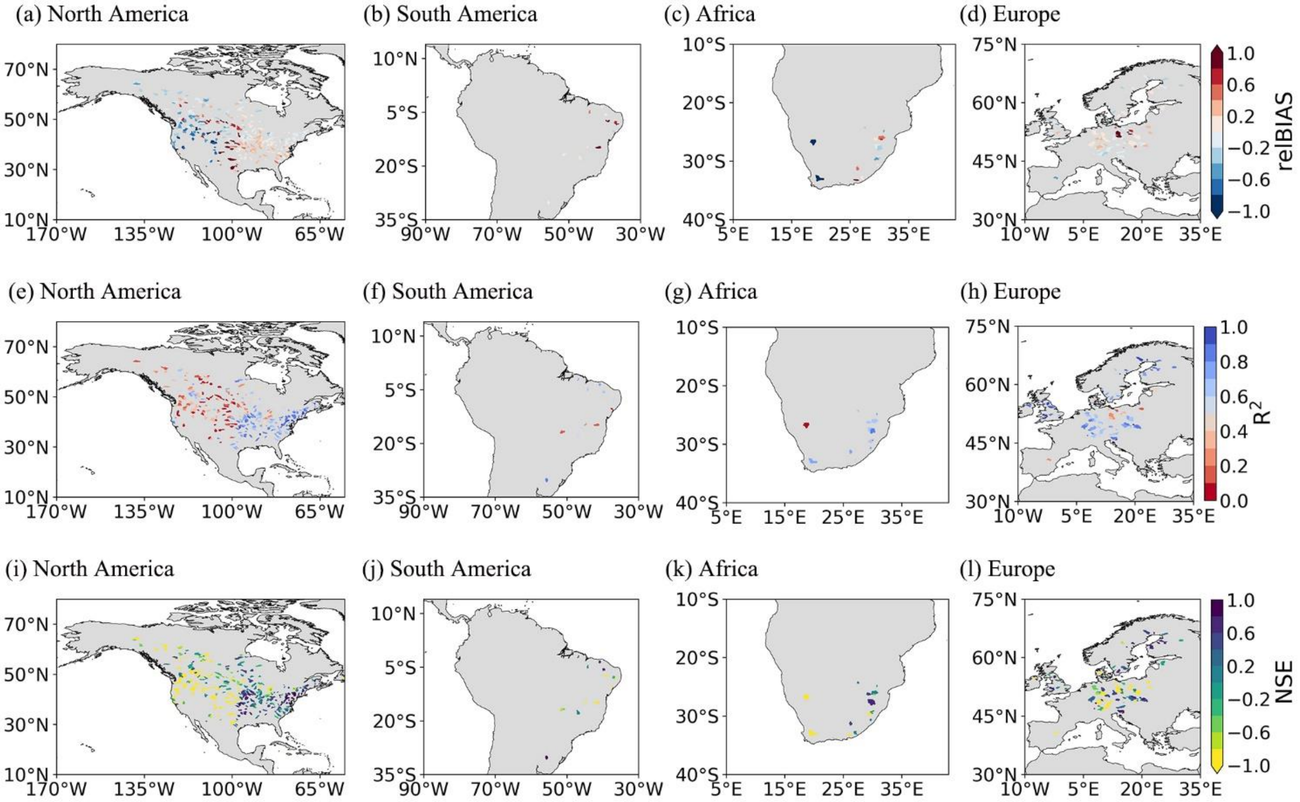


Figure 7. Spatial distribution of the skill scores of the reconstructed time-series runoff.

Additional minor comments:

Comment 6:

Line18 “global watersheds”

They are watersheds all over the globe (more or less). The term global watershed suggests that the watersheds covers the entire globe.

Later in the text you also use global to mean 'at various locations on the globe'. Perhaps rephrase these for more clarity.

Response:

Thanks for your consideration. In our study, we collected 726 records of hydrological data in 366 watersheds from globally published datasets for modeling, and used 17 years of runoff data in selected 545 GRDC stations for validation. To avoid confusion, we modified the relevant expression as follows,

“We firstly classified the selected 366 watersheds worldwide into six hydrologically similar groups based on watershed attributes, including climate, soil moisture, and vegetation.” (Lines 16-17 in the revised manuscript)

“Overall, 726 records of hydrological data in 366 watersheds from globally published datasets were collected for analyses (Supplement 1). These 366 watersheds were classified into six hydrologically similar groups according to the hydrologically homogenous attributes of watersheds using the Decision Tree Regressor method.” (Lines 78-81 in the revised manuscript)

“For the selected 545 GRDC watersheds, the annual runoff estimated by the PwM ranges from 229.84 to 320.34 mm, which is slightly lower than the observed range of GRDC (265.82 ~ 345.50 mm yr^{-1}) (Fig. 6a).” (Lines 256-257 in the revised manuscript)

“Generally, the proposed method not only represented the runoff observations in 366 watersheds from global published literatures, but could also reconstruct the time-series runoff in 545 GRDC stations." (Lines 358-360 in the revised manuscript)

Comment 7:

Line32 "Introduction"

The rationale of the work and its objectives are clearly presented here, but it would greatly help if you add a paragraph explaining the properties and meaning of parameter Pw.

Response:

Good idea. As your suggestion, we have added the properties and meaning of the Pw in the introduction, as follows,

"As a result, hydrologists have invested considerable efforts to improve model performance by introducing parameters related to watershed characteristics (watershed characteristic parameter, Pw) into the original Budyko equation. The popular parametric equations of the Budyko framework are presented in Table 1." (Lines 43-46 in the revised manuscript)

"From the hydrological point of view, the Pw controls the fraction of precipitation diverted into the runoff for a given aridity index (Caracciolo et al., 2018). Watersheds with larger Pw values converts larger parts of precipitation to evapotranspiration and consequently less part to runoff than those with smaller Pw value; and some studies defined the Pw as the water retention capacities of watersheds (Fu, 1981; Zhou et al., 2015). Overall, the Pw denotes the adjustment of water-energy partitioning by watershed characteristics (Yao et al., 2017; Li et al., 2013)." (Lines 50-54 in the revised manuscript)

Comment 8:

Line51-53 "Some of the introduced parametric equations include the Fu (Fu, 1981), Zhang (Zhang et al., 2001), Choudhury-Yang (Yang et al., 2008), and Wang-Tang equations (Wang and Tang, 2014)."

There are many more equations. Is there a particular reason for focusing on this subset?

Response:

Thanks for your question. The Fu (Fu, 1981), Zhang (Zhang et al., 2001), Choudhury-Yang (Choudhury, 1999), and Wang-Tang (Wang and Tang, 2014) equations are the popular Budyko-type parametric equations. They have been proven the good performance in previous studies (Guan et al., 2022; Caracciolo et al., 2018). Among the parametric equations, Fu's equation has received the most application and turned out to be a more generalized form (Zhou et al., 2015). So, we focused on this subset and used Fu's equation to analyze the Pw in the Budyko framework.

Comment 9:

Line54 "Table 1." To make this table intelligible on its own, please provide units or dimensions for all variables, as well as their range, if and when appropriate.

Response:

Good idea. As your suggestion, we have added the units of variables, and the theoretical range and reference values of Pw in the table1, as follows,

Table 1. Parametric Budyko-type formulations (Pw - watershed characteristic parameter; ET - actual evaporation, R - runoff, P - precipitation, PET - potential evapotranspiration, all in mm yr^{-1}).

Reference	Formulation	Pw (Theoretical range)	Reference values of Pw

Budyko (1974)	$\frac{ET}{P} = \left[\frac{PET}{P}\tanh\left(\frac{PET}{P}\right)^{-1}(1-exp(-\frac{PET}{P}))\right]^{0.5}$	0.5	0.5
Zhang et al. (2001)	$\frac{ET}{P} = \frac{1+w\frac{PET}{P}}{1+w\frac{PET}{P}+(\frac{PET}{P})^{-1}}$	w (0, ∞)	Trees – 2.0, Plants – 0.5
Turc (1954), Mezentsev (1955), Choudhury (1999), Yang et al. (2008)	$\frac{ET}{P} = \frac{1}{\left[1+(\frac{P}{PET})^{n}\right]^{\frac{1}{n}}}$	n (0, ∞)	Field – 2.6, River basins – 1.8
Wang and Tang (2014)	$\frac{ET}{P} = \frac{1+\frac{PET}{P}-\sqrt{(1+\frac{PET}{P})^{2}-4\varepsilon(2-\varepsilon)\frac{PET}{P}}}{2\varepsilon(2-\varepsilon)}$	ε (0,1)	0.55 - 0.58
Tixeront (1964), Fu (1981), Zhou et al. (2015)	$\frac{R}{P} = \left[1+\left(\frac{P}{PET}\right)^{-m}\right]^{\frac{1}{m}} - (\frac{P}{PET})^{-1}$	m (1, ∞)	Forest – 2.83, Shrub – 2.33, Grassland or cropland – 2.28, Mixed land – 2.12

(Lines 47-49 in the revised manuscript)

Comment 10:

"Table 1." "Fu (1981)" This parenthesis must go.

Response:

Sorry for neglecting. We have carefully reviewed the relevant formulas and revised them.

Comment 11:

Line56-57 "taking into account the influence of watershed characteristics"

Please explain how.

Response:

Thank you. The parametric Budyko-type formulations introduced the parameters related to watershed characteristics (Pw, i.e., *w* in Zhang equations, *n* in Yang equations, and *m* in Fu equations) to control the fraction of precipitation diverted into the runoff for a given aridity index(Caracciolo et al., 2018), and denote the adjustment of water-energy partitioning by watershed characteristics (Yao et al., 2017; Li et al., 2013). To explain this more clearly, in our revised manuscript, we have rewritten this section, as follows,

"From the hydrological point of view, the Pw controls the fraction of precipitation diverted into the runoff for a given aridity index (Caracciolo et al., 2018). Watersheds with larger Pw values converts larger parts of precipitation to evapotranspiration and consequently less part to runoff than those with smaller Pw value; and some studies defined the Pw as the water retention capacities of watersheds (Fu, 1981; Zhou et al., 2015). Overall, the Pw denotes the adjustment of water-energy partitioning by watershed characteristics (Yao et al., 2017; Li et al., 2013).

During the past decades, researchers have done lots of work to quantify the Pw for the accurate simulation of evapotranspiration or runoff using the Budyko framework (Wang et al., 2022; Yao et al., 2017; Guo et al., 2019; Yu et al., 2021) and made considerable contributions for improving the estimation of Pw by taking into account the influences from watershed characteristics (Fu, 1981; Liu and Liang, 2015; Guan et al., 2022; Yang et al., 2008)."

(Lines 50-58 in the revised manuscript)

Comment 12:

Line59-60 “watershed characteristic parameter (Pw)”

This parameter does not appear in any of the equations of Table 1. Please introduce it a bit better, clarify its role, and how it connects to the equations you introduced before.

Response:

Thank you. The watershed characteristic parameter is w in the Zhang equations, n in the Yang equations, ε in the Wang and Tang equations, and m in the Fu equations. In the revised manuscript, we have listed the Pw symbol of the parametric Budyko-type formulations to show how the Pw relates to the equations in Table. 1. Subsequently, we have added the descriptions of the role of Pw in the introduction. The modifications are as follows,

“As a result, hydrologists have invested considerable efforts to improve model performance by introducing parameters related to watershed characteristics (watershed characteristic parameter, Pw) into the original Budyko equation. The popular parametric equations of the Budyko framework are presented in Table 1.

