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HESS Opinions: Beyond the Long-term Water Balance: Evolving Budyko's Legacy for the Anthropocene towards a Global Synthesis of Land-surface Fluxes under Natural and Human-altered Watersheds

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Abstract

Global hydroclimatic conditions have been significantly altered over the past century by anthropogenic influences that arise from the warming global climate and also from local/regional anthropogenic disturbances. Traditionally, studies have used coupling of multiple models to understand how land-surface fluxes vary due to changes in global climatic patterns and local land-use changes. We argue that Budyko's framework that relies on the supply and demand concept could be effectively adapted and extended to quantify the role of drivers – both changing climate and local human disturbances – in altering the land-surface response across the globe. We review the Budyko framework along with potential extensions with an intent to further the

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applicability of the framework to emerging hydrologic questions. Challenges in extending the Budyko framework over various spatio-temporal scales and evaluating the water balance at these various scales with global data sets are also discussed.

The historical evolution of the Budyko framework in hydroclimatology

The traditional Budyko formulation provides the long-term water balance as a single-stage partitioning of precipitation into runoff and evapotranspiration; and it has been verified over thousands of natural watersheds around the globe (Zhang et al., 2004; Yang et al., 2007; Sivapalan et al., 2011; Williams et al., 2012; Padrón et al., 2017). Besides the aridity index, which is defined as the ratio of the mean annual potential evapotranspiration to the mean annual precipitation, Milly et al. (1994) and Sankarasubramanian and Vogel (2002) proposed additional controls on the long-term water balance including seasonality and soil moisture holding capacity that enhanced the Budyko framework for explaining the spatial variability in mean annual runoff at the continental scale. Studies have also extended the Budyko framework for capturing the interannual variability in runoff (Koster and Suarez, 1999; Sankarasubramanian and Vogel, 2002, 2003). More recently, the Budyko framework has been extended for explaining the seasonal hydroclimatology of basins (Petersen et al., 2012; Chen et al. 2013; Petersen et al. 2018). Similarly, the Budyko framework has been extended for quantifying the non-dimensional sensitivity (also termed elasticity) of land-surface response to changes in climatic controls under different hydroclimatic regimes (Dooge, 1992; Dooge et al., 1999; Sankarasubramanian et al., 2001).

Perhaps the most unique aspect of the Budyko framework lies in its Darwinian approach which enables us to view the entire hydroclimatic system without focusing on each physical process in isolation (Harman and Troch, 2014; Wang and Tang, 2014). Darwinian approach seeks to document patterns of variation in populations of hydrologic systems and develop theories that explain these observed patterns in terms of the mechanisms and conditions that determine their historical development (Harman and Troch, 2014). Even though most studies which employed Budyko's framework have focused on natural basins, the original monograph (Budyko, 1974), Climate and Life, considered the role of human influence on climate including impacts of reservoir storage and irrigation on evapotranspiration. As hydroclimatic regimes evolve in the Anthropocene, it is critical to understand how land-surface fluxes change due to changes in local watershed conditions and due to global climate change. Given the Budyko framework's emphasis on a Darwinian approach and its ability to capture the fundamental dimensions of land-surface fluxes, a global synthesis on the variability in these fluxes across natural and human-altered watersheds should provide insights on the sensitivity of the critical hydroclimatic processes to local and global changes in the Anthropocene.

Budyko Framework for the Anthropocene

We are at a critical time in which the hydroclimate, particularly land-surface fluxes, has been significantly altered over the past century by anthropogenic disturbances (Entekhabi et al., 1999; Vogel et al., 2015). For instance, both annual precipitation and streamflow have increased during the period of 1948–1997 across the eastern United States, and those trends appear to arise primarily from increases in autumn precipitation (Small et al., 2006; Rice et al., 2015). Similarly, the frequency of floods is increasing in many regions, while magnitudes of flooding appear only to be systematically increasing in certain spatially cohesive regions (Hirsch and Archfield, 2015; Malikpour and Villarini, 2015; Archfield et al., 2016) particularly in urban areas (Vogel et al., 2011; Barros et al., 2014 and Prosdocimi et al., 2015). Irrigation in the U.S. high plains leads to increases in summer rainfall and streamflow in the Midwest due to land-surface and atmosphere feedback (Kustu et al., 2011). Based on hydroclimatic observations from 100 large hydrological basins globally, Jaramillo and Destouni (2015) found consistent and dominant effects of increasing relative evapotranspiration from flow regulation and irrigation and decreasing temporal runoff variability from flow regulation. Development of irrigation networks and man-made reservoirs also increased surface water and groundwater withdrawals and land-use changes (Maupin et al., 2014; Sankarasubramanian et al., 2017; Das et al., 2018). Similarly, construction of large dams has significantly altered the downstream flow variations impacting downstream ecology (Gao et al., 2008; Wang et al., 2017). Changes in land-use and land-cover also impact the local energy balance creating urban heat islands (Memon et al., 2008), affecting recharge and baseflow (Price, 2011), which in turn impacts a very broad range of streamflows (Allaire et al., 2015) with particularly significant increases in high flows (Vogel et al., 2011; Barros et al. 2014; Prosdocimi et al. 2015). Thus, anthropogenic influences arising from global climate change and local to regional disturbances can significantly impact the land-surface response from the watershed. Anthropogenic influences including changes in climate, land use, and water use exhibit complex interactions which must be considered jointly, to understand their impact on hydrologic flow alteration (Allaire et al. 2015). Performing a synthesis on how the spatio-temporal variability of land-surface fluxes – runoff, evapotranspiration, net radiation, and hydrologic flow alteration – differ globally in natural and human-altered watersheds is a critical need to enable a complete understanding of global hydroclimate during the Anthropocene. The Budyko framework provides an ideal approach for such inquiry, because it has been used to decompose changes in long-term land-surface fluxes due to both natural variability and human influence (e.g., Roderick and Farquhar, 2011; Wang and Hejazi, 2011; Yang et al., 2014; Jiang et al., 2015).

