Budyko framework
towards non-steady state conditions

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Budyko framework; towards non-steady state conditions

Abstract

The Budyko framework was first developed to estimate actual evaporation as a function of precipitation and the aridity index at steady state conditions. Based on this framework, the water storage change in the watershed is assumed to be negligible at large spatial and temporal scales. However, steady state conditions are not valid for many watersheds worldwide or at finer temporal or spatial scales. Accordingly, the application of the Budyko framework has become challenging for these situations. Therefore, many researchers have tried to extend the Budyko framework for non-steady state conditions. The aim of this study is to provide a review of the extended equations and to discuss about using the Budyko framework in a changing world. While the extended equations are more complex than the original ones, they require less data. Thus, the Budyko framework, either the original or the extended can be a very useful tool for hydrological modeling with lots of applications, especially in data scarce regions.

Keywords

Budyko, Aridity index, Hydrological Modeling, Anthropogenic Activities, Non-steady state conditions.

1-**Introduction**

Estimating water balance components is an important part of hydrological modeling. The relationship between mean annual precipitation, actual and potential evaporation and runoff at watershed scale was explained by several physical, empirical and statistical hydrological models (Budyko, 1974, 1958; Fu, 1981; Gerrits et al., 2009; Mezentsev, 1955; Porporato et al., 2004; Yang et al., 2008). Hydrological models can be classified into lumped and distributed models, where lumped models are often simpler in favor or less computation time in comparison to distributed models. In spite of considerable progress in technology and computational power, the calibration of fully distributed models with many parameters is still a challenging issue with the problems of equifinality (Beven, 1996, 1993).

The Budyko framework can be considered as a lumped model and is a quick first-order estimate of precipitation partitioning into evaporation and runoff. It is simple and has little input requirements compared to complex hydrological models, such as the semi-distributed SWAT (Arnold et al., 1998) or the fully-distributed model AFFDEF (Moretti and Montanari, 2007). Next to giving a first-order estimate of evaporation (Gerrits et al., 2009; Tekleab et al., 2011; Zhang et al., 2008), the Budyko framework is also used for studying the sensitivity of runoff to changes in climate variables and characteristics of the catchments (Liu et al., 2013; Sankarasubramanian and Vogel, 2002, 2001; Sun et al., 2014; Yang et al., 2014), investigate the impact of climate change on the hydrological response of catchments and long-term water availability for water resources management (Donohue et al., 2007; Liu and Yang, 2010; Mcvicar et al., 2007; Teng et al., 2012), and separating the impact of natural climate change and direct human activities on the change in mean annual runoff (Jiang et al., 2015; Roderick and Farquhar, 2011; Wang and Hejazi, 2011).

While the origins of the Budyko framework are ranging back to the beginning of the 20th century (Ol'dekop, 1911; Schreiber, 1904), the framework was firstly developed by Budyko (1958), who introduced a simple relationship between mean annual actual evaporation, mean annual precipitation and aridity index at the watershed scale, known as the Budyko curve. He assumed that mean annual evaporation is controlled by water availability, approximated by precipitation and atmospheric demand, represented by net radiation. In very dry regions of the world with sufficient energy available for evaporation, annual evaporation may approach annual precipitation (water limitation). On the contrary, in very wet regions, annual evaporation may approach atmospheric demand or potential evaporation (energy limitation). Depending on the dryness of the region, the available water or the available energy limits evaporation as expressed by the following equations (Budyko, 1958):

$$\frac{E}{P} \to 1 \ \text{ when } \frac{R_n}{P} \to \infty \quad \text{(very dry conditions)} \tag{1}$$

$$E \to R_n \ \text{ when } \frac{R_n}{P} \to 0 \quad \text{(very wet conditions)} \tag{2}$$

in which, E, P, and R_n are mean annual evaporation, mean annual precipitation and net radiation. The Budyko framework is obtained based on the water and energy balance, as described by Arora (2002):

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P - Q - E \tag{3}$$

$$R_n = \rho \lambda E + H + G \tag{4}$$

where $\mathrm{d}S$ is the water storage change over time $\mathrm{d}t$, Q is the catchment runoff, λ is the latent heat of vaporization, ρ is the density of water, H the sensible heat flux, and G the ground heat flux. At mean annual scale, the water storage change over time ($\mathrm{d}S/\mathrm{d}t$) and net ground heat flux (G) is assumed to be negligible. Furthermore, it is assumed that the sensible heat flux is positive. Dividing equation 4 by P, the following equation is obtained:

$$\frac{R_n}{P} = \frac{\rho \lambda E}{P} + \frac{H}{P} \tag{5}$$

By considering $R_n = \rho \lambda E_p$ and $B_r = \frac{H}{\rho \lambda E}$ (B_r: Bowen ratio), equation 5 can be rewritten as:

$$\frac{E_p}{P} = \frac{E}{P} + \frac{B_r E}{P} = \phi = \frac{E}{P}(1 + B_r) \tag{6}$$

The Bowen ratio is a function of the aridity index ($\phi = \frac{E_p}{P}$). Therefore, by rearranging equation 6, the general Budyko equation is obtained:

$$\frac{E}{P} = \frac{\phi}{1 + f(\phi)} = F(\phi) = F(\frac{E_p}{P}) \tag{7}$$

Equation 7 is the so-called Budyko hypothesis, which was first introduced by Schreiber (1904) and written in this form by Arora (2002). This equation indicates that the water balance is mainly controlled by the macro-climate of the catchment. However, several researchers suggested that the water balance is also controlled by dynamic interactions between climate, soil and vegetation characteristics (Donohue et al., 2007; Li et al., 2013; Milly, 1994; Padrón et al., 2017; Potter et al., 2005; Williams et al., 2012; Xu et al., 2013) and hence some different curves were provided accordingly. Additionally, the Budyko framework was firstly developed for the steady state conditions in the catchments. In these conditions, the watershed must be natural, closed and the only source of available water for evaporation is the local precipitation (Du et al., 2016). Furthermore, the water storage change in the watershed is assumed to be negligible at large spatial and temporal scales. However, for many watersheds worldwide or at finer temporal or spatial scales, the steady state conditions are not valid. Many previous studies showed that hydrological processes are under influence of natural and anthropogenic change (Frans et al., 2013; Istanbulluoglu et al., 2012; Li et al., 2014; Vogel et al., 2011; Zhang and Schilling, 2006). The human interference with nature such as urbanization, groundwater withdrawal, deforestation, and land cover alteration caused significant changes in the natural hydrological cycle and water balance of most catchments worldwide. For example, transferring water from another basin through the inter-basin water transfer projects (Bonacci and Andri, 2010) or applying water as irrigation for the water requirement of the crops in dry regions (Gordon et al., 2005) would increase water availability for evaporation. Such situations caused a new concept to be emerged in the context of hydrology: socio-hydrology (Sivapalan et al., 2012), in which human activities are taking into account as a central part of hydrological modeling. Furthermore, at finer temporal scales, high variability of the water storage content becomes an important issue of the water balance in the Budyko framework (Wang et al., 2009; Yokoo et al., 2008; Zhang et al., 2008). Therefore, most watersheds are under non-steady state conditions, for which the application of the original Budyko framework has become challenging. As a consequence, many researchers have tried to extend the Budyko framework to be applicable for non-steady state conditions.