Table 1. Parametric Budyko-type formulations (Pw - watershed characteristic parameter; ET - actual evaporation, R - runoff, P - precipitation, PET - potential evapotranspiration, all in mm yr^{-1}).

Reference	Formulation	Pw (Theoretical range)	Reference values of Pw
Budyko (1974)	$\frac{ET}{P}=\left[\frac{PET}{P}\tanh\left(\frac{PET}{P}\right)^{-1}(1-exp(-\frac{PET}{P}))\right]^{0.5}$	0.5	0.5
Zhang et al. (2001)	$\frac{ET}{P}=\frac{1+w\frac{PET}{P}}{1+w\frac{PET}{P}+(\frac{PET}{P})^{-1}}$	w (0, ∞)	Trees – 2.0, Plants – 0.5
Turc (1954), Mezentsev (1955), Choudhury (1999), Yang et al. (2008)	$\frac{ET}{P}=\frac{1}{\left[1+(\frac{P}{PET})^{n}\right]^{\frac{1}{n}}}$	n (0, ∞)	Field – 2.6, River basins – 1.8
Wang and Tang (2014)	$\frac{ET}{P}=\frac{1+\frac{PET}{P}-\sqrt{(1+\frac{PET}{P})^{2}-4\varepsilon(2-\varepsilon)\frac{PET}{P}}}{2\varepsilon(2-\varepsilon)}$	ε (0,1)	0.55 - 0.58
Tixeront (1964), Fu (1981), Zhou et al. (2015)	$\frac{R}{P}=\left[1+\left(\frac{P}{PET}\right)^{-m}\right]^{\frac{1}{m}}-(\frac{P}{PET})^{-1}$	m (1, ∞)	Forest – 2.83, Shrub – 2.33, Grassland or cropland – 2.28, Mixed land – 2.12

From the hydrological point of view, the Pw controls the fraction of precipitation diverted into the runoff for a given aridity index (Caracciolo et al., 2018). Watersheds with larger Pw values converts larger parts of precipitation to evapotranspiration and consequently less part to runoff than those with smaller Pw value; and some studies defined the Pw as the water retention capacities of watersheds (Fu, 1981; Zhou et al., 2015). Overall, the Pw denotes the adjustment of water-energy partitioning by watershed characteristics (Yao et al., 2017; Li et al., 2013).” (Lines 43-54 in the revised manuscript)

Comment 13:

Line71-73 "Although many studies have researched the relationship between the Pw and various watershed characteristics factors, they have shown contradictory results."

This appears to contradict line 60-61. Apparently, it is not a terribly convincing parameter according to some. In the next paragraph it becomes clear where you are going with your line of thinking, so perhaps it is OK to leave the text as it is.

Response:

Thanks for your consideration. Previous studies have proved that the parametric Budyko-type formulations have better performance than non-parametric equations by assigning empirical value to Pw (Guan et al., 2022). However, the further study found that Pw values varied greatly in different watersheds and deviate from the previously given empirical value (Zhang et al., 2018). During the past decades, researchers have done lots of work to quantify the Pw for the accurate simulation of evapotranspiration or runoff using the Budyko framework (Wang et al., 2022; Yao et al., 2017; Guo et al., 2019; Yu et al., 2021) and made considerable contributions for improving the estimation of Pw by taking into account the influences from watershed characteristics (Fu, 1981; Liu and Liang, 2015; Guan et al., 2022; Yang et al., 2008). Although previous studies still differed greatly as to what factors and effects should relate to the Pw and failed to give a general framework for quantifying the Pw, the Pw is undeniably a very important parameter for the Budyko Framework. Therefore, more in-depth studies are in need for revisiting the hydrological Basis of Pw in the Budyko Framework. In the revised manuscript, we rewrote this section to describe that in detail.

"During the past decades, researchers have done lots of work to quantify the Pw for the accurate simulation of evapotranspiration or runoff using the Budyko framework (Wang et al., 2022; Yao et al., 2017; Guo et al., 2019; Yu et al., 2021) and made considerable contributions for improving the estimation of Pw by taking into account the influences from watershed characteristics (Fu, 1981; Liu and Liang, 2015; Guan et al., 2022; Yang et al., 2008). Although there is agreement that the Pw represents the integrated effects of various environmental factors (Wang et al., 2022; Liu et al., 2022; Yu et al., 2021; Gan et al., 2021), studies still differed greatly as to what factors and effects should relate to the Pw and failed to give a general framework for quantifying the Pw. For instance, whether the Pw in the Budyko framework is controlled by vegetation or not has been much debated. Ning et al. (2017) found that the Pw generally had a positive correlation with vegetation coverage. Zhang et al. (2018) obtained the sensitivity of the Pw to changes in LAI by taking a derivative of the Pw function with respect to LAI, implying a crucial role of vegetation cover in impacting the Pw. However, some other studies indicated that most regions or watersheds show no significant influences of vegetation indices or coverage on Pw (Li et al., 2013; Liu et al., 2021). For example, Li et al. (2013) pointed out the variations in the Pw values are not entirely controlled by vegetation coverage in the small catchments. Another study from Liu et al. (2021) also found a weak correlation between the vegetation leaf area index and the Pw. Therefore, more in-depth studies are in need for revisiting the hydrological Basis of Pw in the Budyko Framework." (Lines 55-69 in the revised manuscript)

Comment 14:

Line96 "PET"

Was that not labeled ET_sub_zero above? If yes, make the notation consistent throughout.

Response:

Thanks for your consideration. As your suggestion, the abbreviated symbol for potential evapotranspiration was unified as PET in our revised manuscript.

Comment 15:

Line118 "the new Fu's formula"

To me it appears to be exactly the same as Fu's equation in Table 1 if m is set equal to w.
So, what is new about it? Because you did not explain the meaning of Pw above we cannot tell.
Response:

Thank you for your question. The “new Fu’s formula” in the original manuscript is the variation form of Fu’s formula. We have changed “the new Fu’s formula” to “the Fu’s formula” in the revised manuscript.

Comment 16:
Line123 “m is a dimensionless integration constant”
There is no integration carried out. Also, integration constants by definition cannot have a limited range of validity.
Response:

Thank you, according to your comments, we have changed the “a dimensionless integration constant” to “a dimensionless constant”.

Comment 17:
Line124-125 “Based on the randomly selected 726 samples from global hydrological studies, we derived the Pw (m) values for each sample.”
How? Did you fit Eq. (1) to catchments with R, P, and PET observed?
Response:

Thanks for your question. First, we calculated the R/P and P/PET for each site by using collected and extracted the R, P, and PET data. Then, we derived the Pw values according to Equation 1. In the revised manuscript, we have added relevant descriptions in Sect. 3.1 as follows,

“Using collected and extracted the R, P and PET data, we calculated the R/P and P/PET for each site. Then, we derived the Pw values according to Equation 1.” (Lines 105-107 in the revised manuscript)

Comment 18:
Line129 “variable”
'any suitable watershed characteristic variable'
Response:

Thanks. we have changed “the relationship between Pw and a variable does not change substantially in a hydrologically similar group” to “the relationship between Pw and the watershed characteristic variable does not change substantially in a hydrologically similar group” in the revised manuscript.

Comment 19:
Line132 “soil moisture (SM)”
How do you define this? For me it is a volume fraction occupied by liquid water, but in Table 3 it is larger than 1.
Response:

Thanks. The soil moisture (SM) in our study is the water that is in the upper 10 cm of soil extracted from GLDAS Noah Land Surface Model L4 and its unit is kg m^{-2}. To be consistent with the units of runoff depth, we changed the units of SM to “mm” representing the depth of water in the 10cm soil layer. In the revised manuscript, we have made the following modifications to the relevant parts,

“The watershed characteristic factors selected in this study include surface soil moisture (0-10cm underground, SM), fractional vegetation cover (FVC) and seasonal index (SI) of Walsh and Lawler (1981).” (Lines 133-134 in the revised manuscript)

Table 2. Data sources for watershed characteristic factors

Watershed characteristic factors	Data source/version	Units	Reference
Surface soil moisture (0-10cm underground, SM)	GLDAS Noah Land Surface Model L4	mm	Rodell et al. (2004)
Fractional vegetation cover (FVC)	GLASS FVC V4	$m^2\ m^{-2}$	Liang et al. (2021)
Seasonal index (SI)	CRU TS dataset version 4.03, global maps of seasonality indices	dimensionless	Walsh and Lawler (1981);Feng (2019)

(Lines 139-140 in the revised manuscript)

Comment 20:

Line148 “x_i represents the input variables”

Only the ith one, it is not a vector, otherwise the summation makes no sense.

Is there a reason why you made the model additive, and not multiplkicative, for instance?

Response:

(1) For the symbol of the input variables

We have redefined the symbol of the input variable in Equation 2 as follows,

“We performed regression analysis between the Pw and watershed characteristic variables to determine the input variables of the PwM. The variables whose R^2 of the regression model was greater than 0.1 were selected as input variables. We used a polynomial as the basic model form. Each term of the polynomial depends on the regression model of the corresponding variable and the Pw. For each hydrological group, the PwM is modeled as a function as,

$$Pw = \sum Coef\_n \times f(Var\_n) \tag{2}$$

where Pw represents the value of the Pw; Var_n represents the input variable that pass the regression test; f corresponds to the function derived from the regression of Pw on Var_n; $Coef\_n$ represents the empirical coefficient fitted by multiple non-linear regression (MNR).” (Lines 160-167 in the revised manuscript)

(2) Reasons for using addition

On the one hand, we want to set up the model with the simplest possible operations. The polynomial in addition is one of the simplest operations. On the other hand, error scales linearly with addition, and scales up to be proportional to your original data with multiplication. To avoid the extreme error that may be caused by the original data, we chose a more conservative addition as the basic operational framework.

Comment 21:

Line163

The outer brackets are not needed.

Response:

Thank you. We have done as suggested.

Comment 22:

Line192 “(10)”

Is this an emprical upper limit of m? It does not arise from the structure of the equation.

Line193-194 “extremely unlikely”

Well, you have around 700 catchments and many years of discharge data for each of them. There are bound to be a few very unlikely recharge events in your dataset.

Response:

Thank you for your question. Yes, 10 is an empirical value of Pw (i.e., m in Fu's equation). The Budyko approach was developed based on water balance concepts, so we need to assume that the watersheds in question are "conservative" (i.e., precipitation is the sum of streamflow and evapotranspiration). However, the natural watersheds with a large Pw value may be "non-conservative", because part of the water remain in the watershed may come from groundwater flow and other hardly or not measurable flows. To be more cautious, in this study, the empirical upper limit for Pw was 10 to ensure that the watersheds in question were conservative. In this regard, we have added the following contents in the revised manuscript,

"where R/P is a dimensionless annual water yield coefficient; P/PET is an aridity index; and Pw is a dimensionless constant varying from 1 to infinity, and represents water retention capacity for evapotranspiration. When Pw=1, all the precipitation would become flow and the residence time is 0. When Pw→infinity, all precipitation would remain in the watershed and residence time would equal the time for all precipitation conversion to evapotranspiration. So, the natural watersheds with a large Pw value may be "non-conservative" (i.e., precipitation is not the sum of streamflow and evapotranspiration), because part of the water remains in the watershed may come from groundwater flow and other hardly or not measurable flows. To be more cautious, in this study, the empirical upper limit for Pw was 10 to ensure that the watersheds in question were conservative." (Lines 90-97 in the revised manuscript)

Comment 23:

Line221 "SM is soil moisture (kg m-2); FVC is fractional vegetation cover (m2 m-2)."

