Defining Reasonable Use in Transboundary Water Governance

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Abstract
Ambiguity in the principle of "equitable and reasonable use," central to Article 5 of the 1997 UN Watercourses Convention, has long hindered transboundary water negotiations. Without a clear definition, states invoke this principle to justify conflicting claims, prolonging transboundary water disputes across the world. We propose a sequenced interpretation: first define *reasonable use* quantitatively using physical science, then negotiate *equitable use* within those physically reasonable boundaries. Building on Budyko's hydroclimatic framework and the distinction between a river's natural drainage and irrigation services, we propose a definition for "reasonable use" of water resources in a river and show how to identify and quantify the physically sustainable envelope of river use across annual, seasonal, as well as spatial scales. Applied to the Nile and Ganges, this approach reframes disputes not as zero-sum volume allocations but as negotiations over complementary services provided by a shared river. By anchoring transboundary water negotiations in physical realism, this framework reduces contestation over hydroclimatic realities, improves transparency, and provides a quantifiable and replicable tool for resilient treaty design.

Introduction
Allocating shared water resources remains one of the most persistent and politically sensitive challenges in international relations. Article 5 of the 1997 UN Watercourses Convention mandates that states "shall utilize an international watercourse in an equitable and reasonable manner," yet the operational meaning of this mandate remains elusive. Current practice often treats "reasonable" and "equitable" as intertwined normative goals, leaving negotiators to navigate a complex mix of physical realities, political priorities, and societal needs without a shared and actionable understanding of the mandate.

We argue for separating these concepts: defining "reasonable" through quantifiable, physically grounded metrics and leaving "equitable" to context-specific, negotiated processes. This separation does not diminish the role of equity but rather strengthens it by anchoring negotiations in a transparent and evidence-based conversation for a shared understanding and implementation of equitable use.

Our framework builds on Budyko's hydroclimatic theory, which relates long-term water balance to climate drivers, and ecological needs of shared water. This provides a physically defensible starting point: natural function of a river (drainage and irrigation) and the amount of water that can be used without compromising basin-scale ecological function of a river. We acknowledge that physical science-based arguments cannot determine what is equitable. Reasonableness based on physical processes is a necessary starting point but not sufficient to address political, economic, and cultural factors that inevitably will shape any definition of equitable use.

The Ganges and Nile basins illustrate this tension. On the surface, both face familiar transboundary issues over water allocation, but their underlying dispute mechanisms differ sharply. In the Nile, upstream hydropower expansion and irrigation interact with downstream dependence on a single flow source; in the Ganges, seasonal monsoon variability complicates both flood control and dry season flows. Any attempt to apply a universal allocation formula across these basins would be difficult to justify as "reasonable" and would miss the unique physical constraints and opportunities each presents.

Here, we operationalize this definition of reasonable use by applying the Budyko framework, which relates long-term water and energy balances to determine the physical hydrological characteristics of a basin. Building on the distinction between a river's natural drainage service (moving excess water downstream) and its natural irrigation service (naturally providing water to meet deficits), we classify each basin's annual and seasonal regimes. This yields a physically based definition of what a river can sustainably provide without compromising its ecological integrity and long-term productivity. Such a definition does not dictate allocations; rather, they define the envelope of sustainable use — the physical space within which one can begin the conversation about equitable use of shared rivers.

Recognizing these differences is essential for moving beyond generic calls for "cooperation" toward agreements that are physically sustainable, socially acceptable, and politically resilient. This paper proposes that a first step toward such agreements is to decouple and sequence the two principles of Article 5: define reasonable use objectively based on physical science, then negotiate equitable use within those quantifiable limits. We argue that "reasonable" can be framed in hydrological terms using a metric grounded in physical science, before context-specific equity considerations are brought to the table.

By integrating hydrological metrics with a sequenced legal interpretation of Article 5, this work bridges physical science and negotiated problem-solving. The approach provides a common evidentiary base for transboundary conversations, making the "reasonable" principle actionable and transparent while leaving the "equitable" principle to reflect each basin's unique history, politics, and development priorities. This combination — physical realism first, political negotiation second — offers a pathway toward agreements that are both sustainable in a physical sense and legitimate in a societal sense. This paper attempts to establish the physical realism of reasonable use.