An extensive review of the advances in hydrological modeling with the Budyko framework has been provided by Wang et al. (2016) mainly for steady state conditions with little focus on non-steady state conditions. Therefore, in this paper, we focus on the advances in the Budyko framework for non-steady state conditions. However, for better understanding the non-steady state conditions, we first provide a short history of the Budyko curves for steady state conditions in Section 2. Both parametric and non-parametric equations will be discussed and then the non-steady state equations will be provided in Section 3. In Section 4, we discuss the way the Budyko framework may be matured and converted to a robust tool in prediction processes.

2-Budyko framework under steady state conditions: a short overview

2-1-Non-parametric equations

Schreiber (1904) developed the first Budyko equation to model annual flow, without any explicit knowledge about the physical base of the framework:

$$\frac{Q}{P} = \exp\left(-\frac{k}{P}\right) \tag{8}$$

where k is an empirical constant. Ol'dekop (1911) rewrote Schreiber's equation by replacing the empirical constant by long-term average potential evaporation and proposed the following equation, which is a function of the aridity (Andréassian et al., 2016):

$$\frac{E}{P} = 1 - \exp\left(-\frac{E_p}{P}\right) = 1 - \exp(-\phi) \tag{9}$$

This equation shows that evaporation depends on the available water (P) and the potential evaporation (E_p). Afterward, by analyzing the data in some catchments in Russia, Ol'dekop (1911) found that the evaporation ratio could be better described by a hyperbolic tangent -

function instead of an exponential one. He suggested that the curve must have “a slope of 45° for the tangent at the origin, [and] the slope must then decrease until finally, the curve turns parallel to the abscissa axis” (Andréassian et al., 2016; Ol’dekop, 1911). Then, based on the data from several catchments, he found that the hyperbolic tangent is the most suitable function and thus, he provided the following equation:

$$\frac{E}{P} = \phi \tanh\left(\frac{1}{\phi}\right) = \frac{E_p}{P} \tanh\left(\frac{P}{E_p}\right) \tag{10}$$

Further, based on empirical evidence, Budyko (1948) found that the data lay between the curves of Schreiber (1904) and Ol’dekop (1911) and, therefore, he suggested a new equation which was the geometrically the mean of those two equations.

$$\frac{E}{P} = \left(\frac{E_p}{P} \tanh\left(\frac{P}{E_p}\right)(1 - \exp(-\frac{E_p}{P})\right)^{0.5} \tag{11}$$

Based on more data, Budyko (1951) and Budyko and Zubenok (1961) found that the proposed curve was applicable for large basins at the long-term mean annual time scale. Afterwards other researchers developed new equations in various forms within the Budyko framework. For example, based on new data and considering the constraints of water and energy availability (Andreassian and Sari, 2019), Turc (1954) empirically proposed, the following equation:

$$\frac{E}{P} = \frac{1}{\sqrt{0.9 + \left(\frac{1}{\phi}\right)^2}} = \frac{1}{\sqrt{0.9 + \left(\frac{P}{E_p}\right)^2}} \tag{12}$$

This equation was updated by Pike (1964), who found that replacing 0.9 by 1 in equation 12 gave better results. The new equation was named as Turc-Pike equation. The equations mentioned above (equations 9-12) have a numerical behavior in a similar manner (Fig. 1) (Arora, 2002).

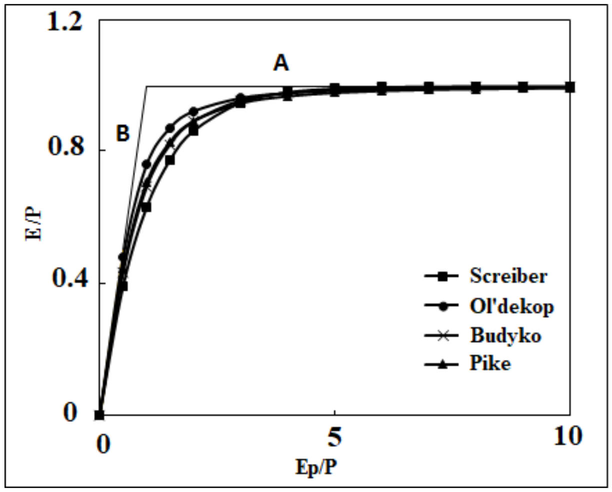

Figure 1- The non-parametric Budyko curves. "A" and "B" are asymptotes representing the water-limited and energy-limited lines, respectively.

2-2- Parametric equations

Some researchers attempted to feed the equations by more physics and provide theoretical and physical support for the Budyko framework. A summary of these attempts is provided in Table 1. Accordingly, Fu (1981) developed a new analytical model based on phenomenological considerations with dimensional analysis and mathematical reasoning. The new model is expressed as follows (Zhang et al., 2004):

$$\frac{E}{P} = 1 + \frac{E_p}{P} - \left[1 + \left(\frac{E_p}{P}\right)^{\omega}\right]^{\frac{1}{\omega}} \tag{13}$$

In this equation, ω is the model parameter representing the catchment characteristics ($\omega \in [1, \infty)$).

By assuming that the potential evaporation rate is constant, the arrival of precipitation events has a Poisson distribution, the events are instantaneous, and that the storm depths are independent with an exponential distribution, Milly (1993) developed the following equation:

$$\frac{E}{P} = \frac{\exp\left[\alpha\left(1 - \frac{P}{E_p}\right)\right] - 1}{\exp\left[\alpha\left(1 - \frac{P}{E_p}\right)\right] - \frac{P}{E_p}} \tag{14}$$

with α the ratio of soil water holding capacity to the mean storm depth. Milly's work indicated that the storage capacity of the root zone has an important role in controlling evaporation.

Later, Milly (1994) indicated that for a constant climate (no seasonality), evaporation is equal to the maximum of precipitation or potential evaporation. It can be stated that when precipitation and potential evaporation are in phase (out of phase), the catchments plot closer to (away from) the asymptotes (Budyko and Zubenok, 1961). Milly (1994) mentioned that other reasons for this deviation are the water-holding capacity of the root zone, infiltration capacity of the soil, and the rate of water flow toward the plant roots. He further proposed and tested a supply–demand-storage hypothesis, in which the long-term water balance is determined only by the interaction between local precipitation (as supply) and potential evaporation (as demand), mediated by soil water storage. According to his proposed hypothesis, the partitioning of mean annual precipitation into runoff and evaporation is under the influence of seven dimensionless variables.