This information needs to be given on first occurrence, and for the other variables as well.

How deep is the soil layer for which SM is provided?

You use equivalent water layers (mm) for water throughout. Why not be consistent and report soil moisture as mm as well? The numbers won't change.

Response:

Thanks. As your suggestion, the properties and units of the variables were given in the section of data. The soil moisture (SM) in our study is the water that is in the upper 10 cm of soil extracted from GLDAS Noah Land Surface Model L4 and its unit is kg m^{-2}. According to your suggestion, we changed the unit of SM to "mm" representing the depth of water in the 10cm soil layer to make it consistent with the units of runoff depth. The changes in the revised manuscript are as follows,

"Table 1. Parametric formulations of the Budyko framework (Pw - watershed characteristic parameter; ET - actual evaporation, R - runoff, P - precipitation, PET - potential evapotranspiration, all in mm yr-1)." (Lines 47-48 in the revised manuscript)

Table 2. Data sources for watershed characteristic factors

Watershed characteristic factors	Data source/version	Units	Reference
Surface soil moisture (0-10cm underground, SM)	GLDAS Noah Land Surface Model L4	mm	Rodell et al. (2004)
Fractional vegetation cover (FVC)	GLASS FVC V4	m^2 m^{-2}	Liang et al. (2021)
Seasonal index (SI)	CRU TS dataset version 4.03, global maps of seasonality indices	dimensionless	Walsh and Lawler (1981);Feng (2019)

(Lines 139-140 in the revised manuscript)

Comment 24:

Line242-243 "(c) Difference between the R/P values from the PmM and the published observations."

The color scale is not very clear in the middle range.

Response:

Thank you. We changed the color of the figure as follows,

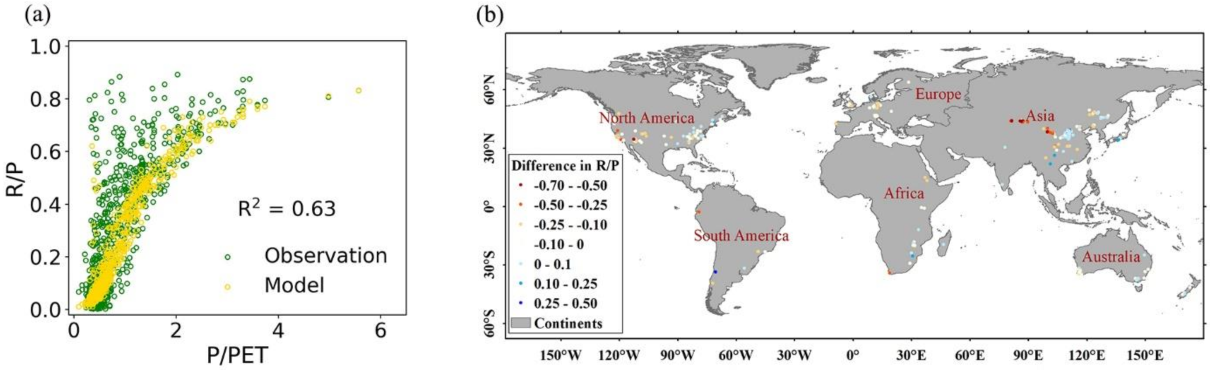


Figure 5. Simulated R/P using PwM in comparison with the observations collected from published literatures. (a) Scatter plots between R/P (yellow: simulation; green: observations) and P/PET; (b) Difference between simulated R/P from the PmM and observations from the published datasets. (Lines 251-254 in the revised manuscript)

Comment 25:

Line248-249 "the value of the lower adjacent larger than zero"

Unclear, please rephrase.

Response:

Thank you. We have modified this statement as follows,

"The grouped NSE scores show more uncertainty than the overall, especially in the IN$_{WMS}$: the lower adjacent value (LAV) larger than zero indicates more skill than the mean of observations, however, the outliers are far below zero." (Lines 241-243 in the revised manuscript)

Comment 26:

Line253 "at bootstrapped works"

Unclear, please rephrase.

Response:

Thank you. We have modified this statement as follows,

"**Figure 4.** Cross-validation results of PwM for (a) IN$_{D}$, (b) IN$_{WP}$, (c) IN$_{WMS}$, (d) IN$_{WMM}$, (e) IN$_{WML}$, and (f) IN$_{WE}$." (Lines 250 in the revised manuscript)

Comment 27:

Line256 "global annual runoff"

Do you really mean the estimated runoff from all the landmasses of the Earth? Because your use of 'global' is sometimes ambiguous I am not sure here.

Response:

Thanks for your consideration. The global annual runoff here refers to the annual runoff estimated from the selected 545 GRDC watersheds. In the revised manuscript, we modified it as,

"For the selected 545 GRDC watersheds, the annual runoff estimated by the PwM ranges from 229.84 to 320.34 mm, which is slightly lower than the observed range of GRDC (265.82 ~ 345.50 mm yr^{-1}) (Fig. 6a)." (Lines 256-257 in the revised manuscript)

Comment 28:

Line282 "on a global scale"

You do the opposite: you refine the scale from global to continental.

Line283-288 "The temporal evolution of runoff is, in general, well captured, except in the western United States, where runoff was consistently underestimated. In addition, the runoff estimated by PwM is underestimated in 2011 to a greater extent than in other years. The regions where runoff was underestimated include the western United States and high latitudes in North America, and the runoff underestimation is more severe in the arid western United States than in the relatively wet northwest of North America."

You do the opposite: you refine the scale from global to continental.

Response:

Thanks for your consideration. To avoid confusion, we have rewritten this section, as follows,

"Figure 7 displays the skill scores of the reconstructed runoff by the PwM in comparison with the GRDC ensemble from 2000-2016. It can be seen that the result of reconstruction by PwM, in general, is satisfactory, as indicated by the RelBIAS close to 0. The underestimation of runoff mainly occurs in the high mountains of the western United States (Fig. 7a), when the runoff is much smaller. Humid regions such as the northeastern United States and the European Mediterranean area have quite high R^2 values, while lower values are observed in the Semi-arid (0.2≤Aridity Index<0.5) and the Dry sub-humid (0.5≤Aridity Index<0.65) regions, which are mainly located in the western and midwestern United States (Fig. 7e-h). There is low NSE scores in the watersheds where runoff is unusually under-estimated or over-estimated (Fig. 7i-l), especially in the western United States." (Lines 270-277 in the revised manuscript)

Comment 29:

Line300 "Discussion"

This section sometimes a bit wordy, but overall I like your analysis. Food for thought.

Response:

Thank you for your positive comments.

Comment 30:

Line327 "paradox"

It may be a contradiction, but it is by no means a paradox.

Response:

Thank you, according to your comments, we have changed the "paradox" to "confusion".

References

Budyko, M. I.: Climate and life, Academic press1974.

Caracciolo, D., Pumo, D., and Viola, F.: Budyko's based method for annual runoff characterization across different climatic areas: an application to United States, Water Resources Management, 32, 3189-3202, 2018.

Choudhury, B.: Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model, Journal of Hydrology, 216, 99-110, 1999.

Feng, X.: Global maps of seasonality indices, HydroShare [dataset], 2019.

Fu, B.: On the calculation of the evaporation from land surface, Chinese Journal of Atmospheric Sciences, 5, 23-31, 1981.

Gan, G., Liu, Y., and Sun, G.: Understanding interactions among climate, water, and vegetation with the Budyko framework, Earth-Science Reviews, 212, 103451, 2021.

Guan, X., Zhang, J., Yang, Q., and Wang, G.: Quantifying the effects of climate and watershed structure changes on runoff variations in the Tao River basin by using three different methods under the Budyko framework, Theoretical and Applied Climatology, 1-14, 2022.

Guo, A., Chang, J., Wang, Y., Huang, Q., Guo, Z., and Li, Y.: Uncertainty analysis of water availability assessment through the Budyko framework, Journal of Hydrology, 576, 396-407, 2019.

Li, D., Pan, M., Cong, Z., Zhang, L., and Wood, E.: Vegetation control on water and energy balance within the Budyko framework, Water Resources Research, 49, 969-976, 2013.

Liang, S., Cheng, J., Jia, K., Jiang, B., Liu, Q., Xiao, Z., Yao, Y., Yuan, W., Zhang, X., and Zhao, X.: The global land surface satellite (GLASS) product suite, Bulletin of the American Meteorological Society, 102, E323-E337, 2021.

Liu, J., You, Y., Zhang, Q., and Gu, X.: Attribution of streamflow changes across the globe based on the Budyko framework, Science of The Total Environment, 794, 148662, 2021.

Liu, Q. and Liang, L.: Impacts of climate change on the water balance of a large nonhumid natural basin in China, Theoretical and Applied Climatology, 121, 489-497, 2015.

Liu, S., Wang, X., Zhang, L., Kong, W., Gao, H., and Xiao, C.: Effect of glaciers on the annual catchment water balance within Budyko framework, Advances in Climate Change Research, 13, 51-62, 2022.

Mezentsev, V.: Back to the computation of total evaporation, Meteorologia i Gidrologia, 5, 24-26, 1955.

Ning, T., Li, Z., and Liu, W.: Vegetation dynamics and climate seasonality jointly control the interannual catchment water balance in the Loess Plateau under the Budyko framework, Hydrology and Earth System Sciences, 21, 1515-1526, 2017.

Rodell, M., Houser, P., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., and Bosilovich, M.: The global land data assimilation system, Bulletin of the American Meteorological society, 85, 381-394, 2004.

Tixeront, J.: Prediction of streamflow, IAHS publication, 118-126, 1964.

Turc, L.: The water balance of soils. Relation between precipitation, evaporation and flow, Ann. Agron, 5, 491-569, 1954.

Walsh, R. and Lawler, D.: Rainfall seasonality: description, spatial patterns and change through time, Weather, 36, 201-208, 1981.

Wang, D. and Tang, Y.: A one-parameter Budyko model for water balance captures emergent behavior in Darwinian hydrologic models, Geophysical Research Letters, 41, 4569-4577, 2014.

Wang, F., Xia, J., Zou, L., Zhan, C., and Liang, W.: Estimation of time-varying parameter in Budyko framework using long short-term memory network over the Loess Plateau, China, Journal of Hydrology, 607, 127571, 2022.

Yang, H., Yang, D., Lei, Z., and Sun, F.: New analytical derivation of the mean annual water-energy balance equation, Water resources research, 44, 2008.

Yao, J., Mao, W., Yang, Q., Xu, X., and Liu, Z.: Annual actual evapotranspiration in inland river catchments of China based on the Budyko framework, Stochastic Environmental Research and Risk Assessment, 31, 1409-1421, 2017.