This framing has several advantages. It reduces disputes over quantifiable hydrological metrics, narrows the range of technically feasible options, and creates a common evidentiary basis for negotiation. However, it does not attempt to resolve differences in values, priorities, or trust— these need to be discussed by the parties involved. By explicitly linking physical science to negotiated problem solving, we aim to make "reasonable use" not just a legal aspiration but a practical tool for transboundary water governance for mutually desirable outcomes.

In this paper, we (1) review the hydrological basis for defining reasonable use; (2) propose a physically grounded, scalable methodology; (3) apply it to the Ganges and Nile at annual and seasonal scales; and (4) discuss how embedding this approach into negotiations can bridge the gap between physically grounded assessments and politically sustainable agreements.

Defining the Reasonableness

The concept of *reasonable use* in Article 5 of the 1997 UN Watercourses Convention can be anchored in hydrologic reality by identifying the physical limits of a river's capacity to serve competing needs. This requires moving from aspirational language to measurable and replicable criteria. We distinguish between two fundamental hydrologic services of a river system: (a) Natural drainage – the capacity to safely convey excess water to prevent flooding and maintain environmental flows; and (b) Natural irrigation – the capacity to supply water and add to soil moisture in the area around the river channel. The term natural irrigation is defined here as the physical process through which the river water irrigates the surroundings either through year round infiltration, or through seasonal flooding. This term does not include engineered irrigation practiced by forcibly removing water from the river using infrastructure such as dams and canals. Such a distinction between natural drainage and irrigation allows us to respect the physical characteristics of a river without any human interventions.

The Budyko framework provides such an integrative, physically based tool to quantify these characteristics. By relating long-term average evapotranspiration to water availability, Budyko curves can diagnose whether a basin or sub-basin is energy-limited (excess water, constrained by energy for evapotranspiration) or water-limited (scarce water, constrained by availability of water). This classification can be made at multiple scales—annual vs. seasonal, wet vs. dry, and national vs. subnational—to quantify how hydrologic constraints may vary across space and time. A detailed description of the Budyko framework is available in Donohue et al. (2007). The climate index (dryness index) is defined by the ratio of atmospheric demand for evaporation (potential evaporation (PET)) to the actual atmospheric supply of water (precipitation (P)). The hydrologic index (also known as evaporative index) is defined by the ratio of actual evaporation (AET) to the actual atmospheric supply of water (P). Budyko postulates that the relationship between the two indices is context independent and can be described by the black line (Budyko curve) in Figure 1. Observations from many different regions support the generalizability of the Budyko curve (Donohue et al. 2007).

The Budyko curve (Figure 1) characterizes two regimes: a regime where evaporation is smaller than precipitation and the rate of evaporation is limited by the availability of energy to vaporize water, and a regime where evaporation consumes all the water provided by precipitation and hence the lack of additional water limits the rate of evaporation. The relationship between dryness index and evaporative index in Figure 1 shows the physically sustainable envelope that can be used to define reasonable use.

Precipitation as an input to a river basin is primarily partitioned into two components: runoff and evaporation. Under the energy-limited regime, runoff is produced at the hillslopes, as the difference between precipitation and evaporation, and rivers take the task of transporting that water away, driven by the force of gravity. In the absence of a river channel network and topographic gradients, the generated runoff piles up on the hillslopes leading to flooding and swampy conditions. The main hydrologic service of the river network, under these conditions, is to transport the water generated by runoff away, draining the soils, enabling growth of natural vegetation. Some major rivers such as the Amazon and the Congo flow across vast basins that lie within the energy-limited regime, transporting substantial loads of water and sediment downstream and ultimately discharging into the oceans. However, other rivers, such as the Nile, Tigris, and Euphrates, carry water from energy-limited sub-basins into water-limited sub-basins. Under the water-limited regime, no runoff is generated because all the precipitation is consumed by evaporation. Nevertheless, some rivers flowing into sub-basins dominated by this regime may flood surrounding valleys and irrigate soils naturally.

Here, we emphasize that two important "hydrologic" services of rivers are to offer natural drainage for some sub-basins, and to offer natural flooding and irrigation in other sub-basins.

Which of these services dominates would depend on the "climate" and "hydrology" of the basin considered (see Figure 1). Hence, in discussing and implementing the water convention, we need to interpret the "reasonable utilization" concept considering these two hydrologic services offered by the river. The rationale behind this concept stems from the notion that these hydrologic services physically define and quantify the how the resources are utilized without any interventions.