Budyko Framework Adaptation in Watershed Modeling

Figure 1 provides the general setup of the Budyko framework to explain the spatio-temporal variability of land-surface fluxes in natural watersheds and human-altered landscapes. The framework relies on conservation of mass and energy to model and predict the "actual" hydroclimatic variable of interest based on the available "demand" and "supply" of mass and energy (Figure 1). The rationale for using the Budyko framework for understanding the spatial variability in land-surface fluxes over natural/human-altered watersheds lies in its ability to capture the hydroclimatic dimensions of supply and demand, thereby providing a low-dimensional parsimonious approach (Figure 1) to this multidimensional problem. Here, we evaluate and extend the Budyko framework for understanding the spatio-temporal variability of different land-surface fluxes.

Long-term Water Balance

The most commonly used framework for modeling long-term water balance is to estimate the mean annual evapotranspiration ("actual") based on the ratio of mean annual potential evapotranspiration ("demand") to the mean annual precipitation ("supply"). Thus, the upper limit for mean annual evapotranspiration is potential evapotranspiration (precipitation) in a humid (arid) region. The family of Budyko curves estimates the evapotranspiration ratio ("actual"/ "supply") based on the aridity index ("demand"/"supply"). For additional details, see Sankarasubramanian and Vogel (2001). Most studies have focused on evaluating the long-term water balance at regional and continental scale (see Wang et al., 2016 for a detailed review). Studies have also focused on the impact of land cover and climate on long-term water yield using

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global data (Zhou et al., 2015). Here, we evaluate the Budyko framework to the global scale using the data from the Global Land-Surface Data Assimilation System, version 2 (GLDAS2) (Rodell et al., 2004). Data points of mean annual evapotranspiration and aridity index are obtained from the GLDAS2 dataset with a spatial resolution of 0.25 ° for the period 1948-2010. Figure 2 shows the performance of the Budyko curve in estimating the mean annual evapotranspiration based on the aridity index data between 60° S to 60° N. Even though the Budyko curve provides a first-order approximation of the spatial variability in the evapotranspiration ratio (Figure 2), the scatter around the curve is quite considerable. Studies have shown that seasonality in moisture and energy and their co-availability (i.e., phase difference between moisture and energy availability within the year) and soil moisture holding capacity partially control the scatter around the Budyko curves (Milly et al., 1994, Sankarasubramanian and Vogel, 2003). Another question of interest is to understand the lower bound on the evapotranspiration ratio, which is typically limited by the moisture availability in a region (Wang and Tang, 2014). Numerous studies on long-term balance have employed fitting the observed long-term water balance by parameterizing the Budyko curves (see Wang et al., 2016 review paper). However, limited/no effort has been undertaken on how this data cloud of long-term water balance cloud is expected to change under potential climate change and how this interplay between moisture and energy is expected to affect the long-term water balance under different type of watersheds (Creed et al., 2014). Similarly, recent studies have extended Budyko's steady-state supply-to-demand framework for modeling land-surface fluxes over fine (daily and monthly) time scales (Zhang et al., 2008). Validating these emerging frameworks with global hydrologic data will provide an understanding of the critical process controls in estimating land-surface fluxes. This validation effort will also help in understanding the advantages and

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limitations of such parsimonious modeling approach towards estimating evapotranspiration and streamflow at various spatio-temporal scales.

Extension of Budyko's "supply and demand" concept for infiltration

The upper bounds on the Budyko framework arise from the conservation of mass and energy. Hence, in principle, it could be applied to other hydrological processes. Zhang et al. (2008) applied the Budyko's monthly supply and demand attributes to estimate the catchment retention and the overland runoff from the soil moisture zone. Wang (2018) developed the infiltration equation for saturation excess in the Budyko's supply and demand framework, i.e., modelling the ratio of infiltration to rainfall depth as a function of the ratio between infiltration capacity and rainfall depth (Figure 3). The cumulative infiltration depth during a rainfall event is defined as the "actual" variable of interest, and the cumulative rainfall depth during an event is defined as the "supply". The effective soil water storage capacity for the event is defined as the "demand", which is dependent on the initial soil moisture condition. In Figure 3, the initial soil moisture condition is represented by the degree of saturation, ψ, which is defined as the ratio of initial soil water storage and storage capacity (Wang, 2018). For a dry soil with low ψ, infiltration is expected to be higher with lower surface runoff potential. The upper bounds of these curves (Figure 3) are similar to the Budyko's asymptotes corresponding to infiltration capacity-limited and rainfall depth-limited conditions. In this illustration, the Budyko framework is extended to estimate the temporal variability of infiltration into the soil based on soil water storage capacity and antecedent conditions (ψ). Thus, the parsimonious framework stems from the Budyko's supply and demand concept to develop the asymptotes and then use those asymptotes to identify and explain various critical process controls (e.g., infiltration in Figure 3).