Yu, K.-x., Zhang, X., Xu, B., Li, P., Zhang, X., Li, Z., and Zhao, Y.: Evaluating the impact of ecological construction measures on water balance in the Loess Plateau region of China within the Budyko framework, Journal of Hydrology, 601, 126596, 2021.

Zhang, L., Dawes, W., and Walker, G.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water resources research, 37, 701-708, 2001.

Zhang, S., Yang, Y., McVicar, T. R., and Yang, D.: An analytical solution for the impact of vegetation changes on hydrological partitioning within the Budyko framework, Water Resources Research, 54, 519-537, 2018.

Zhou, G., Wei, X., Chen, X., Zhou, P., Liu, X., Xiao, Y., Sun, G., Scott, D. F., Zhou, S., and Han, L.: Global pattern for the effect of climate and land cover on water yield, Nature communications, 6, 1-9, 2015.

Response to Reviewer#2

General Comments:

This manuscript proposes a framework to estimate the parameter of a parametric Budyko-type equation. The originality compared to other studies on the same issue is the preliminary classification of the catchments.

In general, I enjoyed reading the paper and some results are very interesting, e.g., the ambiguous role of soil moisture on the evaporative ratio. There are two major comments that I think the authors should respond.

Response:

Thank you for your positive comments. Your suggestions are very useful for us to improve our research. We revised our manuscript according to your comments. The changes in our manuscript are underlined with red. We believe our manuscript improved a lot after the modification. Please see the response below.

Major Comments of Reviewer 2#:

Comment 1:

Some methodological choices are not presented / enough discussed. See the exhaustive list in the minor comments below. Some key information is missing, e.g., the time step used for establishing the equations between m and vegetation fractions, and the settings of the classifier are not presented, as the output of the classification performance.

Response:

(1) For the time step

The time step used in our study is annual. For the collected datasets, the times of observation are discrete and discontinuous (listed in Supplement 1). The time range of verification datasets, including the data used for reconstructing runoff and the observed runoff data from GRDC, is from 2000 to 2016.

(2) For the classifier

In the revised manuscript, we further describe the setup and performance of classifier, as follows,

“Three watershed characteristic variables — surface soil moisture (SM), rainfall seasonality index (SI), and fractional vegetation cover (FVC) — were selected for classification. For SM and FVC, the bounded intervals of the variables were given by the Decision Tree Regressor (DTR). The locations of splits in DTR were used as dividing intervals. The Scikit-learn library (Pedregosa et al., 2011) in Python provides the DTR used in this study. The criterion for measuring the quality of the split was set to “poisson” which uses reduction in Poisson deviance to find splits. The “random” strategy was used to choose local optimal splitting at each node. The results and performances of DTR are shown in Supplement 2. Based on the criteria using by Walsh and Lawler (1981), we divided the SI into three parts (SI≤0.4, 0.4<SI≤0.8, SI>0.8) to represent three hydroclimatic seasonality (precipitation spread throughout the year, marked seasonality with a short drier season, extreme seasonality with a long drier season). Finally, six hydrologically similar groups were classified (Table 3).

Table 3. Classification of watersheds

Soil moisture classifier	Water soil regime	Seasonality index classifier	Seasonality precipitation regime	Fractional vegetation cover classifier	vegetation cover regime	Name of the group
SM≤20	Dry soil	——	——	——	——	IN$_{\mathrm{D}}$
SM>20	Wet soil	SI ≤ 0.4	Seasonless	——	——	IN$_{\mathrm{WP}}$
		0.4 < SI ≤ 0.8	Marked seasonality	FVC ≤ 0.2	Low density	IN$_{\mathrm{WMS}}$
				0.2 < FVC ≤ 0.5	Middle density	IN$_{\mathrm{WMM}}$
				FVC > 0.5	High density	IN$_{\mathrm{WML}}$
		SI > 0.8	Extreme seasonality	——		IN$_{\mathrm{WE}}$

” (Lines 148-157 in the revised manuscript)

Comment 2:

The added value of the classification step is not demonstrated. I suggest the authors compare the performance of the model with relationships for each group with the performance of the model when a single relationship is used for the whole catchment set. At this stage, the classification provides insights in terms of the physical processes but we cannot measure the added value of this refined description in terms of predicted runoff.

Response:

Good idea. In our revised manuscript, we have setup a prediction model without the hydrologically similar groups (non_PwM) to show the effect of grouping on the PwM. The Cross-validations result of the PwM and non_PwM show that the performance of the PwM with the hydrologically similar groups is better and more stable than that of the non_PwM. In the revised manuscript, we have added the description and analysis of this part.

“4.2.2 PwM without the hydrologically similar groups

For comparison, we estimated Pw without the hydrologically similar groups, defined as non_PwM. The non_PwM is as follows:

$$non\_Pw = a_1 \times SM^2 + a_2 \times SM + b_1 \times FVC^2 + b_2 \times FVC \tag{3}$$

where non_Pw is the annual value of Pw simulated by non_PwM; *SM* is annual average value of surface soil moisture (0-10cm underground); *FVC* is annual average value of fractional vegetation cover; a_1, a_2, b_1 and b_2 represent the empirical coefficient fitted by least square method.” (Lines 168-174 in the revised manuscript)

“5.2 Cross-validations based on data collected from globally published literatures

The performance of the PwM and non_PwM were cross-validated based on the data collected from globally published literatures using the bootstrap sampling method (Fig. 3). On average, the ensemble RelBIAS of the Pw simulated by the PwM is slightly negative (Fig. 3a), indicating a weak tendency to underestimate the values of Pw, but the maximum relative bias is less than 0.1. The interquartile range of R^2 for the PwM is from 0.35 to 0.40, with a median of 0.37. The scores of R^2 are higher than 0.3 in more than 95% of the bootstrap sampling events. The NSE skill scores show that in most bootstrap samplings, the estimation error estimated variance for the PwM is less than the variance of the observations (NSE > 0), with the interquartile range from 0.33 to 0.39. In comparison, the maximum relative bias of the Pw simulated by the non_PwM is 0.12, the median of R^2 is 0.13, and the median of NSE is 0.13. Overall, cross validations show that the performance of the PwM with the hydrologically similar groups is better and more stable than that of the non_PwM.

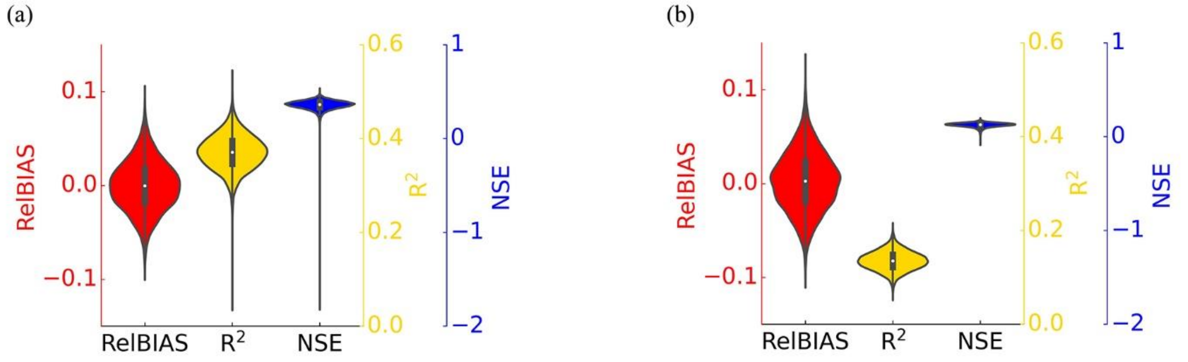


Figure 3. Cross-validation results of (a) PwM and (b) non_PwM. A violin represents the distribution of the considered skill scores. The white dot on the violin plot represents the median. The black bar in the center of the violin represents the interquartile range. Colors distinguish three performance metrics: Red (RelBIAS), yellow (R^2) and blue (NSE)." (Lines 222-237 in the revised manuscript)

Minor comments:

Comment 3:

l.48: Note that the climate seasonality is not taken into account in basic Budyko-type equations so the sentence needs modification, maybe change "climatic conditions" by "mean annual climatic conditions".

Response:

Thank you, according to your comments, we have changed the "climatic conditions" to "mean annual climatic conditions".

Comment 4:

Table 1: please add a column with the parameter to be calibrated, the analytical role of the parameter in the equation (increase/decrease of evaporative ratio with increasing parameter value) and it would be highly beneficial to the reader if some information on previous estimation/calibration of these parameters could be given in this table.

Response:

Thank you. We have added two columns in table 1. One column is used to list the symbols for the watershed characteristic parameter (Pw) and their theoretical range, and the other column is used to list the reference values of Pw in the previous research. Table 1 in the revised manuscript was modified as follows,

Table 1. Parametric Budyko-type formulations (Pw - watershed characteristic parameter; ET - actual evaporation, R - runoff, P - precipitation, PET - potential evapotranspiration, all in mm yr^{-1}).

Reference	Formulation	Pw (Theoretical range)	Reference values of Pw
Budyko (1974)	$\frac{ET}{P}=\left[\frac{PET}{P}\tanh\left(\frac{PET}{P}\right)^{-1}(1-exp(-\frac{PET}{P}))\right]^{0.5}$	0.5	0.5
Zhang et al. (2001)	$\frac{ET}{P}=\frac{1+w\frac{PET}{P}}{1+w\frac{PET}{P}+(\frac{PET}{P})^{-1}}$	w (0, ∞)	Trees – 2.0, Plants – 0.5
Turc (1954), Mezentsev (1955), Choudhury (1999), Yang et al. (2008)	$\frac{ET}{P}=\frac{1}{\left[1+(\frac{P}{PET})^{n}\right]^{\frac{1}{n}}}$	n (0, ∞)	Field – 2.6, River basins – 1.8
Wang and Tang (2014)	$\frac{ET}{P}=\frac{1+\frac{PET}{P}-\sqrt{(1+\frac{PET}{P})^{2}-4\varepsilon(2-\varepsilon)\frac{PET}{P}}}{2\varepsilon(2-\varepsilon)}$	ε (0,1)	0.55 - 0.58
Tixeront (1964), Fu (1981), Zhou et al. (2015)	$\frac{R}{P}=\left[1+\left(\frac{P}{PET}\right)^{-m}\right]^{\frac{1}{m}}-(\frac{P}{PET})^{-1}$	m (1, ∞)	Forest – 2.83, Shrub – 2.33, Grassland or cropland – 2.28, Mixed land – 2.12

(Lines 47-49 in the revised manuscript)

Comment 5:

l.58-63: At this stage of the manuscript, it is unclear what Pw stands for. Is it an a priori estimation of the parameters that are apparent in the equations of Table 1? To make things clearer the column of table 1 indicating the free parameter could be headed Pw.

Response:

Thanks for your question. The Pw is the w in Zhang equations, n in Yang equations, ε in Wang and Tang equations, and m in Fu equations. As you suggested, we have added a column for listing the symbol of Pw and their theoretical range respectively. The modifications are as follows,

"As a result, hydrologists have invested considerable efforts to improve model performance by introducing parameters related to watershed characteristics (watershed characteristic parameter, Pw) into the original Budyko equation. The popular parametric equations are presented in Table 1.

Table 1. Parametric Budyko-type formulations (Pw - watershed characteristic parameter; ET - actual evaporation, R - runoff, P - precipitation, PET - potential evapotranspiration, all in mm yr^{-1}).