There are two categories of international rivers: rivers that provide spatially uniform hydrologic service draining the soils, and eventually discharging excess water to the ocean and rivers that provide a mix of hydrologic services: draining the soils in upstream sub-basins, followed by irrigation of soils in downstream sub-basins. To illustrate the applicability and efficacy of Budyko framework in defining the reasonable use, we will examine two transboundary basins: the Ganges and the Nile (Figure 2).

We must emphasize that hydrologic "reasonableness" is *necessary but not sufficient* for determining "equitable utilization". Physical science-based observations and rationale will provide the context independent and quantifiable boundaries—e.g., minimum environmental flows, maximum irrigation withdrawals given basin's physical characteristics. This physics first and negotiation next approach provides a common vocabulary for transboundary conversations, making the "reasonable" principle quantifiable while leaving the "equitable" principle to reflect each basin's unique history, politics, and development priorities.

Case Study 1: Ganges River Basin

At the annual scale, the Ganges River basin appears dominated by drainage services, reflecting the overwhelming influence of the monsoon. Vast volumes of water — hundreds of cubic kilometers in August and September — are transported downstream, draining catchments in India and Bangladesh and preventing widespread waterlogging (Figure 1). This drainage service benefits India and Bangladesh during the monsoon season but in some years may impose substantial costs on Bangladesh, where excess flows can create devastating floods (Figures 3 and 4).

The picture changes dramatically at the seasonal time scale. During the dry season, the Ganges transitions into an irrigation regime, almost everywhere, with markedly reduced flows across northern India. Here, water scarcity rather than excess becomes the defining condition. The same river that drains excess rainfall in the wet season is dominated by irrigation service in the dry season.

This stark seasonal asymmetry highlights why an annual average alone cannot define "reasonable use" in the Ganges. Physical science shows that reasonableness must be anchored in recognition of the dual hydrologic services: drainage during the wet season and irrigation during the dry.

For the Ganges, hydrologic diagnostics suggest that negotiations should explicitly account for seasonal asymmetries. A physics-based framing makes it reasonable for India to acknowledge Bangladesh's costs of drainage services in the wet season, just as Bangladesh should recognize

India's dependence on irrigation services of the Ganges in the dry season. This opens the door to cooperative arrangements such as seasonal flow-sharing agreements, joint flood-control infrastructure, and dry-season augmentation strategies, rather than zero-sum volume allocations.

Case Study 2: Eastern Nile River Basin

The Eastern Nile, sourced in Ethiopia and flowing into Sudan and Egypt, exemplifies rivers where spatial variability is more dominant than seasonal variability in the distribution of hydrologic services. Here, the natural character of the river, in all seasons, shifts from drainage to irrigation regimes along the course of this water body.

At the annual scale, the Ethiopian highlands lie firmly in the drainage regime, with steep terrain and intense rainfall generating runoff that the river conveys downstream. In contrast, northern Sudan and Egypt occupy a stretch of the river dominated by natural irrigation services, year round.

This spatial asymmetry is even sharper during the rainy season (Figure 5). Ethiopia benefits immensely from the drainage service of the river transporting monsoon runoff, while Sudan and Egypt rely heavily on irrigation services. During the dry season, however, Ethiopia itself may experience a mixed regime, while Sudan and Egypt maintain their irrigation service. The hydrologic diagnostics therefore show a river system offering significantly different services to its different riparian countries, for most of the year (Figures 5 and 6).

This framing provides a more nuanced interpretation of reasonable use in the Nile. It is physically reasonable for Sudan and Egypt to rely on the irrigation service of the river, most of the year, while Ethiopia may justifiably seek limited allocations for supplementary irrigation during the dry season. The real question to be negotiated is not whether Ethiopia has a right to use the Nile, but how much water can be allocated to Ethiopia while respecting the natural character of the river and its irrigation services downstream.

For the Nile, a service-based definition of reasonableness reframes the dispute from a zero-sum allocation of volumes to a complementary recognition of drainage and irrigation services. This makes it possible to negotiate equitable allocations that allow Ethiopia to meet its dry-season needs without compromising Sudan's and Egypt's reliance on irrigation. Such a reframing shifts attention toward cooperative benefit-sharing and adaptive treaty mechanisms, rather than rigid allocations that risk misalignment with natural hydrologic regimes.