Although the above extensions of the Budyko framework demonstrate the potential for developing a low-dimensional parsimonious modeling strategy, data-based validation efforts have focused primarily on the long-term hydroclimatic attributes (i.e., mean, variance and elasticity) of observed land-surface fluxes in natural basins (Figure 2) (Sankarasubramanian and Vogel, 2001; Abatzoglou and Ficklin, 2017). Representing a hydroclimatic variable of interest (i.e., "actual") as a ratio to the "supply" and explaining its spatio-temporal variability based on the demand/supply ratio and other variables (e.g., soil moisture holding capacity for long-term water balance) provides a simplistic, non-dimensional form for understanding the process controls. For instance, in the long-term water balance context, defining the demand/supply relationship explains the predominant controls on the spatio-temporal variability of mean annual runoff and mean annual evapotranspiration based on the basin aridity, seasonality of demand and supply (i.e., in-phase or out-of-phase between moisture and energy) attributes and soil moisture holding capacity (Milly, 1991). Synthesizing relevant process controls and representing them within the Budyko low-dimensional framework will also help us in the catchment classification and in understanding how different hydroclimatic processes of interest vary across wider regimes and landscapes.

Extending Budyko Framework for Human-altered Watersheds and Landscapes

Figures 4-6 extend the Budyko framework to explain the spatio-temporal variability in land-surface fluxes in human-altered watersheds and landscapes. A synthesis involving extension and evaluation of the Budyko framework for estimating land-surface fluxes in human-altered watersheds will help us understand the role of key drivers and anthropogenic disturbances (e.g., reservoir storage, land use and land cover changes) in altering the land-surface fluxes at various spatio-temporal scales.

Extension of Budyko's "supply and demand" Framework for Reservoir Operation and Hedging

We extend the Budyko framework for reservoir operation to meet the target demand based on the standard operating policy (SOP) and linear hedging policy (Draper and Lund, 2004). A hedging policy in reservoir operation aims to conserve water for future use by curtaining the current demand (Draper and Lund, 2004). Given an initial storage (S_{t-1}), inflow (I_t), demand (D_t) and evaporation (E_t) over a given time step (t), one could obtain the actual release (R_t), and ending storage (S_t) along with spill (SP_t) using a simple mass balance (equation 1).

$$S_t = S_{t-1} + I_t - E_t - R_t - SP_t \qquad \ldots (1)$$

By defining available water, $AW_t = S_{t-1} + I_t - E_t$, we obtain release (as "actual") under a given hedging fraction ($0 \leq \alpha \leq 1$) for three reservoir storage conditions using equation 2. The SOP of a reservoir simply corresponds to $\alpha = 1$ by supplying available water or demand at a given time.

$$\begin{array}{ll} S_t = S_{\max}, R_t = D_t, SP_t = AW_t - D_t - S_{\max} & \text{if } AW_t - D \geq S_{\max} \\ S_t = AW_t - R_t, R_t = \alpha D_t, SP_t = 0 & \text{if } S_{\min} < AW_t - D_t < S_{\max} \\ S_t = S_{\min}, R_t = AW_t, SP_t = 0 & \text{if } S_{\min} \leq AW_t - D_t \end{array} \qquad \ldots .(2)$$

Rewriting AW_t as "supply", D_t as "demand" and R_t ("actual"), we develop the Budyko framework for the reservoir operation under SOP and hedging policy (Figure 4). The SOP simply provides the asymptotes, the upper bounds, for the R_t / AW_t ("actual"/ "supply") ratio. Figure 4 also demonstrates the developed framework for a hypothetical system for estimating the

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monthly releases (see supporting information (SI) Tables 1-2 for data and details). Increased hedging reduces the release and increases the storage and spill from the system. For demonstration, a linear hedging policy is applied. But the real-world system operation will have a complex non-linear release policy, still the data points are expected to lie within the bounds. For systems with a small storage-to-demand ratio, the spill portion on the left asymptote is expected to be much longer than a system with large storage-to-demand ratio. Similarly, for systems with large (small) storage-to-demand ratio, most data points are expected to lie below (on) the asymptotes portion of the framework. Given that this framework in Figure 4 is non-dimensional, we could analyze release to demand characteristics for reservoirs with competing purposes (e.g., hydroelectric vs flood control) and synthesize how release patterns vary based on the demand-to-available water ratio across different type of systems. Similarly, one can also formulate the functional forms for non-linear hedging policy like Budyko equations as the upper bounds are specified by the "supply and demand" relationship.

Representing Human Demand and Environmental Flows from Reservoir Operation

Reservoir storages reduce the runoff variability to meet the human demand, thereby resulting in significant flow alterations (Wang et al., 2014). By adding a dedicated term, environmental flow, EF_t, we rewrite the reservoir mass balance in equation (3).

$$S_t = AW_t - R_t - EF_t - SP_t \qquad \dots (3)$$

Given our variable of interest here is EF_t ("actual"), we represent the "demand" as $R_t + EF_t$ and available water, AW_t, as "supply", which gives us a simple framework to visualize the ratio, environmental flow allocation EF_t / AW_t, has the upper bound AW_t, which is specified by the

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1:1 line. The term, $1-EF_t/AW_t$, simply represents the alteration ratio at a given time step. The lower bound specifies only allocation ($R_t/EF_t = 0$) for human demand and a slope of 0.5 indicates equal allocation for human need and ecological demand. For instance, if R_t/EF_t falls below the slope of 0.5, it indicates significant flow alteration to meet human demand. In the case of Falls Lake (Figure 5), a major water supply reservoir in the triangle area in NC (see SI Table 3 for data and additional details), it is evident that flow alteration is significant due to increased allocation for human demand since more data points lie below the equal allocation line. Using the proposed framework in Figure 5, one could synthesize how reservoir systems with large residence times, which is otherwise known as degree of regulation, impact flow alteration under arid and humid conditions. The negative linear trend indicates (Figure 5) increased allocation human use results in decreased environmental flow allocation. For instance, reservoirs in arid (humid) climates are typically larger to reduce the larger (smaller) interannual variability in runoff, hence such systems are expected to have higher (lower) degree of regulation. However, this synthesis of reservoir systems across different climatic regimes needs to be evaluated in the context of withdrawal for human use and their purpose and the consumptive use associated with it. We argue the proposed framework could be useful for understanding the trade-off between water allocation for human use and downstream ecological requirements.