Reference	Formulation	Pw (Theoretical range)	Reference values of Pw
Budyko (1974)	$\frac{ET}{P}=\left[\frac{PET}{P}\tanh\left(\frac{PET}{P}\right)^{-1}(1-exp(-\frac{PET}{P}))\right]^{0.5}$	0.5	0.5
Zhang et al. (2001)	$\frac{ET}{P}=\frac{1+w\frac{PET}{P}}{1+w\frac{PET}{P}+(\frac{PET}{P})^{-1}}$	w $(0,\infty)$	Trees – 2.0, Plants – 0.5
Turc (1954), Mezentsev (1955), Choudhury (1999), Yang et al. (2008)	$\frac{ET}{P}=\frac{1}{\left[1+(\frac{P}{PET})^{n}\right]^{\frac{1}{n}}}$	n $(0,\infty)$	Field – 2.6, River basins – 1.8
Wang and Tang (2014)	$\frac{ET}{P}=\frac{1+\frac{PET}{P}-\sqrt{(1+\frac{PET}{P})^{2}-4\varepsilon(2-\varepsilon)\frac{PET}{P}}}{2\varepsilon(2-\varepsilon)}$	ε $(0,1)$	0.55 - 0.58
Tixeront (1964), Fu (1981), Zhou et al. (2015)	$\frac{R}{P}=\left[1+\left(\frac{P}{PET}\right)^{-m}\right]^{\frac{1}{m}}-(\frac{P}{PET})^{-1}$	m $(1,\infty)$	Forest – 2.83, Shrub – 2.33, Grassland or cropland – 2.28, Mixed land – 2.12

(Lines 43-49 in the revised manuscript)

Comment 6:

l.67-68: Does it depend on the equation? Since the statement is general and not specific to a given equation, this needs more details.

Response:

Thanks for your question. These results are based on the parametric Budyko-type formulations. We have rewritten this fragment in the revised manuscript, detailing the relationship between the Pw and the watershed characteristic factors in previous studies.

“During the past decades, researchers have done lots of work to quantify the Pw for the accurate simulation of evapotranspiration or runoff using the Budyko framework (Wang et al., 2022; Yao et al., 2017; Guo et al., 2019; Yu et al., 2021) and made considerable contributions for improving the estimation of Pw by taking into account the influences from watershed characteristics (Fu, 1981; Liu and Liang, 2015; Guan et al., 2022; Yang et al., 2008). Although there is agreement that the Pw represents the integrated effects of various environmental factors (Wang et al., 2022; Liu et al., 2022b; Yu et al., 2021; Gan et al., 2021), studies still differed greatly as to what factors and effects should relate to the Pw and failed to give a general framework for quantifying the Pw. For instance, whether the Pw in the Budyko framework is controlled by vegetation or not has been much debated. Ning et al. (2017) found that the Pw generally had a positive correlation with vegetation coverage. Zhang et al. (2018) obtained the sensitivity of the Pw to changes in LAI by taking a derivative of the Pw function with respect to LAI, implying a crucial role of vegetation cover in impacting the Pw. However, some other studies indicated that most regions or watersheds show no significant influences of vegetation indices or coverage on Pw (Li et al., 2013; Liu et al., 2021). For example, Li et al. (2013) pointed out the variations in the Pw values are not entirely controlled by vegetation coverage in the small catchments. Another study from Liu et al. (2021) also found a weak correlation between vegetation leaf area index and the Pw. Therefore, more in-depth studies are in need for revisiting the hydrological Basis of Pw in the Budyko Framework.” (Lines 55-69 in the revised manuscript)

Comment 7:

l.72: The term “contradictory” is not appropriate. There is no clear consensus but some results are relatively consensual (e.g., positive relationship between Pw and vegetation cover).

Response:

Thank you, according to your comments, we have replaced the simple word "contradiction" with the description of the results of the previous studies. The details are as follows,

“During the past decades, researchers have done lots of work to quantify the Pw for the accurate simulation of evapotranspiration or runoff using the Budyko framework (Wang et al., 2022; Yao et al., 2017; Guo et al., 2019; Yu et al., 2021) and made considerable contributions for improving the estimation of Pw by taking into account the influences from watershed characteristics (Fu, 1981; Liu and Liang, 2015; Guan et al., 2022; Yang et al., 2008). Although there is agreement that the Pw represents the integrated effects of various environmental factors (Wang et al., 2022; Liu et al., 2022b; Yu et al., 2021; Gan et al., 2021), studies still differed greatly as to what factors and effects should relate to the Pw and failed to give a general framework for quantifying the Pw. For instance, whether the Pw in the Budyko framework is controlled by vegetation or not has been much debated. Ning et al. (2017) found that the Pw generally had a positive correlation with vegetation coverage. Zhang et al. (2018) obtained the sensitivity of the Pw to changes in LAI by taking a derivative of the Pw function with respect to LAI, implying a crucial role of vegetation cover in impacting the Pw. However, some other studies indicated that most regions or watersheds show no significant influences of vegetation indices or coverage on Pw (Li et al., 2013; Liu et al., 2021). For example, Li et al. (2013) pointed out the variations in the Pw values are not entirely controlled by vegetation coverage in the small catchments. Another study from Liu et al. (2021) also found a weak correlation between vegetation leaf area index and the Pw. Therefore, more in-depth studies are in need for revisiting the hydrological Basis of Pw in the Budyko Framework.” (Lines 55-69 in the revised manuscript)

Comment 8:

l.78: the term essential is debatable. Splitting into groups leads to non-universal laws. I agree this could lead to better performance and it is, therefore, to be tested but the motivations in terms of the physical process are

not clear at this stage of the manuscript. So the term essential is in my opinion too strong and I suggest changing it to "useful".

Response:

Thank you, according to your comments, we have changed the “essential” to “useful”.

Comment 9:

Data section: it is unclear why data are not taken homogeneously among published datasets and GRDC. The main caveat lies in the differences in the climatic forcing data (P and PET). Why not merge the data and use a single product to derive precipitation? Also, this would allow the authors to homogenize the calibration and validation datasets that appear largely different in terms of geographic locations (and climate settings). Also, is there a criterion on the number of years of data for including a catchment in the dataset? Last, it is not clear if climatic data are aggregated over catchment areas. Do the authors delineate catchment boundaries?

Response:

(1) Reasons for using published datasets and GRDC datasets

We used the published datasets for modeling and the GRDC data for verification of runoff reconstruction. All of the published data we collected in this study came from the conservative watersheds (i.e., precipitation is the sum of streamflow and evapotranspiration). We need to use such conservative watershed data for modeling. However, the time of collected datasets are discrete and discontinuous. To verify the performance of the model in time series, we used the GRDC data to verify reconstructed time-series runoff.

(2) Reasons for using GPCC precipitation data

Compared to the CRU TS precipitation dataset, the Global Precipitation Climatology Centre (GPCC) precipitation data was found to be more agreeable with the observation in the previous researches (Ahmed et al., 2019; Degefu et al., 2022; Fiedler and Döll, 2007; Hu et al., 2018; Salaudeen et al., 2021). Therefore, the P values for runoff reconstruction were extracted from GPCC Precipitation data. In the revised manuscript, we have added the explanation on the reasons for using GPCC precipitation data, as follows,

“The P values for runoff reconstruction were extracted from Global Precipitation Climatology Centre (GPCC) Precipitation Total Full V2018 (0.5×0.5) data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA. It is because that the Global Precipitation Climatology Centre (GPCC) precipitation data was found to be more agreeable with the observation in the previous researches compared to the CRU TS precipitation dataset(Ahmed et al., 2019; Degefu et al., 2022; Fiedler and Döll, 2007; Hu et al., 2018; Salaudeen et al., 2021)” (Lines 119-124 in the revised manuscript)

(3) The time range of datasets

For the collected datasets, the times of observation are discrete and discontinuous (listed in Supplement 1). The time range of verification datasets, including the data used for reconstructing runoff and the observed runoff data from GRDC, is from 2000 to 2016.

(4) The Climate data extraction method

For the GRDC watersheds, the climate data (including P and PET data) were extracted from grid data based on the boundary files provided by GRDC Watershed Boundaries (2011). For the collected watersheds from published literatures without boundary files, the PET data were extracted from grid data according to the coordinate points of these watersheds. We have added that description in the revised manuscript,

“Potential evapotranspiration (PET, mm yr^{-1}) data were downloaded from version 4.05 of the CRU TS (Climatic Research Unit gridded Time Series) climate dataset (https://doi.org/10.6084/m9.figshare.11980500), which is produced by the CRU at the University of East Anglia. For consistency, we used PET values extracted from the CRU TS dataset of all watersheds listed in Supplement 1, even for studies with PET values reported. The PET values were extracted based on the coordinate points of watersheds." (Lines 101-105 in the revised manuscript)

"We used the boundary of watersheds provided by GRDC Watershed Boundaries (2011) to extract the average values of PET and P from grid datasets for each watershed. The PET values were extracted from the CRU TS dataset. The P values for runoff reconstruction were extracted from Global Precipitation Climatology Centre (GPCC) Precipitation Total Full V2018 (0.5×0.5) data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA." (Lines 118-121 in the revised manuscript)

Comment 10:

l.95-96: Please indicate the formulation used for potential evaporation.

Response:

The potential evapotranspiration (PET, mm yr^{-1}) data were downloaded from version 4.05 of the CRU TS (Climatic Research Unit gridded Time Series) climate dataset (https://doi.org/10.6084/m9.figshare.11980500), which is produced by the CRU at the University of East Anglia. The formulation used for CRU TS potential evapotranspiration is as follows,

$$PET = \frac{0.408 \triangle (R_n - G) + \gamma \frac{900}{T + 273.16} U_2 (e_a - e_d)}{\triangle + \gamma (1 + 0.34 U_2)}$$

We have added this formula to Supplement 1.

Comment 11:

l.98-100: why not do the same for precipitation data?

Response:

Thank you for your question. Generally, the monitoring data of watershed stations are more accurate than the data extracted by remote sensing data. Modelling may be more beneficial by using climate data monitored from watersheds stations. However, many sites in the collected data set did not provide corresponding values for potential evapotranspiration. Therefore, we used potential evapotranspiration values extracted from the CRU TS dataset of all watersheds in the collected data set, and used precipitation data collected from published data sets.

Comment 12:

l.132-133: why these three watershed characteristics? why only three? why not topographic attributes? These watershed characteristics are not stationary, do the authors change the value of these characteristics each year, or do they use aggregated statistics?

Response:

Thank you. In natural watershed, there are many factors affecting Pw, including soil moisture, vegetation coverage, seasonality, topography and so on. However, the topographic factor has little influence by other factors and remains stable for a long time. Therefore, topographic features are not considered in this study. Additional watershed characteristic factors may be considered in future studies. In the discussion section of the revised manuscript, we put forward the direction of future research, as follows,

"Although the overall performance of PwM was satisfactory, we noted that the accuracy of the runoff simulated by the Budyko framework in some regions show either an overestimation or an underestimation. It is because the Pw in our study is only forced with soil moisture, seasonality index and fractional vegetation cover, and thus the estimated runoff could not clearly account for impacts from other drivers, like the effects of temperature anomalies and glacial meltwater on the hydrological regimes (Liu et al., 2022a). This is probably one of the main reasons for the severe underestimation of runoff in western North America and southern Europe (Fig. 7a, d). Future in-depth researches are in need to examine influences from other impact factors to improve the accuracy of Pw estimation in the Budyko framework.” (Lines 349-355 in the revised manuscript)

Comment 13:

l.133-139: it is not clear how the regression tree is parametrized and optimized. Is it a supervised or unsupervised classification? As stated in lines 130-131, it seems that the authors want a supervised classification, but this would require a preliminary calibration of m. Is the number of groups imposed by the authors or it is the result of a cross-calibration experiment?