Choudhury (1999) attempted to assess if the non-parametric empirical equations are independent of the spatial scale. For this purpose, he investigated the effects of spatial variations of precipitation and net radiation (R_n) on evaporation using a generalized form of the empirical equation of Pike (1964). Choudhury (1999) added an adjustable parameter a which is related to the characteristics of soil, topography, and vegetation of the catchment (Xu et al., 2014) and changes between spatial scales of micrometeorological measurements (areas ca. 1 km^2) and large river basins (areas ca. 10^6 km^2).

$$\frac{E}{P} = \frac{1}{\left(1 + \left(\frac{P}{R_n}\right)^a\right)^{\frac{1}{a}}} \qquad (15)$$

Zhang et al. (2001) found that plant-available water coefficient (w), which is representative of the type of vegetation, has an important role on partitioning precipitation into evaporation and runoff and proposed the following equation:

$$\frac{E}{P} = \frac{1 + w\frac{E_p}{P}}{1 + w\frac{E_p}{P} + \left(\frac{E_p}{P}\right)^{-1}} \qquad (16)$$

Sankarasubramanian and Vogel (2002) used the “abcd” model and developed an expression for evaporation ratio ($\frac{E}{P}$) according to a new soil moisture storage index (γ), with better fitting and fitted better to the observations than the Budyko-type equations (Schreiber, Ol’dekop, Turc-Pike):

$$\frac{E}{P} = \frac{1}{2}\{1 + \gamma(1 - R) - [1 - 2\gamma(1 - R) + \gamma^2(1 - 2R + R^2)]^{0.5}\} \qquad (17)$$

In this equation, $\gamma = b/P$, (b is the model parameter), $R = \exp(-\emptyset/\gamma)$ and $\emptyset = \frac{E_p}{P}$. They mentioned that the abcd model contains a soil moisture accounting component and therefore equation 17 could incorporate the impact of soil moisture changes for the long-term water balance of the catchment.

Considering the effect of both the frequency and depth of the rainfall events on the soil water balance and incorporating the soil properties (i.e., maximum soil water storage capacity (w_0)), Porporato et al. (2004) proposed the following model:

$$\frac{E}{P} = 1 - \frac{\emptyset q^{\frac{q}{\emptyset}-1}\exp(-q)}{\Gamma\left(\frac{q}{\emptyset}\right) - \Gamma(\frac{q}{\emptyset}, q)} \tag{18}$$

in which, $\emptyset = \frac{E_p}{P}$, $q = \frac{w_0}{d}$ and d is mean depth per storm event. They found that for $q = 5.5$, their model reproduces the Budyko (1948) curve very well.

Finally, Wang and Tang (2014) developed a one-parameter Budyko-type model for the mean annual time scale based on a generalization of the proportionality hypothesis of the Soil Conservation Service (SCS) model. The new-introduced parameter of their model (ε) is defined as the ratio of the initial evaporation ratio and Horton index (Wang and Tang, 2014). The Horton index is the ratio between evaporation and catchment wetting (water available for evaporation) (Horton, 1933; Troch et al., 2009), and is relatively constant from year-to-year and is controlled by the vegetation properties (Troch et al., 2009; Voepel et al., 2011). Accordingly, they provided the following equation:

$$\frac{E}{P} = \frac{1 + \frac{E_p}{P} - \sqrt{(1 + \frac{E_p}{P})^2 - 4\varepsilon(2-\varepsilon)\frac{E_p}{P}}}{2\varepsilon(2-\varepsilon)} \tag{19}$$

Despite the development of several Budyko equations, Zhou et al. (2015) believed that a simpler method to generate Budyko functions was needed, which meets the water and energy constraints. Thus, they incorporated the complementary relationship. They suggested that their complementary relationship could be applied for evaluating impacts of change in climate and/or catchment characteristics on hydrological response of the catchment. Moreover, their proposed function can be used to develop any number of valid Budyko functions and/or to test the validity of the existing functions.

It should be mentioned that in addition to the studies that developed a new model to take different physical factors (such as vegetation, soil moisture, topography, rainfall characteristics) into account, many other researchers tried to investigate the effect of these factors on the water balance of the catchments, through the Budyko framework (Donohue et al., 2010, 2007; Dooge et al., 1999; Feng et al., 2012; Gerrits et al., 2009; Hickel and Zhang, 2006; Mianabadi et al., 2019; Ning et al., 2017; Padrón et al., 2017; Potter et al., 2005).

Table 1- Summary of non-parametric equations at steady state conditions.

Equation	Reference	Parameter	Representative for
$\frac{E}{P} = 1 + \frac{E_p}{P} - \left[1 + \left(\frac{E_p}{P}\right)^{\omega}\right]^{\frac{1}{\omega}}$	Fu (1981); Zhang et al. (2004)	ω	the catchment characteristics modifying the partitioning of P between E and Q

$\frac{E}{P}=\frac{\exp\left[\alpha\left(1-\frac{P}{E_p}\right)\right]-1}{\exp\left[\alpha\left(1-\frac{P}{E_p}\right)\right]-\frac{P}{E_p}}$	Milly (1993)	α	storage capacity of the root zone
$\frac{E}{P}=\frac{1}{\left(1+\left(\frac{P}{R_n}\right)^{a}\right)^{\frac{1}{a}}}$	Choudhury (1999)	a	characteristics of soil, topography and vegetation of the catchment modifying the partitioning of P between E and Q
$\frac{E}{P}=\frac{1+w\frac{E_p}{P}}{1+w\frac{E_p}{P}+\left(\frac{E_p}{P}\right)^{-1}}$	Zhang et al. (2001)	w	type of vegetation (plant-available water)
$\frac{E}{P}=\frac{1}{2}\{1+\gamma(1-R)-[1-2\gamma(1-R)+\gamma^2(1-2R+R^2)]^{0.5}\}$	Sankarasubramanian and Vogel (2002)	γ	soil moisture storage
$\frac{E}{P}=1-\frac{\emptyset q^{\frac{q}{\emptyset}-1}\exp(-q)}{\Gamma\left(\frac{q}{\emptyset}\right)-\Gamma(\frac{q}{\emptyset},q)}$	Porporato et al. (2004)	q	soil properties and frequency and depth of the rainfall events on the soil water balance

$\frac{E}{P}=\frac{1+\frac{E_p}{P}-\sqrt{(1+\frac{E_p}{P})^2-4\varepsilon(2-\varepsilon)\frac{E_p}{P}}}{2\varepsilon(2-\varepsilon)}$	Wang and Tang (2014)	ε	vegetation properties

3-Budyko framework under non-steady state conditions

Generally, the Budyko framework is quite an applicable method for estimating the water-energy balance of both gauged and ungauged catchments. But an important issue in its applicability is that it assumes the catchments are under hydrological steady state conditions, which are controlled by macro-climatic factors. This assumption can lead to deviations from the observations when the Budyko hypothesis is applied for the finer spatial and temporal scales. Thus the Budyko framework should be extended to have a more accurate estimation of evaporation and runoff at finer spatial and temporal scales. In this section, the Budyko models developed for the non-steady state conditions are presented.