Interaction between Evapotranspiration and Sensible Heat

Land use and land cover changes due to urbanization modify the evapotranspiration due to limited water availability resulting in increased differences between urban and rural temperature during the nighttime, which creates an urban heat island. Expressing the net radiation, R_n, as the “supply” of energy available at the surface, the latent heat flux (*LE*) as the

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"demand", and the sensible heat flux, *H*, as the "actual" variable of interest, we developed the bounds (Figure 6) between the latent heat flux ratio (LE/R_n) and the sensible heat flux ratio (H/R_n). The basis for considering the latent heat flux as the "demand" stems from the view that net radiation is effectively utilized for evapotranspiration in regions with increased water availability with the residual energy being converted to net sensible heat flux. For the hourly data presented in Figure 6, latent heat flux indirectly quantifies the available soil water. The proposed framework in Figure 6 could also be obtained by representing the evapotranspiration ratio (Figure 1) as latent heat ratio with latent heat as "actual", net radiation as "supply" and potential evapotranspiration as latent heat capacity (i.e., "demand"). Given Figure 6, one could use this framework to evaluate the differences in sensible heat flux between urban and rural settings by comparing across regions with abundant and limited water availability. Figure 6 evaluates the proposed framework by plotting the hourly (7 AM- 5 PM) climatology of latent heat flux ratio and sensible heat flux ratio in August from two FLUXNET towers ((https://fluxnet.fluxdata.org/), one from the urban setting and another from the rural setting, near Minneapolis, MN. The hourly climatology of H, LE and Rn, show the urban tower experience more sensible heat than the rural tower during the daytime (Figure SI-1). However, the primary challenge in using the FLUXNET data for evaluating the framework is due to the non-availability of FLUXNET towers in urban settings. Identifying pairs of FLUXNET stations in urban and rural settings and synthesizing the differences in urban and rural temperature under different climatic regimes would provide us a pathway to understand the urban heat island effect. Information available on the infrastructure characteristics and the type of pavement could also be useful in explaining the spatial variability in the difference between urban and rural temperature. Understanding how the sensible heat flux varies between urban and rural regimes across different hydroclimatic regimes (i.e., arid vs humid) as the water availability in the urban landscapes control the sensible heat.

We argue Budyko's supply and demand framework should not be considered just for long-term water balance. As the supply and demand framework is based on conservation equations, it could be exploited for understanding and quantifying the spatial variability in land-surface fluxes under natural and human-altered landscapes. Figures 4-6 provide an extension of the Budyko framework for understanding how land-surface fluxes are modified due to human influence. Understanding the key drivers that alter the spatial variability of land-surface fluxes using the modified and extended Budyko's framework should help in identifying the relevant low-dimensional attributes that control the regional hydroclimate of human-altered watersheds/landscapes. For long-term ET, it is the aridity index. For infiltration, it is the ratio of infiltration capacity to rainfall depth. For reservoir operation, it is the ratio of human water demand to available water in reservoir. For environmental flows, it is the competition with human demand and available water. For the urban heat island, it is the water availability that suppresses the sensible heat due to evaporative cooling. Thus, the low-dimensional attribute varies for each environmental issue. Further, extending Budyko's framework for such anthropogenic causes should enable the explicit decomposition and attribution of changes in land-surface fluxes at various temporal scales resulting from changes in local/regional hydroclimate or watershed-level modification. To refine existing hydroclimatologic models and datasets developed at the regional, continental, global scale, a synthesis study is neeeded to understand how the land-surface response varies across natural and human-altered watersheds. Such a synthesis effort is also expected to enable a systematic decomposition of watershed-scale

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anthropogenic influences and large-scale climate impacts in modulating land-surface fluxes at a global scale, providing a tribute to Budyko's legacy.

Opportunities, challenges, and relevance to other hydrologic synthesis studies

Emphasis on understanding the complex interactions and feedback between human and hydrological systems has renewed focus on "Socio-hydrology" (Sivapalan et al., 2012). The impact of water use, land use and land cover and other anthropogenic influences on watershed runoff and the associated non-stationary issues have been referred to as the study of "Hydro-morphology" (Vogel, 2011). Vogel et al. (2015) argue that "to resolve the complex water problems that the world faces today, nearly every theoretical hydrologic model introduced previously is in need of revision to accommodate how climate, land, vegetation, and socioeconomic factors interact, change, and evolve over time." Study of the interaction between humans and the earth system has also received considerable support from various agencies such as the National Science Foundation, the National Institute of Food and Agriculture and the U.S. Geological Survey with targeted programs (e.g., Water Sustainability and Climate, Coupled Human-Natural Systems and Innovations in Food-Energy-Water Systems, NAQWA). Thus, evolving the Budyko framework to understand how land-surface responses vary under natural and human-altered landscapes will also support various ongoing studies on the impact of human influence on hydrological systems.