Response:

Thanks for your consideration. Since watershed feature factor data are continuous data, we used Decision Tree Regressor (DTR) instead of Decision Tree Classification (DTC) to find the turning point of the relationship between Pw and SM, and Pw and FVC in the study. The DTR does not involve supervised classification or unsupervised classification. We used the locations of splits in DTR as dividing intervals. We further describe the setup and performance of classifier in the revised manuscript,

“Three watershed characteristic variables — surface soil moisture (SM), rainfall seasonality index (SI), and fractional vegetation cover (FVC) — were selected for classification. For SM and FVC, the bounded intervals of the variables were given by the Decision Tree Regressor (DTR). The locations of splits in DTR were used as dividing intervals. The Scikit-learn library (Pedregosa et al., 2011) in Python provides the DTR used in this study. The criterion for measuring the quality of the split was set to “poisson” which uses reduction in Poisson deviance to find splits. The “random” strategy was used to choose local optimal splitting at each node. The results and performances of DTR are shown in Supplement 2. Based on the criteria using by Walsh and Lawler (1981), we divided the SI into three parts (SI≤0.4, 0.4<SI≤0.8, SI>0.8) to represent three hydroclimatic seasonality (precipitation spread throughout the year, marked seasonality with a short drier season, extreme seasonality with a long drier season). Finally, six hydrologically similar groups were classified (Table 3).

Table 3. Classification of watersheds

Soil moisture classifier	Water soil regime	Seasonality index classifier	Seasonality precipitation regime	Fractional vegetation cover classifier	vegetation cover regime	Name of the group
SM≤20	Dry soil	——	——	——	——	IN$_{D}$
SM>20	Wet soil	SI ≤ 0.4	Seasonless	——	——	IN$_{WP}$
		0.4 < SI ≤ 0.8	Marked seasonality	FVC ≤ 0.2	Low density	IN$_{WMS}$
				0.2 < FVC ≤ 0.5	Middle density	IN$_{WMM}$
				FVC > 0.5	High density	IN$_{WML}$
		SI > 0.8	Extreme seasonality	——		IN$_{WE}$

” (Lines 148-157 in the revised manuscript)

Comment 14:

l.153-155: Not clear at this stage whether the time step is annual. Numerous studies pointed out the problems of using the Budyko-type equations on an annual time step. This should be taken into account by the authors.

Response:

Thanks for your consideration. The time step used in our study is annual.

Comment 15:

l.159-168: Are the metrics computed on each catchment or all catchment runoff values? What is the minimum number of years for considering a catchment? If the record periods are too short, the resulting performance

metrics might be meaningless.

Response:

Thank you. In the process of cross-validation (using the bootstrap sampling method), for the performance metrics, the term N is the number of test sets, i is the i^{th} value to be simulated by the trained PwM, and y_s and y_o are the simulated and observed series of test sets, respectively. In the process of runoff reconstruction verification, for the performance metrics, the terms y_s and y_o are the simulated and observed 17 years of each watershed, respectively. n the revised manuscript, we have added explanations on these terms,

"**4.3.2 Cross-validations using the bootstrap sampling method**

We used cross-validation to test the stability of the proposed PwM using the bootstrap sampling method. The collected public data were split into two parts, one for model training and the other for model validation. A subset of 60% of the data was randomly selected using the bootstrap sampling method for training PwM. The remaining 40% of the runoff data were used to evaluate the model performance using the validation metrics in section 4.3.1. For each metric, the term N is the number of test sets, i is the i^{th} value to be simulated by the trained PwM, and y_s and y_o are the simulated and observed series of test sets, respectively. The process was repeated randomly 10000 times. We documented the cross-validation result of each bootstrapping and showed them in the violin plot (Fig. 3).

4.3.3 Validations of GRDC time-series runoff reconstruction results

To further assess the model performance, we applied the proposed PwM into Fu's model to reconstruct the time-series runoff data of GRDC from 2000 to 2016. Finally, the time-series runoff data from 545 GRDC stations, which were selected by Sect. 3.1, were used to evaluate the model performance using the validation metrics in section 4.3.1. For each metric, the terms y_s and y_o represent the simulated and observed time-series runoff data, respectively." (Lines 190-202 in the revised manuscript)

Comment 16:

l.170: In the data section, the authors present a calibration and a validation dataset, now, they say they perform bootstrapping... Is it a bootstrapping on the calibration dataset?

Response:

Thank you. For cross-validation (using the bootstrap sampling method), we split the collected data set into two parts, one for model training and the other for model validation. A subset of 60% of the data was randomly selected using the bootstrap sampling method for training PwM. The remaining 40% of the runoff data were used to evaluate the model performance using the validation metrics in section 4.3.1. The process was repeated randomly 10000 times. For the use of data, we have made the detailed descriptions in the revised manuscript,

"**4.3.2 Cross-validations using the bootstrap sampling method**

We used cross-validation to test the stability of the proposed PwM using the bootstrap sampling method. The collected public data were split into two parts, one for model training and the other for model validation. A subset of 60% of the data was randomly selected using the bootstrap sampling method for training PwM. The remaining 40% of the runoff data were used to evaluate the model performance using the validation metrics in section 4.3.1. For each metric, the term N is the number of test sets, i is the i^{th} value to be simulated by the trained PwM, and y_s and y_o are the simulated and observed series of test sets, respectively. The process was repeated randomly 10000 times. We documented the cross-validation result of each bootstrapping and showed them in the violin plot (Fig. 3).

4.3.3 Validations of GRDC time-series runoff reconstruction results

To further assess the model performance, we applied the proposed PwM into Fu's model to reconstruct the time-series runoff data of GRDC from 2000 to 2016. Finally, the time-series runoff data from 545 GRDC stations, which were selected by Sect. 3.1, were used to evaluate the model performance using the validation metrics in section 4.3.1. For each metric, the terms y_s and y_o represent the simulated and observed time-series runoff data, respectively." (Lines

190-202 in the revised manuscript)

Comment 17:

l.180-201: I think this should be placed in the Data section.

Response:

Good idea. We have placed this to the data section, as follows,

“Observed river discharge data for validation were obtained from the Global Runoff Data Centre (GRDC, https://www.bafg.de/GRDC/EN/02_srvcs/21_tmsrs/riverdischarge_node.html). Only the GRDC stations meeting the following criteria were selected for further analysis: (1) The sites with continuous time-series runoff observations during the period 2000–2016 and corresponding SM, FVC, and SI were also available during such a period; (2) The drainage area reports can be found in the original data to provide area parameters for converting original flow volumes to runoff rates; (3) The geographical coordinates reports can be found in the original data and the shape of the drainage can be found in the GRDC Watershed Boundaries (2011); (4) The watersheds of “non-conservative” (m>10) and unrealistic runoff rates (m<1) are removed. Based on these criteria, 545 GRDC stations were selected for validation (Fig. 1). Then, the flow volumes of selected sites were converted to runoff rates (Ghiggi et al., 2019).” (Lines 108-117 in the revised manuscript)

Comment 18:

l.198-201: I think we can assume that the reader knows how to convert volumetric discharge to runoff depth.

Response:

Thank you. We have deleted this part as suggestion.

Comment 19:

Figure 2: not clear at all what is represented. FVC changes each year. Do the authors plot the aggregated FVC over the temporal range of measured streamflow? Do the calibrated m for each year or globally over the entire record period? Figure caption should detail each panel explicitly.

Response:

Thank you for your question. Figure 2 shows the regressions between Pw in Fu’s formula and watershed characteristic variables collected from globally published datasets. We performed regression analysis between the Pw and watershed characteristic variables to determine the input variables of the PwM. The variables whose R^2 of the regression model was greater than 0.1 were selected as input variables. We used a polynomial as the basic model form. Each term of the polynomial depends on the regression model of the corresponding variable and the Pw. Here, the FVC were the annual average values corresponding to the runoff observation period, and extracted by the coordinates of site from grid data.

We have redrawn Fig. 2 and modified the related description and analysis, as follows,

“We performed regression analysis between the Pw and watershed characteristic variables to determine the input variables of the PwM. The variables whose R^2 of the regression model was greater than 0.1 were selected as input variables. We used a polynomial as the basic model form. Each term of the polynomial depends on the regression model of the corresponding variable and the Pw. For each hydrological group, the PwM is modeled as a function as,

$$Pw = \sum Coef\_n \times f(Var\_n) \quad (2)$$

where *Pw* represents the value of the Pw; *Var_n* represents the input variable that pass the regression test; *f* corresponds to the function derived from the regression of *Pw* on *Var_n*; *Coef_n* represents the empirical coefficient fitted by multiple non-linear regression (MNR).” (Lines 158-167 in the revised manuscript)

"The regressions between Pw in Fu's formula and watershed characteristic variables collected from globally published datasets are shown in Fig. 2. Analyses show that soil moisture (SM) and fractional vegetation cover (FVC) are strongly correlated to Pw in each group. The Pw values in dry watersheds with SM≤20mm monotonically increases with SM following a power function (Fig. 2a). However, in humid watersheds with SM>20mm, the Pw values converts to monotonically decrease with SM, which is also in a power function (Fig. 2b). And the fractional vegetation cover (FVC) shows linearly correlated with the Pw values of watersheds in most hydrologically similar groups but differ greatly between different groups (Fig. 2c-h). There is positive linear correlation between Pw and FVC in the IN_{D}, IN_{WSS} and IN_{WE} groups; while the relationship turns to be a negative linear equation in the IN_{WMM} and IN_{WML} groups. However, in the IN_{WP} group, the relationship between Pw and FVC is not significant. Therefore, in the proposed PwM, SM and FVC were selected as input variables (i.e., *Var_n*) for all the groups, except that FVC was rejected in the IN_{WP} group. The formula in PwM for calculating the Pw is modeled as sum of a power function of SM and a linear function of FVC, given by Equation 7." (Lines 205-215 in the revised manuscript)