Discussion

The Ganges and Nile case studies demonstrate why a universal allocation formula is neither reasonable nor practical. In the Ganges, the primary challenge lies in **temporal asymmetry**: the same river shifts from a drainage service in the wet season to an irrigation service in the dry season, creating sharply different risks and benefits across time. In the Nile, the central issue is **spatial asymmetry**: upstream reaches provide drainage services, while downstream reaches depend almost entirely on irrigation services. These differences underscore that "reasonable use" cannot be defined by generic rules or volumetric shares; it must be grounded in the unique hydrologic character of each basin. By distinguishing drainage and irrigation services across time and space, our framework provides a physically consistent foundation for equitable negotiation that respects the diversity of basin realities.

Together, these contrasting dynamics illustrate the need for a sequenced framework: defining reasonable use first through hydrologic diagnostics and then negotiating equitable use within those physically grounded quantifiable boundaries. Our analysis demonstrates that the principle of "equitable and reasonable use" can be strengthened by sequencing its two components. By defining *reasonable use* through physical diagnostics, we establish transparent and quantifiable boundaries for what rivers can sustainably provide. Within those boundaries, *equitable use* becomes a matter of negotiation, reflecting context-specific histories, vulnerabilities, and aspirations. This sequencing reframes transboundary water disputes: instead of beginning with contested claims, parties begin with a shared recognition of hydrologic realities and then move to the political question of how to share river services within those physical conditions.

Applied to the Ganges and Nile, this approach highlights both the power and the limits of physical science. Hydrologic diagnostics reveal how these basins differ fundamentally in character: the monsoonal pulse of the Ganges versus the upstream drainage and downstream irrigation services of the Nile. These distinctions underscore that disputes often perceived as generic allocation conflicts are, in fact, rooted in basin-specific physical dynamics. Treaties and negotiations that ignore these differences risk misalignment with natural constraints and eventual failure. At the same time, diagnostics cannot substitute for politics. Reasonableness can delimit the sustainable envelope, but only negotiated conversations can determine acceptable and equitable allocations inside that are actionable and sustainable.

The implications of defining reasonable allocation based on quantifiable physical arguments for treaty design are significant. Physically based baselines can reduce the scope for dispute over quantifiable numbers, narrow the range of technically viable options, and improve transparency. They can also reveal complementarities, such as Ethiopia's drainage services and Egypt's irrigation benefits in the Nile, that are obscured when negotiations focus narrowly on volumetric allocations. Yet, physical diagnostics also carry risks. They may be misused in politically charged environments to justify entrenched positions, or they may shift over time with climate change, rendering fixed allocations unsustainable. For this reason, diagnostics must be accompanied by institutions capable of adapting rules as situations evolve.

Embedding humanist principles remains essential. Defining reasonable use purely through hydrology risks overlooking the lived realities of downstream farmers facing salinity intrusion, or upstream communities reliant on seasonal floods. Equity requires engaging with vulnerability, justice, and historical use. This is where our two-steps sequence: physical realism first and political negotiation next becomes vital. It translates quantifiable diagnostics into context-sensitive agreements that respect both physical and societal limits.

Taken together, our results suggest that a sequenced interpretation of Article 5 offers a pathway toward agreements that are physically sustainable and socially legitimate. Hydrologic realism anchors the conversation; political negotiation makes it acceptable. Future work should expand this framework to other basins, such as the Indus, and test its adaptability under climate change scenarios. If adopted, such an approach could move transboundary water governance beyond aspirational rhetoric toward agreements that are both actionable and resilient.