Enhancements to the Budyko framework will also support other ongoing activities that focus on improving the ability to predict the hydrologic behavior of natural and ungauged watersheds. As competition for water has increased, there has been increasing attention placed on the need for water availability information at ungauged locations, even in regions where water has not been considered in the past to be a limited resource. For these reasons, the decade from

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2003 to 2012 was recognized by the International Association of Hydrological Sciences as the Prediction in Ungauged Basins (PUB) Decade (Sivapalan et al., 2003). Blöschl et al. (2013; tables A7-A10) showed that several methods to predict streamflow in ungauged watersheds have been proposed; however, no one method has been universally accepted or demonstrated to work in all hydrologic settings. Other studies have evaluated predictability in ungauged basins at the global scale (Hrachowitz et al., 2013). Since the Budyko framework provides an approach for improving our understanding of ungauged basins, there is potential cross-fertilization in various ongoing studies for evaluating the extended Budyko framework and datasets for supporting various global- and continental-scale hydrologic initiatives.

Another exciting aspect of the extension of the Budyko framework for considering anthropogenic influences, involves the development of hydrologic indicators for a wide range of purposes ranging from watershed classification, environmental permitting and a variety of water management activities. There is a continuing need to develop hydrologic indicators which are founded in the science of hydrology, for the purpose of watershed classification as expressed so nicely by Wagener et al. (2007). The idea of plotting nondimensional variables, analogous to the nondimensional variables proposed in Figure 1, has a very close association with the development of nondimensional hydoclimatologic indicators for both natural (Weiskel et al. 2014) and human dominated (Weiskel et al., 2007) watershed systems. For example, the aridity and runoff ratios, two commonly used nondimensional hydroclimatic indicators arise naturally from the Budyko framework for natural watersheds. We anticipate that a wide range of new hydrologic indicators, founded on the science of hydrology, yet useful for water management and watershed classification, will arise from the types of studies envisioned here which extend the Budyko framework to accommodate anthropogenic influences.

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One significant challenge in evaluating the Budyko framework under human-altered landscapes would be the availability of data on hydroclimate, storages, and human influences - water withdrawal and land use changes, reservoir storages and releases - at different spatio-temporal scales. The monthly change in total water storage is a critical component of accurate assessments of land-surface fluxes particularly in regions of high anthropogenic influence where storage is impacted by pumping of groundwater resources, or conversion of surface water to evapotranspiration through diversion for irrigation. In addition to the tremendous challenges relating to data availability, there is the open research question of how we can capture the complexity of human-water systems with a low dimensional parsimonious modeling approach. One approach involves a gradual refinement of model features – a top-down approach – as needed (Zhang et al., 2008; Sivapalan et al., 2003). Another strategy involves development of critical data sets and then addition of model features as the spatio-temporal scale of the data permits. Such a global synthesis effort will require sources of several global-scale data sets from a variety of sources, including remotely sensed data. The selection of appropriate data at this scale presents challenges in balancing spatial resolution and uncertain accuracy and consistency among the considered data sets. Findings from another synthesis study titled, "Water Availability for Ungaged Basins" revealed that, as various hydrologic modeling communities converge towards continental-domain hydrologic models, these communities will encounter similar limitations and challenges (Archfield et al., 2015). It is our hope and contention that the Budyko framework can provide a unifying perspective for bridging gaps in hydrologic data availability and model resolution over a wide range of spatial and temporal scales. As shown in this opinion article, the framework can also be modified beyond the traditional long-term balance for understanding how the land-surface responses, runoff and evapotranspiration, vary across natural and human-altered landscapes.

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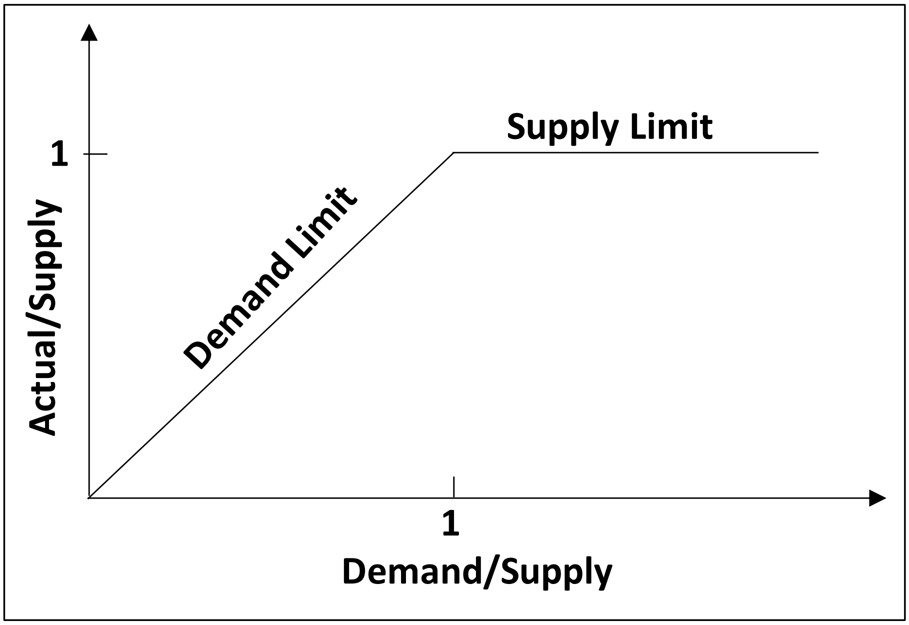

Figure 1: An overview of the Budyko supply and demand framework for understanding the land-surface flux response (actual) over natural and human-altered watersheds. The "limits" concept as suggested by Budyko (1958) quantifies the actual response (Y axis) based on the physical demand-to-supply ratio of energy/moisture over the control volume or the watershed.