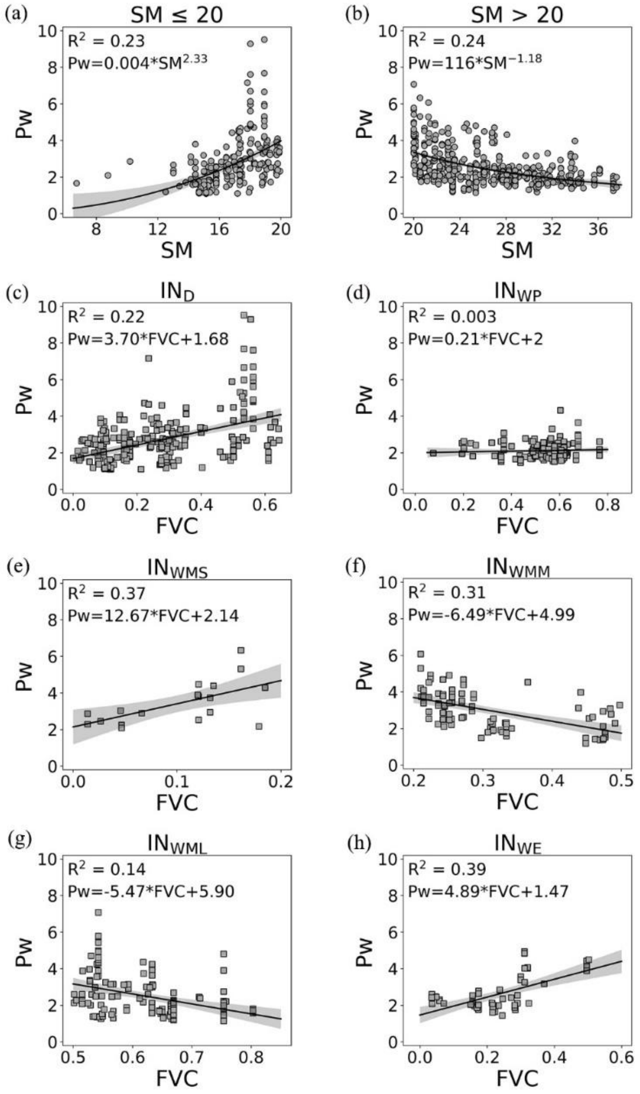


Figure 2. Regression between Pw in Fu's formula and (a) SM (SM≤20mm), (b)SM (SM>20mm), (c)FVC (IN_{D}), (d)FVC (IN_{WP}), (e)FVC (IN_{WMS}), (f)FVC (IN_{WMM}), (g)FVC (IN_{WML}), and (h)FVC (IN_{WE}). Symbol shapes indicate SM (dot) and FVC (square).

References

Ahmed, K., Shahid, S., Wang, X., Nawaz, N., and Khan, N.: Evaluation of gridded precipitation datasets over arid regions of Pakistan, Water, 11, 210, 2019.

Budyko, M. I.: Climate and life, Academic press1974.

Choudhury, B.: Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model, Journal of Hydrology, 216, 99-110, 1999.

Degefu, M. A., Bewket, W., and Amha, Y.: Evaluating performance of 20 global and quasi-global precipitation products in representing drought events in Ethiopia I: Visual and correlation analysis, Weather and Climate Extremes, 35, 100416, 2022.

Fiedler, K. and Döll, P.: Global modelling of continental water storage changes–sensitivity to different climate data sets, Advances in Geosciences, 11, 63-68, 2007.

Fu, B.: On the calculation of the evaporation from land surface, Chinese Journal of Atmospheric Sciences, 5, 23-31, 1981.

Gan, G., Liu, Y., and Sun, G.: Understanding interactions among climate, water, and vegetation with the Budyko framework, Earth-Science Reviews, 212, 103451, 2021.

Ghiggi, G., Humphrey, V., Seneviratne, S. I., and Gudmundsson, L.: GRUN: an observation-based global gridded runoff dataset from 1902 to 2014, Earth System Science Data, 11, 1655-1674, 2019.

GRDC: Watershed Boundaries of GRDC Stations / Global Runoff Data Centre, Federal Institute of Hydrology (BfG) [dataset], 2011.

Guan, X., Zhang, J., Yang, Q., and Wang, G.: Quantifying the effects of climate and watershed structure changes on runoff variations in the Tao River basin by using three different methods under the Budyko framework, Theoretical and Applied Climatology, 1-14, 2022.

Guo, A., Chang, J., Wang, Y., Huang, Q., Guo, Z., and Li, Y.: Uncertainty analysis of water availability assessment through the Budyko framework, Journal of Hydrology, 576, 396-407, 2019.

Hu, Z., Zhou, Q., Chen, X., Li, J., Li, Q., Chen, D., Liu, W., and Yin, G.: Evaluation of three global gridded precipitation data sets in central Asia based on rain gauge observations, International Journal of Climatology, 38, 3475-3493, 2018.

Li, D., Pan, M., Cong, Z., Zhang, L., and Wood, E.: Vegetation control on water and energy balance within the Budyko framework, Water Resources Research, 49, 969-976, 2013.

Liu, J., You, Y., Zhang, Q., and Gu, X.: Attribution of streamflow changes across the globe based on the Budyko framework, Science of The Total Environment, 794, 148662, 2021.

Liu, Q. and Liang, L.: Impacts of climate change on the water balance of a large nonhumid natural basin in China, Theoretical and Applied Climatology, 121, 489-497, 2015.

Liu, S.-W., Wang, X., Zhang, L., Kong, W.-M., Gao, H.-K., and Xiao, C.-D.: Effect of glaciers on the annual catchment water balance within Budyko framework, Advances in Climate Change Research, 13, 51-62, 2022a.

Liu, S., Wang, X., Zhang, L., Kong, W., Gao, H., and Xiao, C.: Effect of glaciers on the annual catchment water balance within Budyko framework, Advances in Climate Change Research, 13, 51-62, 2022b.

Mezentsev, V.: Back to the computation of total evaporation, Meteorologia i Gidrologia, 5, 24-26, 1955.

Ning, T., Li, Z., and Liu, W.: Vegetation dynamics and climate seasonality jointly control the interannual catchment water balance in the Loess Plateau under the Budyko framework, Hydrology and Earth System Sciences, 21, 1515-1526, 2017.

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., and Dubourg, V.: Scikit-learn: Machine learning in Python, the Journal of machine Learning research, 12, 2825-2830, 2011.

Salaudeen, A., Ismail, A., Adeogun, B. K., Ajibike, M. A., and Zubairu, I.: Evaluation of ground-based, daily, gridded precipitation products for Upper Benue River basin, Nigeria, Engineering and Applied Science Research, 48, 397-405, 2021.

Tixeront, J.: Prediction of streamflow, IAHS publication, 118-126, 1964.

Turc, L.: The water balance of soils. Relation between precipitation, evaporation and flow, Ann. Agron, 5, 491-569, 1954.

Walsh, R. and Lawler, D.: Rainfall seasonality: description, spatial patterns and change through time, Weather, 36, 201-208, 1981.

Wang, D. and Tang, Y.: A one-parameter Budyko model for water balance captures emergent behavior in Darwinian hydrologic models, Geophysical Research Letters, 41, 4569-4577, 2014.

Wang, F., Xia, J., Zou, L., Zhan, C., and Liang, W.: Estimation of time-varying parameter in Budyko framework using long short-term memory network over the Loess Plateau, China, Journal of Hydrology, 607, 127571, 2022.

Yang, H., Yang, D., Lei, Z., and Sun, F.: New analytical derivation of the mean annual water-energy balance equation, Water resources research, 44, 2008.

Yao, J., Mao, W., Yang, Q., Xu, X., and Liu, Z.: Annual actual evapotranspiration in inland river catchments of China based on the Budyko framework, Stochastic Environmental Research and Risk Assessment, 31, 1409-1421, 2017.

Yu, K.-x., Zhang, X., Xu, B., Li, P., Zhang, X., Li, Z., and Zhao, Y.: Evaluating the impact of ecological construction measures on water balance in the Loess Plateau region of China within the Budyko framework, Journal of Hydrology, 601, 126596, 2021.

Zhang, L., Dawes, W., and Walker, G.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water resources research, 37, 701-708, 2001.

Zhang, S., Yang, Y., McVicar, T. R., and Yang, D.: An analytical solution for the impact of vegetation changes on hydrological partitioning within the Budyko framework, Water Resources Research, 54, 519-537, 2018.

Zhou, G., Wei, X., Chen, X., Zhou, P., Liu, X., Xiao, Y., Sun, G., Scott, D. F., Zhou, S., and Han, L.: Global pattern for the effect of climate and land cover on water yield, Nature communications, 6, 1-9, 2015.

Response to Vazken Andréassian:

General Comments:

I apologize for posting this note about what you may consider as "details".

But:

Response:

Thank you for your comments. Your suggestions are very useful for us to improve our research. We revised our manuscript according to your comments. The changes in our manuscript are underlined with red. We believe our manuscript improved a lot after the modification. Please see the response below.

Comment 1:

the formula that you identify as "Yang et al (2008)" is much older than that: Turc in 1954 and Mezentsev in 1955 published it simultaneously. If you had read Fu (1981), which you cite, you would have heard about Mezentsev, because Fu cites him.

the formula of Fu (1981) was previously published by a French hydrologist, Tixeront in 1964 (but this citation is more difficult to find, I acknowledge it)

Response:

Thank you, according to your comments, we have supplemented the relevant literature in Table 1.

Table 1. Parametric Budyko-type formulations (Pw - watershed characteristic parameter; ET - actual evaporation, R - runoff, P - precipitation, PET - potential evapotranspiration, all in mm yr^{-1}).

Reference	Formulation	Pw (Theoretical range)	Reference values of Pw
Budyko (1974)	$\frac{ET}{P} = \left[\frac{PET}{P}\tanh\left(\frac{PET}{P}\right)^{-1}(1-exp(-\frac{PET}{P}))\right]^{0.5}$	0.5	0.5
Zhang et al. (2001)	$\frac{ET}{P} = \frac{1+w\frac{PET}{P}}{1+w\frac{PET}{P}+(\frac{PET}{P})^{-1}}$	w $(0, \infty)$	Trees – 2.0, Plants – 0.5
Turc (1954), Mezentsev (1955), Choudhury (1999), Yang et al. (2008)	$\frac{ET}{P} = \frac{1}{\left[1+(\frac{P}{PET})^{n}\right]^{\frac{1}{n}}}$	n $(0, \infty)$	Field – 2.6, River basins – 1.8
Wang and Tang (2014)	$\frac{ET}{P} = \frac{1+\frac{PET}{P}-\sqrt{(1+\frac{PET}{P})^{2}-4\varepsilon(2-\varepsilon)\frac{PET}{P}}}{2\varepsilon(2-\varepsilon)}$	ε $(0,1)$	0.55 - 0.58
Tixeront (1964), Fu (1981), Zhou et al. (2015)	$\frac{R}{P} = \left[1+\left(\frac{P}{PET}\right)^{-m}\right]^{\frac{1}{m}} - (\frac{P}{PET})^{-1}$	m $(1, \infty)$	Forest – 2.83, Shrub – 2.33, Grassland or cropland – 2.28, Mixed land – 2.12

(Lines 45-47 in the revised manuscript)

Comment 2:

the seasonality index of Walsh and Lawler (1981) is extremely weak in that it only deals with rainfall, it does

not address the issue of the relative seasonnality of P and E (and after all, all Budyko's framework is about comparing P and E). I would suggest you have at least a look at the work we published on that topic (de Lavenne & Andréassian, 2018).

Response:

Thank you. We have carefully studied the seasonal index λ you proposed, and thought that was a great algorithm for the indication of seasonality. We tried to use it for our modeling. However, the results of the simulations were not better than those using the seasonality index of Walsh and Lawler (1981).