Han et al. (2011) stated that irrigation can be a large proportion of the lateral water inputs, which contributes to the water supply available for evaporation. In their study basin, the river water withdrawal is the main source of irrigation. Considering a study period with stable annual mean groundwater table depth, Han et al. (2011) contributed irrigation (I) into the water balance of the basin and extended the Fu equation as follows:

$$\frac{E}{P+I}=1+\frac{E_P}{P+I}-\left[1+\left(\frac{E_P}{P+I}\right)^{\tau}\right]^{\frac{1}{\tau}} \tag{20}$$

In which, τ ($\epsilon(1.\infty)$) (Fu, 1981; Yang et al., 2007) is the model parameter. Based on their results, the extended Budyko-type model performed well for 26 subregions in the study basin for estimation of evaporation at mean annual and interannual scales.

Wang (2012) mentioned that the extent to which the annual water balance is under the influence of water storage change is necessary to be examined by water storage data. Thus, he studied the effect of water storage changes (ΔS_i; including soil moisture, groundwater, and surface water changes) on the water balance at mean annual and interannual scales. He considered the total water storage change of a watershed (ΔS_i) as follows:

$$\Delta S_i = \Delta S_{sm,i} + \Delta S_{gw,i} + \Delta S_{sw,i} \tag{21}$$

He investigated the impact of water storage change on interannual water balance from 1982 to 2003 water years ($N = 22$ years). His results showed that the ratio of the annual water storage change to the annual precipitation is larger than 10% during 40% of the years and larger than 5% during 70% of the years. Therefore, he concluded that the interannual storage change cannot be neglected for his case study sites. Since the main land use in his study watersheds was agricultural land with the least human interferes, the groundwater withdrawal was mainly used for irrigation. Therefore, the total water supply under non-steady state conditions included both precipitation and water storage change and it could be presented as effective precipitation ($P_i - \Delta S_i$). Thus, the evaporation ratio and aridity index were calculated as $\frac{E_i}{P_i - \Delta S_i}$ and $\frac{E_{Pi}}{P_i - \Delta S_i}$, respectively. Wang (2012) mentioned that groundwater storage has a more important impact on the annual water balance than the soil moisture storage during drought years.

Chen et al. (2013) examined the Budyko hypothesis at the seasonal and monthly scale under non-steady state conditions when water storage change was significant. For this purpose, they defined the monthly and seasonal aridity index and evaporation ratio by defining effective rainfall as $P_k - \Delta S_k$, where k is the index for the considered time scale (i.e., monthly, seasonal or annual). With this definition, they modified the Turc-Pike equation to model seasonal evaporation and storage change and applied the model to 277 watersheds in the United States for 21 years (1983-2003). In dry months, the depletion of water storage would be added to precipitation and the available water supply includes precipitation and water storage extraction. In wet months, rainfall infiltrates into the ground and replenishes the water storage and thus, the available water supply is the subtraction of water storage from precipitation. Following Wang (2012), Chen et al. (2013) defined the aridity index ($\emptyset_k$) as follows:

$$\emptyset_k = \frac{E_{Pk}}{P_k - \Delta S_k} \tag{22}$$

in which E_{Pk}, P_k, and ΔS_k are evaporation, precipitation and water storage (both soil water and groundwater) change, respectively, for k time scale. Furthermore, Chen et al. (2013) suggested that, while the lower limit of the seasonal aridity index in the Budyko framework is zero, it may be positive or even higher than 1 during dry seasons for a given watershed. Considering the lower bound of the seasonal aridity index for a given watershed and the differentiation between dry and wet seasons, they extended the Budyko-type model for the estimation of seasonal evaporation ratio for wet and dry seasons as follows:

$$\frac{E_w}{P_w - \Delta S_w} = \left[1 + \left(\frac{E_{Pw}}{P_w - \Delta S_w} - \varphi_w\right)^{-v_w}\right]^{-\frac{1}{v_w}} \tag{23}$$

$$\frac{E_d}{P_d - \Delta S_d} = \left[1 + \left(\frac{E_{Pd}}{P_d - \Delta S_d} - \varphi_d\right)^{-v_d}\right]^{-\frac{1}{v_d}} \tag{24}$$

In these equations, v_w and v_d are the Turc-Pike parameters for wet and dry seasons, respectively and φ_w and φ_d are the corresponding lower bounds of aridity indices in wet and dry seasons, respectively. Their results for 277 watersheds in the United States showed that in wet (dry) seasons 99% (90%) of watersheds had Nash-Sutcliffe efficiency coefficients larger than 0.5. Chen et al. (2013) showed that in many cases in their study watersheds, the evaporation ratio is higher than 1 when precipitation is considered as the only source of water supply. They mentioned that the uncertainty of evaporation might be a reason for that, but it does not fully explain that behavior in extremely dry years. Therefore, they concluded that in addition to precipitation, storage change also should be considered in the available water supply. The role of water storage in maintaining evaporation is significant especially for extremely dry years with aridity index higher than 1. Their results showed that, by accurately describing the water and energy supply, the Budyko hypothesis could be applied at the interannual scale.

Greve et al. (2016) used the formulation introduced by Fu (1981) and Zhang et al. (2004) and derived a new two-parameter equation for the non-steady state conditions. As mentioned earlier, Fu's equation is subject to two constraints: water-limit and energy-limit lines. These two limits show that evaporation is limited by precipitation and potential evaporation. Greve et al. (2016) mentioned that, in addition to water storage change, additional water can be available due to human interventions (Milly et al., 2008), landscape changes (Jaramillo and Destouni, 2016), water phase changes (Berghuijs et al., 2014; Jaramillo and Destouni, 2016) or long-term soil moisture changes due to transient climate change (Orlowsky and Seneviratne, 2013; Wang, 2005). While, Zhang et al. (2008), Han et al. (2011), Wang (2012) and Chen et al. (2013) investigated the limitation of the Budyko framework and extended the Budyko hypothesis for the conditions when evaporation exceeds precipitation, Greve et al. (2016) modified the Fu equation analytically using basic phenomenological assumptions, as made by Zhang et al. (2004) and provided the following equation:

$$\frac{E}{P} = F(\emptyset, k, y_0) = 1 + \emptyset - (1 + (1 - y_0)^{k-1}\emptyset^k)^{\frac{1}{k}} \tag{25}$$

In this equation, k, like ω, is the parameter representing the watershed characteristics. The new parameter (y_0) represents the new boundary condition and has a physical interpretation related to the additional water supply for evaporation. If $k = 2.6$ and $y_0 = 0$, the Greve equation corresponds to the Budyko (1948) curve. Greve et al. (2016) used their equation globally at monthly time scale and showed that the evaporation ratio estimated by the new model showed a good correlation with the observed evaporation ratio.