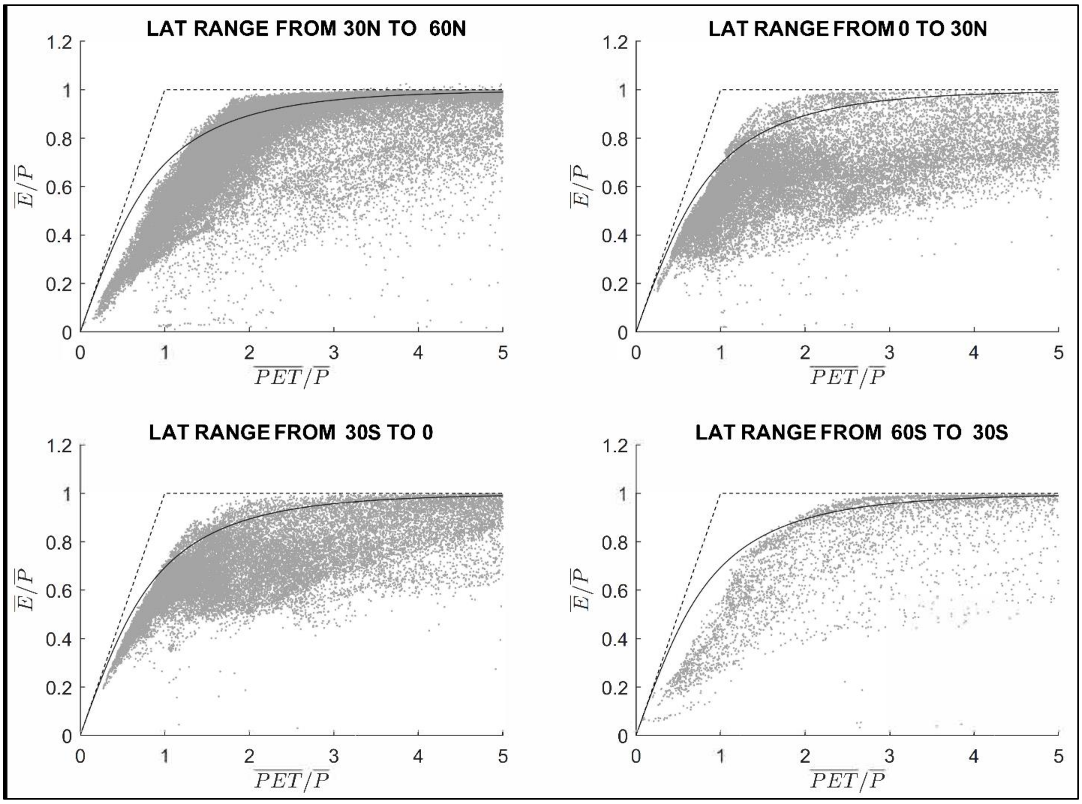

Figure 2: The traditional Budyko framework for long-term water balance along with the asymptotes and the Budyko curve ($\overline{ET}/\overline{P} = \left[\left(1-\exp(-\overline{PET}/\overline{P})\right)*\overline{PET}/\overline{P}*\tanh(\overline{PET}/\overline{P})^{-1}\right]^{0.5}$). The ratio of mean annual potential evapotranspiration ($\overline{PET}$, demand) to mean annual precipitation ($\overline{P}$, supply) explains the ratio of mean annual evapotranspiration ($\overline{ET}$, actual) and $\overline{P}$, and the data points are from GLDAS-2 estimates at the pixel level (0.25 °) for the period 1948-2010 over the northern (top row, 0°-30° and 30°-60° latitudes) and southern (bottom row, -30° to 0° and -30° to -60° latitudes) hemispheres.

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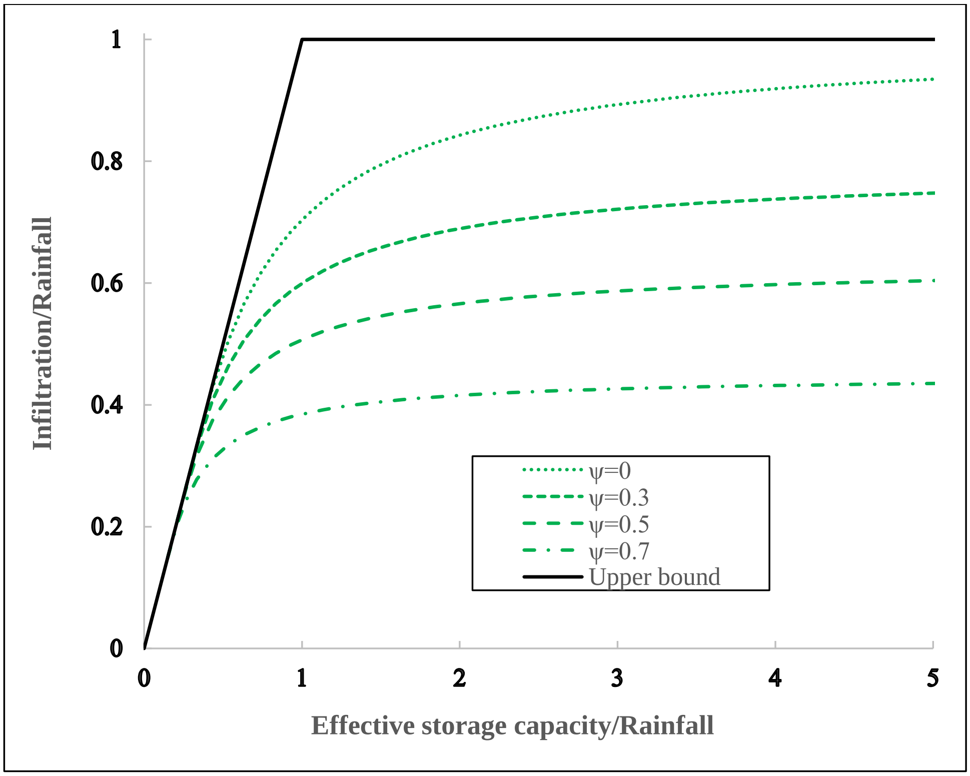