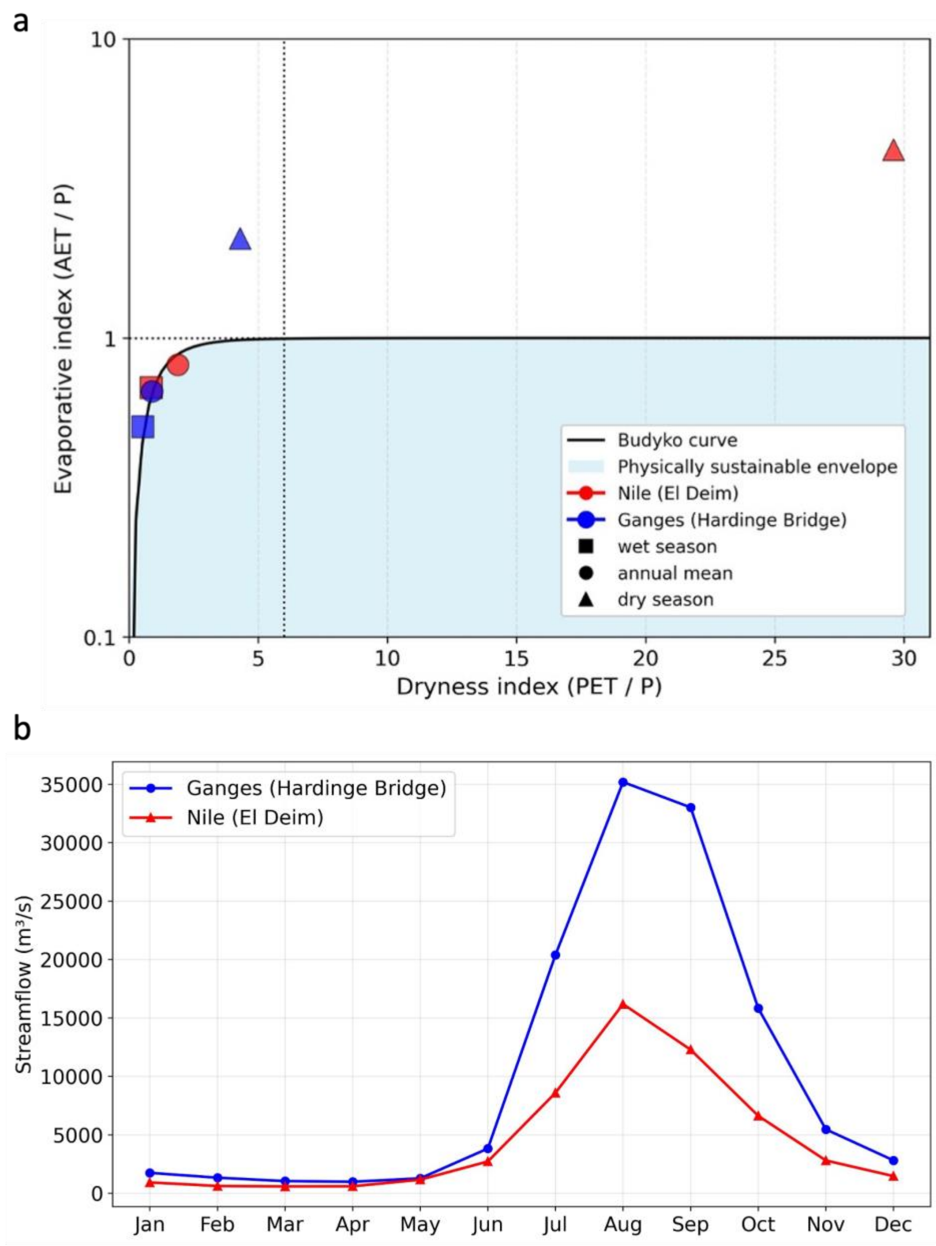

Figure 1. (a) Budyko curve showing the relationship between the dryness index (PET/P) and evaporative index (AET/P) at two representative stations: Ganges (Hardinge Bridge) and Nile (El Deim). Values are calculated using climatological means (1998–2018) extracted from the nearest grid cells of the TerraClimate dataset to each station location. Markers indicate temporal means (triangles for dry season, circles for annual mean, squares for wet season). The physically sustainable envelope is shaded, and the y-axis is shown on a logarithmic scale. The vertical dashed line (PET/P = 6) and the horizontal dashed line (AET/P = 1) represent thresholds

distinguishing natural irrigation regimes (PET/P ≥ 6 or AET/P = 1) from natural drainage regimes (PET/P < 6 or AET/P < 1). (b) Monthly streamflow climatology (m^3/s) at the same stations, based on in situ observations. The climatology in (b) is computed over 1998–2017 for Nile (El Deim) and 1998–2018 for Ganges (Hardinge Bridge).