Although some previous studies incorporated the water storage effects into the Budyko framework, Wang and Zhou (2016) claimed that the role of groundwater-dependent evaporation was not yet evaluated. Both soil water and groundwater changes may be the cause of evaporation ratio higher than one. Wang (2012) reported that during drought year

1988, the evaporation ratio was about 1.1 in two watersheds in Illinois, United States, in which about 100 mm soil water and about 200 mm of groundwater storage was depleted. It showed that the contribution of groundwater was more significant than soil storage. As mentioned by Chen and Hu (2004), the effect of groundwater on surface evaporation depends on the groundwater table depth; a groundwater table near the surface has a significant effect on evaporation. Therefore, shallow groundwater would increase the occurrence of the cases with an evaporation ratio higher than 1 (Chen et al., 2020; Wang and Zhou, 2016). Therefore, Wang and Zhou (2016) developed a method to incorporate the groundwater-dependent evaporation into the annual water balance in the standard Budyko framework. For analyzing the method, they modified the "abcd" model (Thomas, 1981) to incorporate the groundwater-dependent evaporation and then the modified model was applied in the study catchments to estimate the actual evaporation. Using the estimated evaporation by the modified "abcd" model, the interannual water balance for the period of 1957-2010 in the standard and modified Budyko framework were analyzed. Their study area was located in the Erdos Plateau in northern central China, in the middle part of the Yellow River basin with a semiarid to arid climate.

Wang and Zhou (2016) plotted for the average of six catchments the annual $\frac{P-Q}{P}$ versus the aridity index during 1957-1978 and concluded that the long-term water balance of the catchments follows the original Budyko framework under steady-state conditions. In contrast, their results for some individual catchments showed that the annual $\frac{P-Q}{P}$ versus the aridity index had a negative relation and did not follow the Budyko framework. For some other catchments, the relation was positive but still did not follow the original Budyko framework. Such an abnormal relation was also highlighted by Istanbulluoglu et al. (2012) in the North Loup River basin, Nebraska, USA. Istanbulluoglu et al. (2012) concluded that it occurred by ignoring the water storage change in the catchment. Therefore, they replaced the $\frac{P-Q}{P}$ with $\frac{P-Q-\Delta S_{gw}}{P}$ (ΔS_{gw}: the interannual groundwater storage change), and found that the equation followed the Zhang et al. (2001)'s curve for their study catchment. However, they did not take the groundwater-dependent evaporation into account.

Wang and Zhou (2016) mentioned that there is no long-term groundwater-level monitoring data in their study catchments. Furthermore, the $\frac{P-Q-\Delta S_{gw}}{P}$ approach causes the interannual soil moisture storage change to be ignored. Therefore, they estimated the storage change from the monthly baseflow data using the modified "abcd" model. To analyze their method, they divided the study catchments into two zones: Zone-1 with deep groundwater and Zone-2 with shallow groundwater. In Zone-1, the evaporation ratio was smaller than 1 (below the water-limit line) for the whole range of the aridity indices, while for Zone-2 the relation between the evaporation ratio and aridity index did not follow the original Budyko framework and the evaporation ratio was higher than 1. They concluded that the groundwater-dependent evaporation was the reason for this behavior. Generally, they proposed that the evaporation ratio for the whole catchment can be estimated as follows:

$$\frac{E}{P} = (1-r)\left[1 + \emptyset - (1 + \emptyset^{\pi})^{\frac{1}{\pi}}\right] + rgG_a\emptyset \qquad (26)$$

where r is the ratio of the Zone-2 area to the whole catchment area, $\emptyset$ is aridity index, π is the parameter representing the catchment characteristics, g is the parameter controlling the intensity of groundwater-dependent evaporation and G_a is the annual groundwater storage.

Wang and Zhou (2016) mentioned that the water supply in the original Budyko framework (e.g., precipitation) for the steady state condition is not dependent on both evaporation and runoff and thus, the aridity index is an independent variable. However, effective precipitation ($P - \Delta S$) as defined by Wang (2012) and Chen et al. (2013), is under the influence of the feedback mechanism between evaporation and runoff. The interdependency between water supply and evaporation limits the application of the modified Budyko framework in assessing the shift in annual water balance. Therefore, they suggested that the extended formula for annual water balance in the standard Budyko framework, such as their proposed equation (equation 26), is a more efficient and straightforward approach and can keep the aridity index as an independent index for the climatic conditions.

Du et al. (2016) mentioned that in addition to groundwater and soil water storage, the water transfer from other basins in unclosed basins is another important source of water that is available for evaporation. Considering this issue, they investigated the applicability of the Budyko hypothesis for the Heihe River basin in China at the non-steady state condition and then they improved the original Budyko framework based on the basins' water balance.

$$\frac{E}{P_e} = 1 + \frac{E_P}{P_e} - \left[1 + \left(\frac{E_P}{P_e}\right)^{\mu} + C\right]^{\frac{1}{\mu}} \tag{27}$$

where μ and C are two dimensionless fitting parameters. μ ($\epsilon(1.\infty)$) (Fu, 1981; Yang et al., 2007) is a well-known parameter representing the watershed characteristics. P_e is equivalent precipitation which includes the channel inflow coming from the upper basin and/or inter-basin water transfer (Q_{in}) and the soil moisture (root zone water) change (ΔS_{sm}) ($P_e = P + Q_{in} - \Delta S_{sm}$). They did not include the groundwater storage change in their model since they believed that it is the result of the groundwater-baseflow exchange and therefore, does not have direct interaction with evaporation. To test the new Budyko-type curve, Du et al. (2016) used the "abcd" model (Thomas, 1981) to obtain the required data (e.g., soil water storage and actual evaporation) at the monthly scale. Their results showed that due to the impact of water transfer and soil water storage change, the original Budyko framework is not applicable for their study basin. Furthermore, they found that at the annual time scale their new equation performed more or less similar to Fu's equation. At the monthly scale, their proposed model performed better than the original Fu equation for the defined evaporation ratio less than 1 ($\frac{E}{P_e} < 1$), and performed the same for evaporation ratios close to 1 ($\frac{E}{P_e} \approx 1$). They suggested that their new equation could be applied for water balance interpretations over extremely dry regions with non-steady state conditions.