Figure 3: Modeling infiltration in the Budyko's supply and demand framework: the ratio of infiltration (actual) and rainfall depth is a function of the ratio of infiltration capacity (demand)and rainfall depth (supply) as well as the initial soil moisture condition represented by the degree of saturation (ψ) (Reproduced from Wang (2018)).

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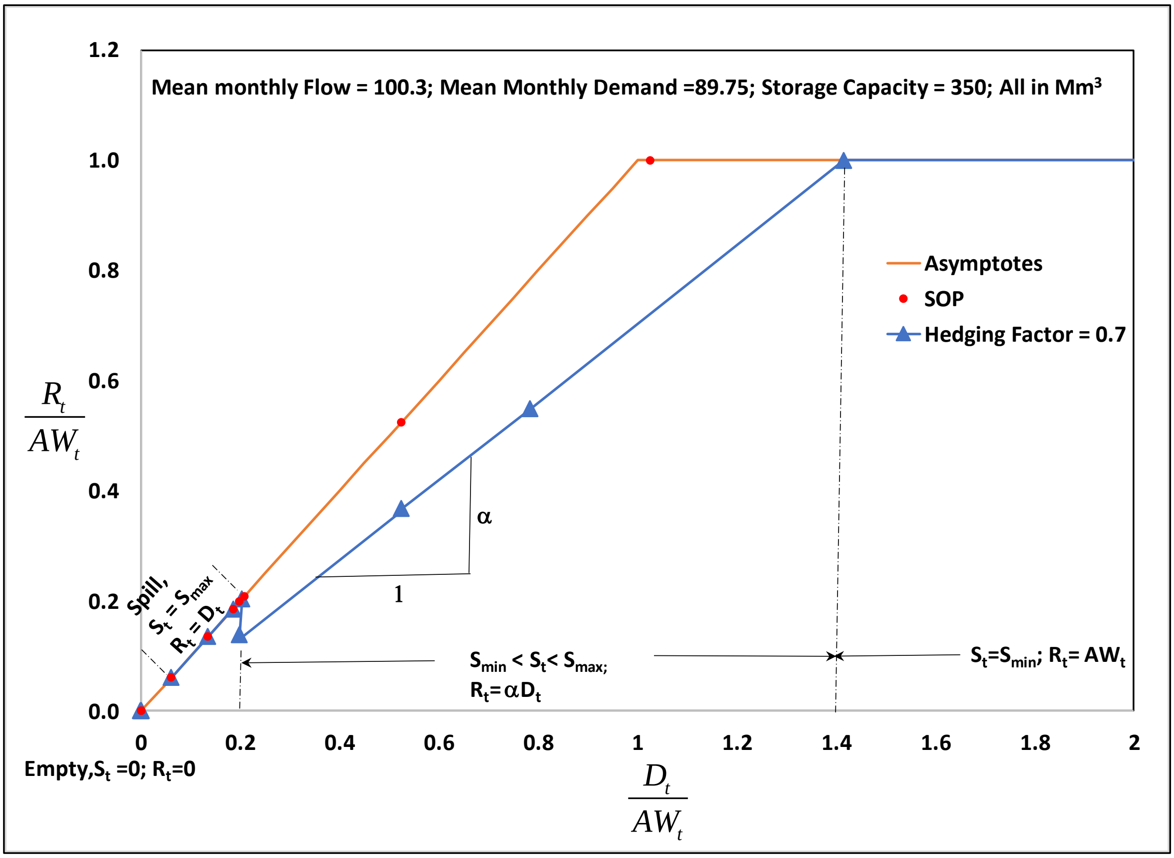

Figure 4: Modeling hedging policy of reservoir operations in the Budyko's supply and demand framework. The standard operating policy (SOP) is corresponding to the asymptotes. For the hedging rule, delivery or release is "actual", available water is "supply", and human use is "demand". For demonstration purpose, a linear function is assumed for the hedging rule (i.e., $R_t = \alpha D_t$). The storage conditions are indicated for the hedging policy alone.