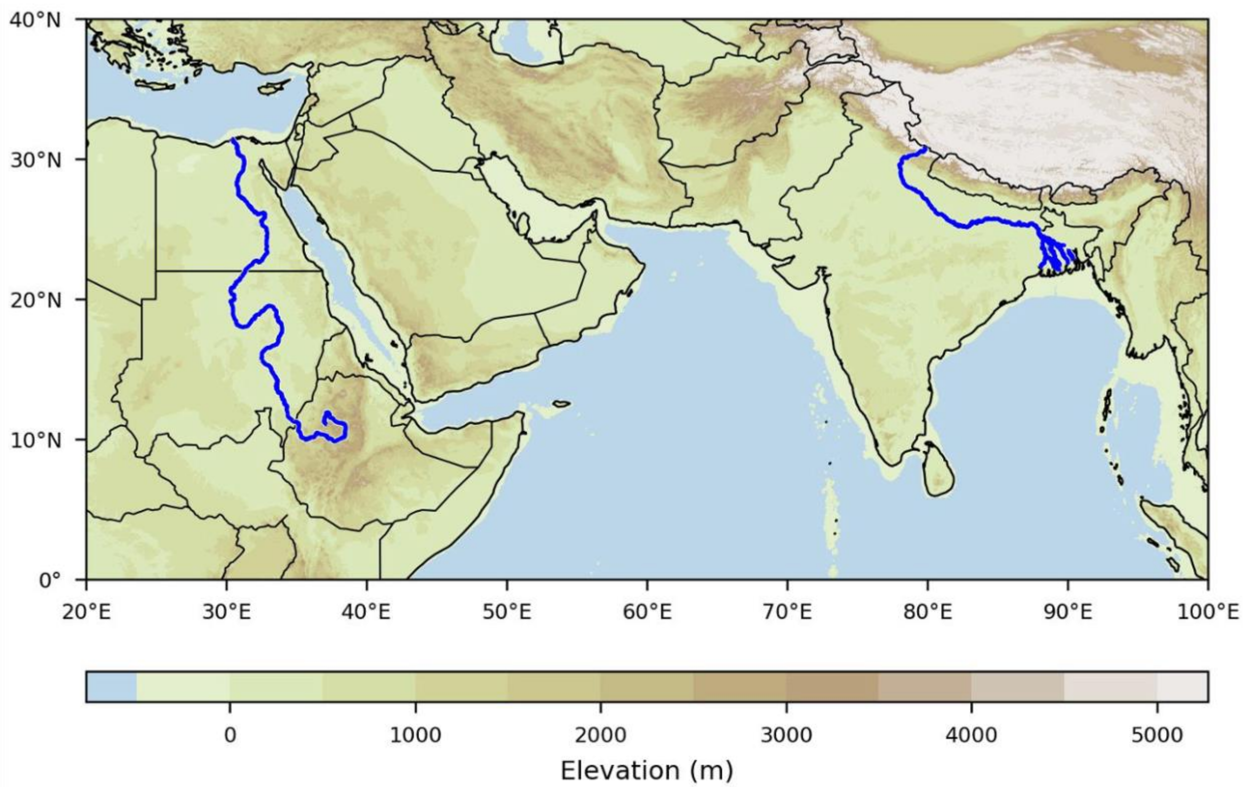

Figure 2. Topographic map of the study region showing the main stems of the Nile and Ganges rivers (blue). Elevation is given in meters above mean sea level. The map covers the area from 20° E to 100° E and 0° N to 40° N.