Considering water storage changes in the watershed, Moussa and Lhomme (2016) proposed a new physically based formulation by introducing the parameter of $H_E = -\Delta S/E_P$, which represents the variable ΔS in a dimensionless form. Their equation can be applied under non-steady state conditions at any time scale with various Budyko functions. Using the Fu-Zhang equation, the new formulation was similar to the equation of Greve et al. (2016) for $\Delta S \leq 0$ in the standard Budyko space (E/P , E_P/P). Moreover, they extended the new formulation in the space of $E/(P - \Delta S)$, $E_P/(P - \Delta S)$. Comparing the new equation to the formulations of Chen et al. (2013) and Du et al. (2016), they found that the upper limit of all formulations was similar, while the lower limit was different. They presented their formulation in both Budyko ($\emptyset = E_P/P\,, E/P$) and Turc ($\emptyset^{-1} = P/E_P\,, E/E_P$) space as defined by Andréassian et al. (2016). In this paper, only the formulation in the Budyko space is presented:

$$\frac{E}{P} = B_1[(1 - H_E)\emptyset] + H_E\emptyset \qquad for\ \Delta S \leq 0 \tag{28}$$

$$\frac{E}{P} = (1 + H_E\emptyset)B_1\left(\frac{\emptyset}{1 + H_E\emptyset}\right) \qquad for\ \Delta S \geq 0 \tag{29}$$

In these equations, B_1 is representative of any Budyko function. Equations 28 and 29 are presented for the standard Budyko space. In the extended space, $(E/(P - \Delta S)\,, E_P/(P - \Delta S))$, the equations are defined as follows:

$$\frac{E}{P - \Delta S} = \frac{1}{1 + H_E\emptyset}\{B_1[(1 - H_E)\emptyset] + H_E\emptyset\} \qquad for\ \Delta S \leq 0 \tag{30}$$

$$\frac{E}{P - \Delta S} = \frac{1}{1 + H_E\emptyset}\left\{(1 + H_E\emptyset)B_1\left(\frac{\emptyset}{1 + H_E\emptyset}\right)\right\} \qquad for\ \Delta S \geq 0 \tag{31}$$

Equation 31 can be written as $\frac{E}{P-\Delta S} = B_1(\emptyset') = B_1(\frac{E_P}{P-\Delta S})$. Therefore, Moussa and Lhomme (2016) mentioned that for $\Delta S \geq 0$, $\frac{E}{P-\Delta S}$ is independent of H_E and is similar to the steady state conditions. It should be mentioned that instead of H_E, another dimensionless parameter, $H_P = -\Delta S/P$, can be included in the new formulation of Moussa and Lhomme (2016), yielding another form of the equations.

Tang et al. (2017) extended the one-parameter equation developed by Wang and Tang (2014) to reconstruct annual terrestrial water storage change (ΔS) and groundwater storage change (ΔS_{gw}) in the large-scale irrigated region in Punjab, Pakistan. Following the method of Chen et al. (2013), the new 2-parameter model was developed as follows:

$$\frac{E}{P_e} = \frac{1 + \left(\frac{E_P}{P_e} - \varphi\right) - \sqrt{\left(1 + \frac{E_P}{P_e} - \varphi\right)^2 - 4\epsilon(2-\epsilon)\left(\frac{E_P}{P_e} - \varphi\right)}}{2\epsilon(2-\epsilon)} \tag{32}$$

in which, P_e is defined as $P - \Delta S$, φ is the lower bound of the annual aridity index and ϵ is the model parameter interpreted as the ratio between initial evaporation and total evaporation. Tang et al. (2017) concluded that their new proposed Budyko-type equation integrated with GRACE data would result in a useful method for assessing the long-term groundwater storage change in the regions with large-scale irrigation.

Despite developing the new Budyko equations, Condon and Maxwell (2017) suggested that the ability to estimate or measure groundwater storage changes is limited and therefore, the implication of the modified Budyko approaches should be more evaluated. For this purpose, they investigated the effect of storage change on the Budyko hypothesis using the evaporation ratio estimated by three common approaches: 1) direct evaporation quantified from field observations divided by precipitation, ($\frac{E}{P}$), 2) evaporation calculated from precipitation and surface runoff divided by precipitation, ($\frac{P-Q}{P}$), and 3) direct evaporation divided by effective precipitation, by taking groundwater contribution (G) into account, ($\frac{E}{P-G}$) when groundwater-surface water exchanges are occurring. Their results for 25.000 nested watersheds (100-3,000,000 km^2) showed that the groundwater storage would shift the Budyko curve, depending on the approach to estimate the evaporation ratio. As expected, for the first approach ($\frac{E}{P}$), some points fell above the water-limit line with evaporation ratio higher than 1. This is explained by the fact that, in this condition, the partitioning occurs between evaporation and runoff plus groundwater storage change, instead of precipitation and runoff only. Their results also showed that in the case with $G = 0$ (i.e. storage change negligible), the three approaches were equivalent.

A comparison among the developed model at non-steady state conditions is provided in Table 3. As shown in the table, most of the studies are developed for arid and semi-arid regions, where precipitation is not enough for meeting the water demand of the watersheds and thus, water is provided through groundwater depletion or inter-basin transfer, which increases the available water of the watersheds, leading to a deviation from the original Budyko framework.

Table 2- A comparison among developed equations at non-steady state conditions.

Equation	Reference	Extra water available	Country	Climatic conditions
$\frac{E}{P+I} = 1 + \frac{E_P}{P+I} - \left[1 + \left(\frac{E_P}{P+I}\right)^{\tau}\right]^{\frac{1}{\tau}}$	Han et al. (2011)	irrigation	China	extremely arid
$\frac{E}{P-\Delta S} = \left[1 + \left(\frac{E_P}{P-\Delta S} - \varphi\right)^{-\upsilon}\right]^{-\frac{1}{\upsilon}}$	Chen et al. (2013) following Wang (2012)	groundwater and soil storage change	U.S	277 watersheds with different climatic conditions (from dry only to wet only)

$\frac{E}{P} = F(\emptyset, k, y_0) = 1 + \emptyset - (1 + (1 - y_0)^{k-1}\emptyset^k)^{\frac{1}{k}}$	Greve et al. (2016)	all kind of additional water (water storage change, additional water can be available due to human interventions, landscape changes, water phase changes, long-term soil moisture changes due to transient climate change	Global	different climatic conditions
$\frac{E}{P} = (1 - r)\left[1 + \emptyset - (1 + \emptyset^{\pi})^{\frac{1}{\pi}}\right] + rgG_a\emptyset$	Wang and Zhou (2016)	shallow groundwater	China	semiarid to arid
$\frac{E}{P_e} = 1 + \frac{E_P}{P_e} - \left[1 + \left(\frac{E_P}{P_e}\right)^{\mu} + C\right]^{\frac{1}{\mu}}$	Du et al. (2016)	water transfer from other basins	China	dry
$\frac{E}{P - \Delta S} = \frac{1}{1 + H_E\emptyset}\{B_1[(1 - H_E)\emptyset] + H_E\emptyset\} \quad for\ \Delta S \leq 0$	Moussa and Lhomme (2016)	water storage change	--	--