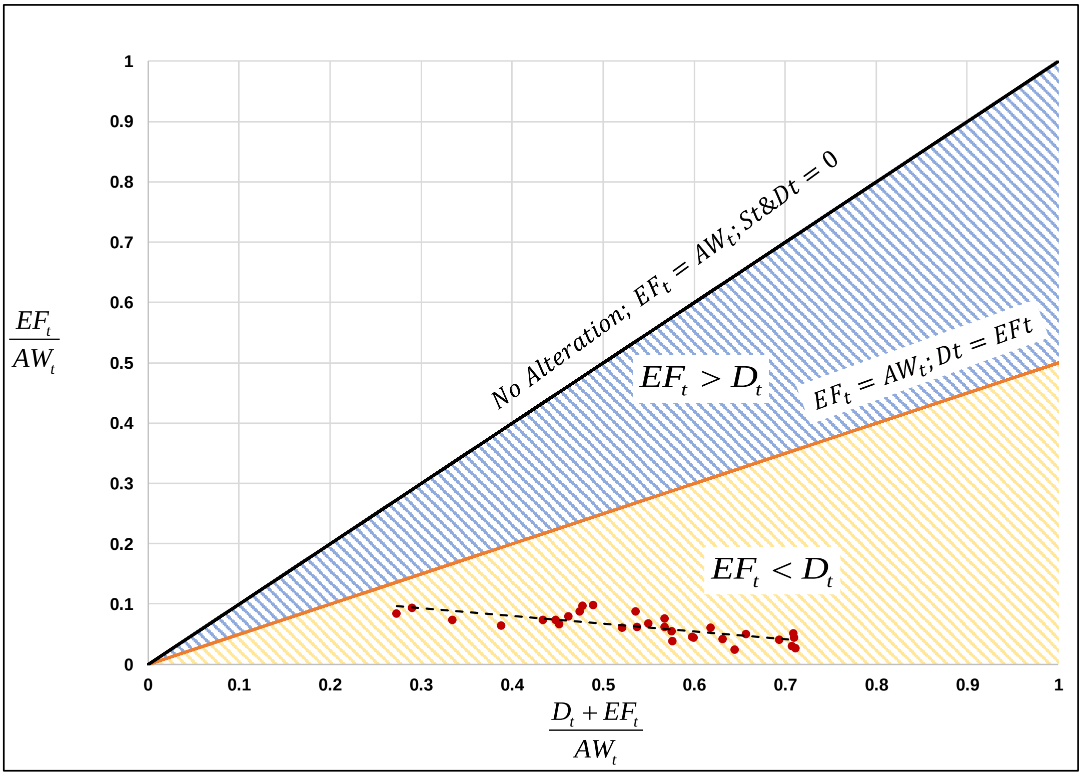

Figure 5: Modeling synthesizing flow alteration in the Budyko's supply and demand framework: the ratio of environmental flow ("actual") and the available water is a function of the ratio the total demand for human and environmental flow ("demand") and the available water ("supply"). Annual flows from Falls Lake (red dots) show human withdrawal for water supply is more than the downstream environmental flow release.

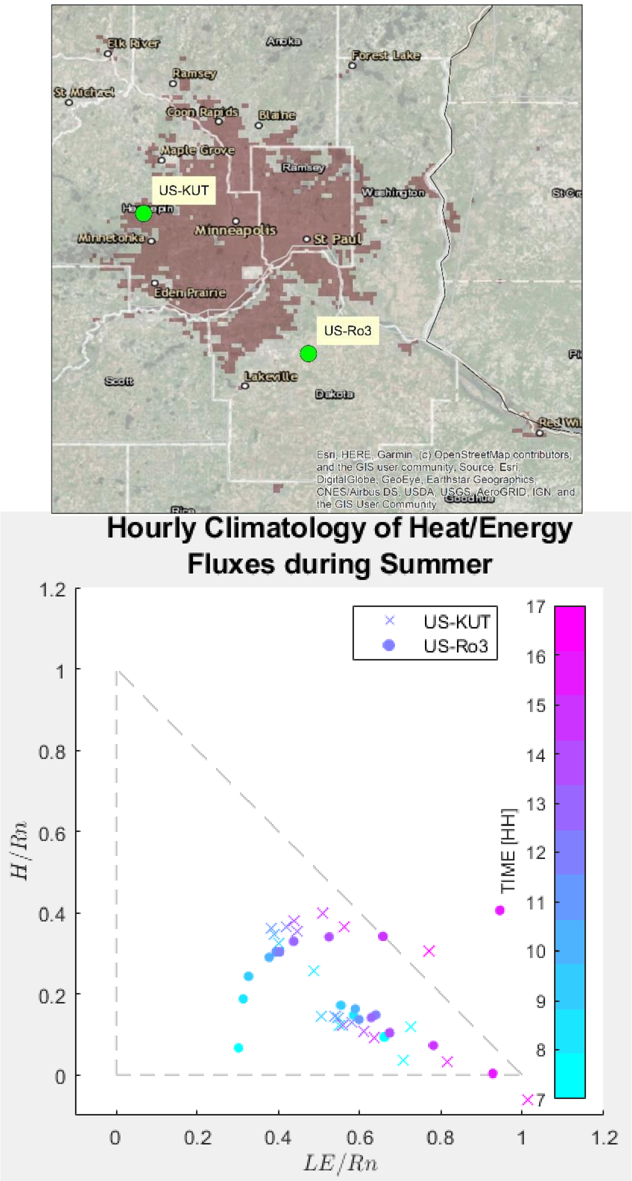

Figure 6: Extending the Budyko framework (bottom figure) for quantifying the sensible heat (“actual”) based on available energy (“supply”) and latent heat (“demand”) for two FLUXNET towers (top figure), US-KUT and US-RO3, from an urban area (brown shaded) and rural area (green shaded). The ratio of mean hourly sensible heat to mean hourly net radiation is plotted against the ratio of mean hourly latent heat to the mean hourly net radiation from the two towers. Figure SI-1 compares the average hourly values from 7 AM to 5 PM for August 2006 and 2007. © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.