We used the seasonal index λ (De Lavenne and Andréassian, 2018) instead of the seasonal index of Walsh and Lawler (1981) for classification, and reset the model (λ_PwM) to estimate Pw. Based on the results of the Decision Tree Regressor (DTR) (Fig. S.1), we divided the λ into three parts (λ≤0.3, 0.3<λ≤0.5, λ>0.5) to represent three hydroclimatic seasonality (low, Medium and High synchronicity of precipitation and potential evapotranspiration). The classifications of surface soil moisture (SM) and fractional vegetation cover (FVC) remain the same as the original. Finally, six hydrologically similar groups were classified (Table S.1).

Table S.1 Classification of watersheds

Soil moisture classifier	Water soil regime	Seasonality index classifier	Seasonality regime	Fractional vegetation cover classifier	vegetation cover regime	Name of the group
SM≤20	Dry soil	——	——	——	——	IN_{D}
SM>20	Wet soil	λ≤ 0.3	Low synchronicity	——	——	IN_{WL}
		0.3 <λ≤ 0.5	Medium synchronicity	FVC ≤ 0.2	Low density	IN_{WMS}
				0.2 < FVC ≤ 0.5	Middle density	IN_{WMM}
				FVC > 0.5	High density	IN_{WML}
		λ> 0.5	High synchronicity	——		IN_{WH}

The regressions between Pw in Fu's formula and watershed characteristic variables collected from globally published datasets are shown in Fig. S.2. The variables whose R^2 of the regression model was greater than 0.1 were selected as input variables. Therefore, in the proposed λ_PwM, SM and FVC were selected as input variables for all the groups, except that FVC was rejected in the IN_{WL}, IN_{WMS}, and IN_{WML} group. The formula in λ_PwM for calculating the Pw is modeled as the sum of a power function of SM and a linear function of FVC, given by Equation S.1.

$$\lambda\_\boldsymbol{Pw} = \begin{cases} \mathbf{0.91} \times \boldsymbol{SM}^{\mathbf{0.38}} + \mathbf{1.48} \times \boldsymbol{FVC} & (IN_D, SM \leq 20) \\ \mathbf{0.0003} \times \boldsymbol{SM}^{\mathbf{-3.02}} & (IN_{WL}, SM > 20, \lambda \leq 0.3) \\ \mathbf{7.82} \times \boldsymbol{SM}^{\mathbf{-0.36}} & (IN_{WMS}, SM > 20, 0.3 < \lambda \leq 0.5, FVC \leq 0.2) \\ \mathbf{31.14} \times \boldsymbol{SM}^{\mathbf{-0.67}} - \mathbf{0.59} \times \boldsymbol{FVC} & (IN_{WMM}, SM > 20, 0.3 < \lambda \leq 0.5, 0.2 < FVC \leq 0.5) \\ \mathbf{73.15} \times \boldsymbol{SM}^{\mathbf{-1.06}} & (IN_{WML}, SM > 20, 0.3 < \lambda \leq 0.5, FVC > 0.5) \\ \mathbf{24.86} \times \boldsymbol{SM}^{\mathbf{-0.67}} - \mathbf{0.85} \times \boldsymbol{FVC} & (IN_{WH}, SM > 20, \lambda > 0.5) \end{cases} \quad \text{(S.1)}$$

The performance of the PwM and λ_PwM were cross-validated based on the data collected from globally published literatures using the bootstrap sampling method (Fig. S.3). On average, the maximum relative bias of the Pw simulated by the PwM is 0.09. The interquartile range of R^2 for the PwM is from 0.35 to 0.40, with a median of 0.37. The NSE interquartile range from 0.33 to 0.39, with a median of 0.36. In comparison, the maximum relative bias of the Pw simulated by the non_PwM is 0.12, the median of R^2 is 0.31, and the median of NSE is 0.30. Overall, the cross-validations show that the performance of the PwM is better and more stable than the λ_PwM. Therefore, in this study, we still use the seasonality index of Walsh and Lawler (1981).

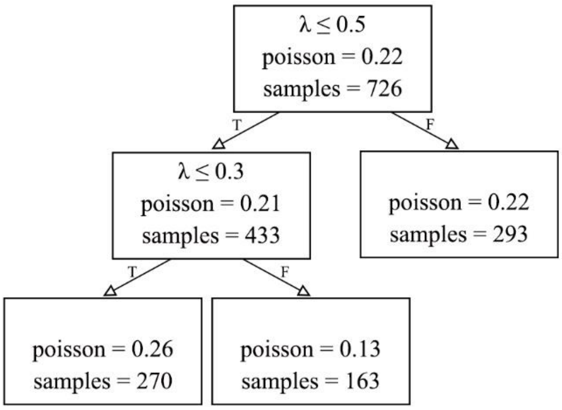


Figure S.1 The results of the Decision Tree Regressor for ensemble seasonal index λ. The “poisson” indicates the value of Poisson deviance, “samples” indicates the number of samples, “T” means True, and “F” means Fales.

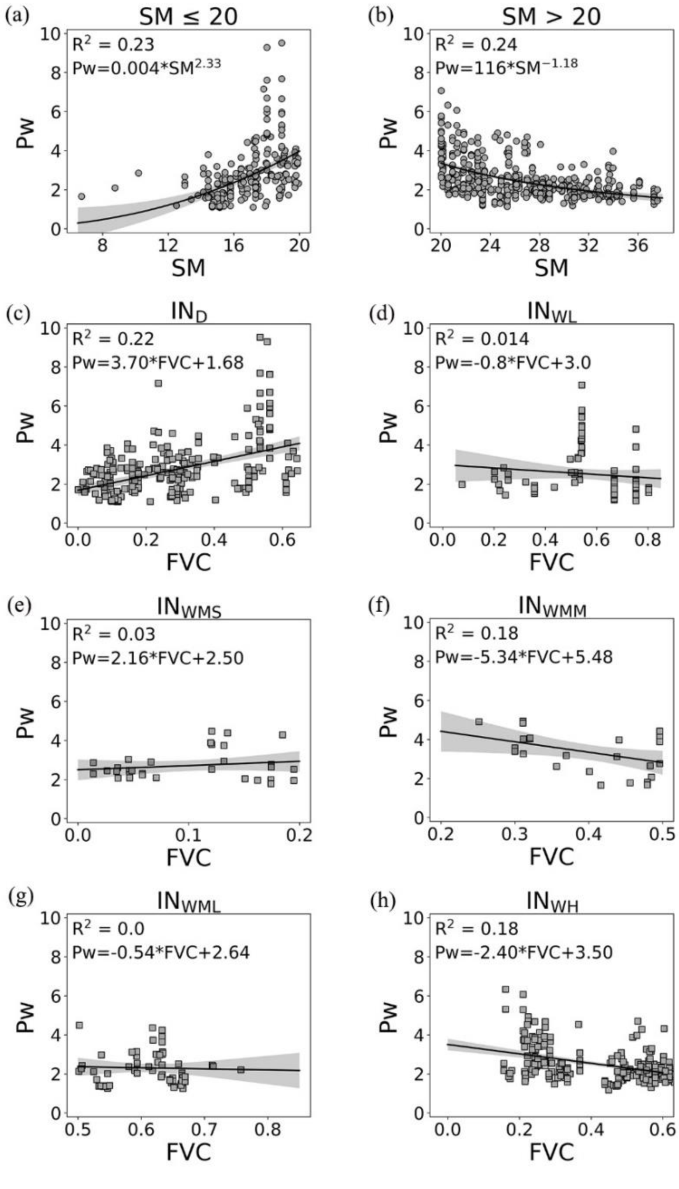


Figure S.2 Regression between Pw in Fu’s formula and (a) SM (SM≤20mm), (b)SM (SM>20mm), (c)FVC (IN_D), (d)FVC (IN_{WL}), (e)FVC (IN$_{WMS}$), (f)FVC (IN$_{WMM}$), (g)FVC (IN$_{WML}$), and (h)FVC (IN$_{WH}$). Symbol shapes indicate SM (dot) and FVC (square).

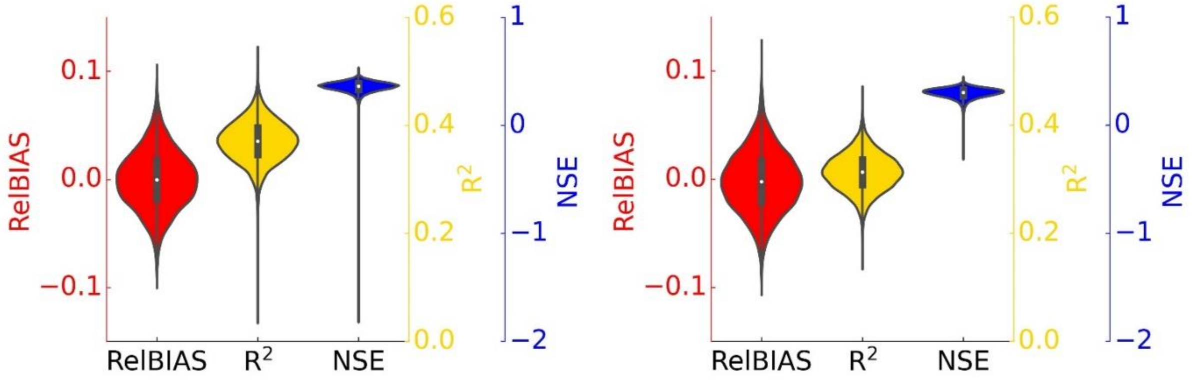


Figure S.3 Cross-validation results of (a) PwM and (b) λ_PwM. A violin represents the distribution of the considered skill scores. The white dot on the violin plot represents the median. The black bar in the center of the violin represents the interquartile range. Colors distinguish three performance metrics: Red (RelBIAS), yellow (R2) and blue (NSE).

References

Budyko, M. I.: Climate and life, Academic press1974.

Choudhury, B.: Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model, Journal of Hydrology, 216, 99-110, 1999.

De Lavenne, A. and Andréassian, V.: Impact of climate seasonality on catchment yield: A parameterization for commonly-used water balance formulas, Journal of Hydrology, 558, 266-274, 2018.

Fu, B.: On the calculation of the evaporation from land surface, Chinese Journal of Atmospheric Sciences, 5, 23-31, 1981.

Mezentsev, V.: Back to the computation of total evaporation, Meteorologia i Gidrologia, 5, 24-26, 1955.

Tixeront, J.: Prediction of streamflow, IAHS publication, 118-126, 1964.

Turc, L.: The water balance of soils. Relation between precipitation, evaporation and flow, Ann. Agron, 5, 491-569, 1954.

Walsh, R. and Lawler, D.: Rainfall seasonality: description, spatial patterns and change through time, Weather, 36, 201-208, 1981.

Wang, D. and Tang, Y.: A one-parameter Budyko model for water balance captures emergent behavior in Darwinian hydrologic models, Geophysical Research Letters, 41, 4569-4577, 2014.

Yang, H., Yang, D., Lei, Z., and Sun, F.: New analytical derivation of the mean annual water-energy balance equation, Water resources research, 44, 2008.

Zhang, L., Dawes, W., and Walker, G.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water resources research, 37, 701-708, 2001.

Zhou, G., Wei, X., Chen, X., Zhou, P., Liu, X., Xiao, Y., Sun, G., Scott, D. F., Zhou, S., and Han, L.: Global pattern for the effect of climate and land cover on water yield, Nature communications, 6, 1-9, 2015.