$\frac{E}{P-\Delta S}=\frac{1}{1+H_E\emptyset}\left\{(1+H_E\emptyset)B_1\left(\frac{\emptyset}{1+H_E\emptyset}\right)\right\} \quad for\ \Delta S \geq 0$				
$\frac{E}{P_e}=\frac{1+\left(\frac{E_P}{P_e}-\varphi\right)-\sqrt{\left(1+\frac{E_P}{P_e}-\varphi\right)^2-4\epsilon(2-\epsilon)\left(\frac{E_P}{P_e}-\varphi\right)}}{2\epsilon(2-\epsilon)}$	Tang et al. (2017)	water storage change	Pakistan	semi-arid

4-On the value of Budyko framework for future hydrological studies

Although several attempts to apply the Budyko framework under non-steady state conditions resulted in more complexity in the framework, its simplicity and accuracy are still enough to be widely applied. The framework is nowadays still highly valuable. Maybe not for studying the process of evaporation in detail, therefore the framework is too simplistic, but it can serve purposes like:

Validation of remote sensing data: The Budyko framework can be used for validation of remote sensing data of precipitation and evaporation as done by Koppa and Gebremichael (2017). They used Fu's equation and showed that, in comparison to the complex distributed hydrological models, the simple Budyko curves can be applied effectively for validation of observational data.

Down sampling of remote sensing data: Rouholahnejad Freund and Kirchner (2017) applied the Budyko curves to derive a simple sub-grid closure relation that estimates how spatial heterogeneity and lateral moisture redistribution affects average evaporation as seen from the atmosphere. They mentioned that they used the Budyko curve as a simple model to find how the supply of available water and evaporative demand controls evaporation. They believed that the Budyko framework can be applied instead of complex ecohydrological models, which obey the same energy and water constraints and their behavior is not greatly different from the Budyko curves. The Budyko curves estimate evaporation as a function of its main drivers (e.g., precipitation and potential evaporation) allowing a general analytical derivation, which might be difficultly derived from the complex models. However, their finding could be compared by further analysis through physically distributed models with high-resolution data.

Constraining (hydrological) models: Evaporation estimates obtained from the Budyko framework, may constrain the parameter search space significantly. For example, besides two daily and eight-daily remote sensing products (LSA-SAF and MOD16), Nijzink et al. (2018) applied the analytical Budyko framework to obtain a long-term estimate of evaporation as the constraint of five rainfall-runoff models. Their results showed that the Budyko framework was helpful with strong improvements in model calibration and performance.

Quantification of the relative impacts of climate variability and direct human activities on mean annual runoff: In continuation of Fu's equation application, Mo et al. (2018) found that the effect of human activities on decline in mean annual runoff is more considerable than climate change in the Bahe river in China.

Identifying the main source of uncertainty in a complex hydrological model using Budyko coefficients: Malago et al. (2018) stated that when the simulated data derived from SWAT are too far from the Budyko curves in wet conditions, it could be related to the uncertainties of the model parameterization. This research tried to use the Budyko curve as a criterion for model calibration so that significant departure from the curve is interpreted as high potential inconsistency of model parameterization.

Determining the crop coefficient: One of the works in applying Budyko curves for its simplicity is the work done by Zhang et al. (2017), who determined the crop coefficient under non-standard conditions by integrating the Budyko framework (under both steady state and non-steady state conditions) into the traditional crop coefficient approach to assess the volume of agricultural virtual water content by minimum data. They showed that despite using less data, their model calculated virtual water content in a good agreement with some previous research studies.

While the above-mentioned studies show that the original Budyko framework performs reasonably well for their given aims, they suggested that the framework is still limited for some cases and the extended framework can be used for dealing with these limitations. For example, Koppa and Gebremichael (2017) mentioned that Fu's equation is limited to consider the catchment storage at long-term temporal scale, and therefore, the developed error metric characterizes the bias in precipitation and evaporation datasets and not the variance. Thus, they suggested using the extended Budyko curves under non-steady state conditions (for example the equation of Greve et al. (2016)) to validate remotely sensed precipitation and evaporation at monthly and daily time scales or at the catchments with considerable long-term water storage changes. Moreover, Mo et al. (2018) suggested that more details on runoff change could be revealed using the extended Budyko curves at inter- and intra-annual scales (e.g., non-steady state conditions). Malago et al. (2018) also noted that, in their study, the points above the water-limit line can indicate the non-steady state conditions in the catchments rather than the uncertainties and therefore, the extended Budyko curves should be considered.

Accordingly, in spite of being more complex than the original framework, using the extended Budyko framework under non-steady state conditions for different purposes of hydrological modeling, would lead to more accurate and reliable results. It is a great advance in hydrological modeling because most of the watersheds worldwide are nowadays under the influence of human interventions and are not steady and natural any longer. Such situations mostly occur in developing countries with insufficient data availability, which limits using complex hydrological models. The contribution of runoff and evaporation into the water balance of each catchment is influenced by human activities and this changes the water cycle of the catchments, leading to the need for a deeper understanding of the human-water system interactions. Moreover, model calibration as the most important part of the hydrological modeling should consider the interactions between human and water systems. Therefore, traditional calibration makes the results less reliable. To take into account the role of human activities in hydrological modeling, the Budyko framework at non-steady state conditions would be a very functional approach, which can efficiently model and assess water balance components, especially at large-scale modeling. For example, recently Lei et al. (2018) presented a new-type Budyko model which is potentially a generalized constraint in water resources system models, simplifying the structure of the current hydrological models to develop new models for the non-steady state conditions. These new models can be applied for the prediction of future human interventions in the water balance of the catchments, especially for large-scale spatial and temporal modeling. According to these studies, the extended Budyko framework is an efficient alternative that can be used instead of the original Budyko framework and complex hydrological models. However, this requires more reliable data such as irrigation and available soil water.

Additionally, a novel issue that may take advantage of the Budyko framework is the design of an efficient water resources planning strategy with improvement in runoff estimation as inflow to dam reservoirs especially in arid regions with high complexity in groundwater modeling. This may be proposed as future contributions in hydrology and water resources context.