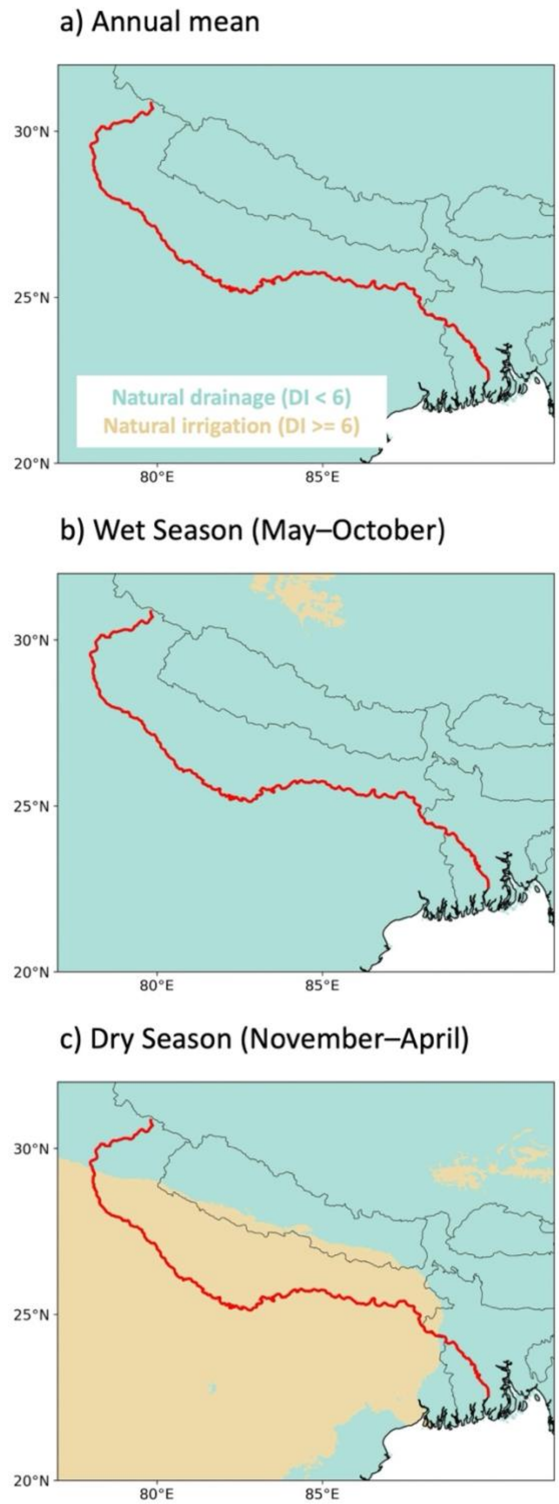

Figure 3. Spatial distribution of natural drainage and natural irrigation regimes along the Ganges River main stem, classified using the dryness index (DI = PET/P). The threshold of DI = 6 distinguishes natural drainage (DI < 6) from natural irrigation (DI ≥ 6). Panels show (a) annual mean, (b) wet season (May–October), and (c) dry season (November–April) conditions.