Moreover, the Budyko framework can be used in hydrological modeling for partitioning total evaporation into interception, soil evaporation and transpiration (e.g., Gerrits et al., 2009; Mianabadi et al., 2019) or for evaluation of evaporation fluxes estimated by the new proposed hydrological or Land Surface Models. For example, while Good et al. (2017) by using field studies and remotely sensed estimates found that the ratio of transpiration to precipitation has a unimodal distribution, their finding was also identified by Porporato et al. (2004)'s model (equation 18) within the Budyko framework. Furthermore, they applied the Porporato's model to partition actual evaporation into interception, ground surface evaporation and transpiration relative to precipitation. However, they mentioned the appropriate application of the Budyko framework for the steady state conditions. Thus, future studies can focus on the way of applying the Budyko framework for partitioning evaporation at non-steady state conditions.

5- Perspectives of Budyko framework

Generally, in spite of some limitations of the Budyko framework, it is expected that the natural and anthropogenic changes such as climate change, land use alteration, and inter-basin water transfer can increase the contribution of the Budyko framework in hydrological modeling. Thus, attempts for applying the framework in a changing world with an increasing role of human activities in the hydrological cycle of catchments might be helpful for hydrological modeling in the future. However, it is not completely clear how the Budyko framework can contribute in the future hydrological modeling, especially under non-steady state conditions. For example, the relationship between land cover change and evaporation in the future with considering the climate change effects has important impacts on catchment hydrology and might be potentially investigated by the Budyko framework as it is slightly discussed by Ning et al. (2020) at steady state conditions. Response to the question on how such issues could be investigated under non-steady state conditions needs efficient solutions with considering the extended Budyko equations. For this purpose, taking advantage of the time series technique (Fathi et al., 2019) and modification of the line integral-based method (Zheng, 2019) can be suggested for non-steady state conditions. It may need meta-research or meta-analysis of the previous researches to predict the future of hydrological modeling based on the Budyko framework.

Meanwhile, there are still some other important unsolved questions involved with Budyko. One question is how the relationship between model parameters and catchment properties would change at non-steady state conditions. For example, while the Greve's model (Greve et al., 2016) has been analytically derived from the Fu equation (Fu, 1981), their parameters are differently related to the catchment properties at steady and non-steady state conditions. Moreover, due to human interference, the water systems have become more complex with increasing interaction and co-evolution of the different processes affecting the water balance. Accordingly, the Budyko framework might be widely used to capture the overall behaviour of the catchment (Zhang et al., 2008). It is believed that the vegetation-landscape co-evolution can help a given watershed not to deviate from the Budyko framework if it encounters with any possible climatic changes; however, the results showed that climate change can change the Budyko curve (van der Velde et al., 2014) through changing the interaction and co-evolution between climate and catchment properties (Wang et al., 2016). Thus, another question is how the extended Budyko framework can help with this issue.

One issue that can also be considered is that more attempts have to be conducted for improving the Budyko framework at smaller temporal scale with diversity controlling factors (e.g., Bai et al., 2020). Therefore, calibration of major important factors through the intelligence search method in future studies can be more conducted on the application of the Budyko hypothesis for smaller catchments and even for hydrological response units (HRUs) in a catchment. However, one important question is how the interactions among the key processes affecting the catchment response would be changing at smaller temporal/ spatial scales.

Last but not the least question might be the role of virtual water (the amount of water needed to produce commodities, which is then transported to other places for consumptions (Chapagain et al., 2006; Mekonnen and Hoekstra, 2010)) in hydrological modeling. As Sivapalan et al. (2012) suggested that socio-hydrology might address the virtual water trade, the question might be that if it is possible to apply the holistic view of the Budyko framework to help the experts of the socio-hydrology to deal with this challenge.

6-Conclusion

The Budyko framework is a useful and more convenient tool which, in some cases, can be used instead of distributed hydrological models, which are complex and time consuming with lots of data requirements and large uncertainties in the input data, model structure, and parameterization. Since it is firstly developed for spatially large- scale catchment with low complexity of real-world processes, this may be known as the most important limitation of the Budyko approach. But it is still an effective tool for assessing the impacts of climate factors and catchment properties on the water-energy balance and the interaction among them. Therefore, the co-evolution of the hydrological processes makes it possible to use the simple Budyko framework to identify the overall behavior of the catchment on the whole.

In some ungauged catchments, especially in developing countries, the data is not sufficiently provided (or if provided, is inaccurate or publicly restricted) to be used as input to the complex models and this can lead to large uncertainty in the model results. In spite of simplicity, the Budyko framework can lead us to identify if our results are reasonable or not. Even if the extended Budyko curves are not directly applicable for catchments with insufficient data, the original Budyko framework can help the researcher to determine that abnormal behavior of the catchments is arising from the catchment characteristics or from the uncertainty of the data. For example, when a data point is located above the water-limit line, it shows that either the input data are uncertain or the catchment is under non-steady state conditions. Such a finding cannot be obtained by complex hydrological models.

On the other hand, in a changing world with human interferes in the hydrologic cycle of water systems (e.g., groundwater withdrawal, inter-basin water transfer, etc.), some watersheds are under non-steady state conditions and the water balance of the watersheds does not follow the original Budyko framework any longer. Furthermore, since the original Budyko framework was developed for long-term temporal and large spatial scales, its application at finer scales, where the water storage change is an important component of the water balance, is challenging. In such situations, the extended Budyko curves have to be used. These extended Budyko equations can enhance our understanding of the overall behavior of eco-hydrological processes, which are valuable for practical applications. While the extended equations are more complex than the original ones, they still are simpler with less data requirements than the complex distributed models. In developing countries in which the hydrological cycle of the catchments is considerably under the influence of anthropogenic activities, the application of the original Budyko framework is limited. On the other hand, in these countries applying complex models is also limited due to unavailable or insufficient data. Therefore, the extended Budyko equations are useful tools for the estimation of evaporation in these regions.

However, in spite of all the advantages provided by the Budyko framework, it is likely still too simple to represent the full complexity of real-world processes and thus, might be subject to over-interpretations leading to flawed and false conclusions. Several studies show that using Budyko equations, especially the parametric equations, result in inconclusive and sometimes potentially contradicting outcomes (Padrón et al., 2017; G. Zhou et al., 2015). Nonetheless, extending the Budyko framework, at both temporal and spatial scales might be helpful for some watershed with less complexity, for evaluating the complex models or for the situations in which very accurate estimations are not needed. Accordingly, the next generation of the hydrological modeling may need to go toward the applying the Budyko framework to estimate the hydrological components at steady and non-steady state conditions in a changing world. Some questions within the Budyko framework remain unsolved, like the interactions among the key processes affecting the catchment response at different temporal/spatial time scales, the relationship between land cover change and evaporation in the future, the relationship between model parameters and catchment properties at non-steady state conditions, using extended Budyko framework to capture the overall behaviour of the catchment considering the co-evolution of the processes, and the role of virtual water in hydrological modeling.

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