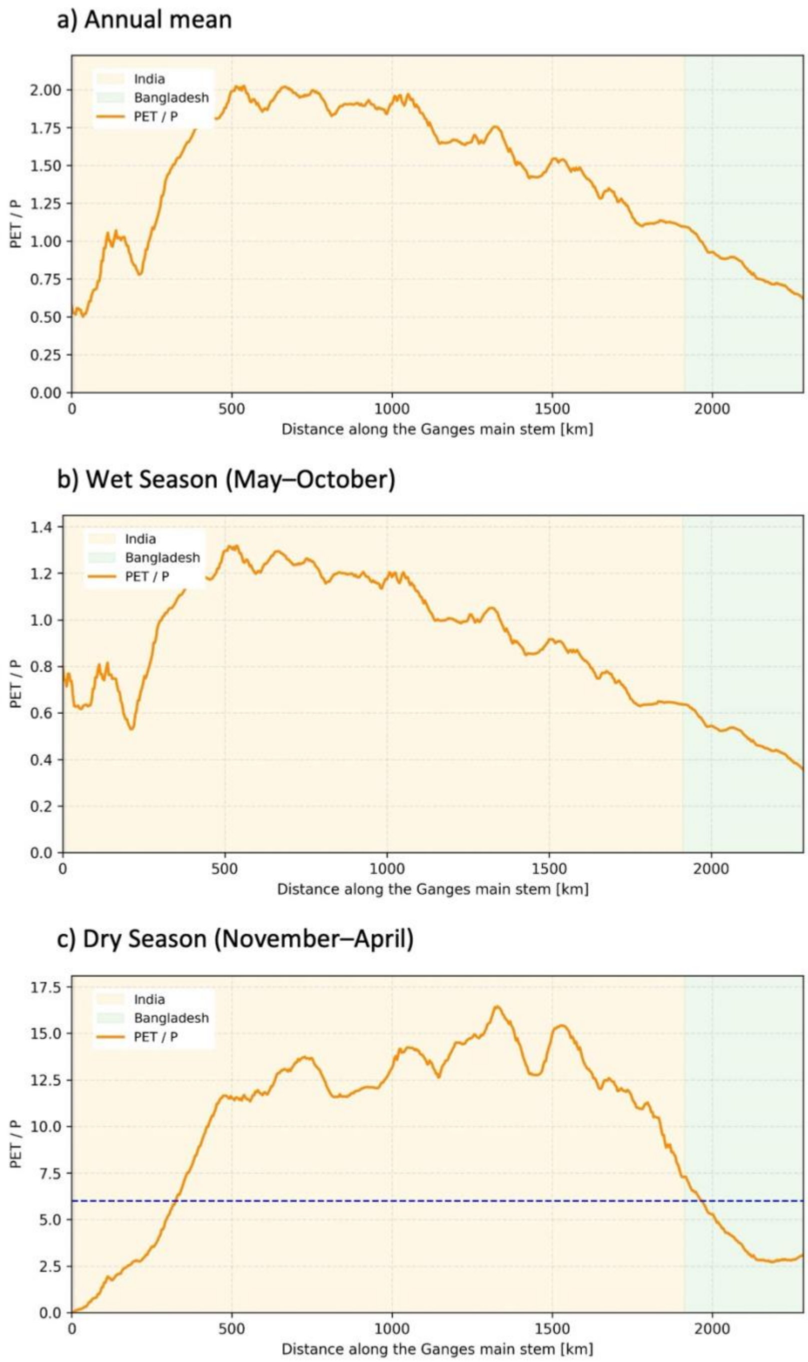

Figure 4. Dryness index along the Ganges main stem for different time periods. The dryness index, defined as the ratio of potential evapotranspiration (PET) to precipitation (P), is shown for (a) the annual mean, (b) the wet season (May–October), and (c) the dry season (November–April). Shaded backgrounds indicate the portions of the river flowing through India and Bangladesh. The horizontal dashed line marks PET/P = 6, a

threshold distinguishing natural irrigation regimes ($PET/P \geq 6$) from natural drainage regimes ($PET/P < 6$).

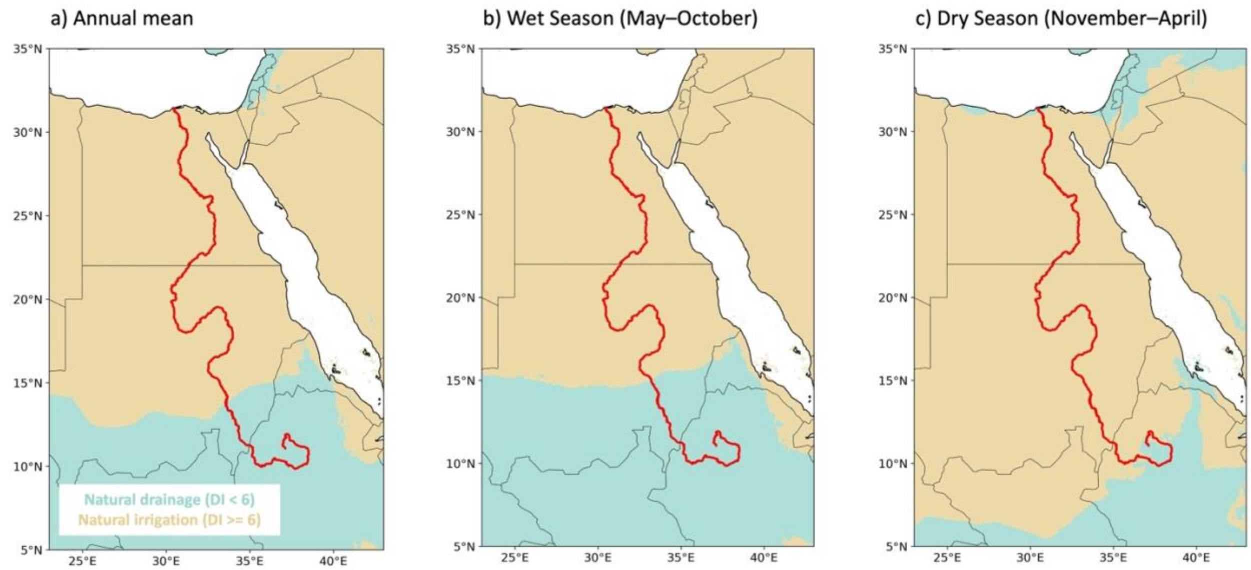

Figure 5. Spatial distribution of natural drainage and natural irrigation regimes along the Nile River main stem, classified using the dryness index (DI = PET/P). The threshold of DI = 6 distinguishes natural drainage (DI < 6) from natural irrigation (DI ≥ 6). Panels show (a) annual mean, (b) wet season (May–October), and (c) dry season (November–April) conditions.

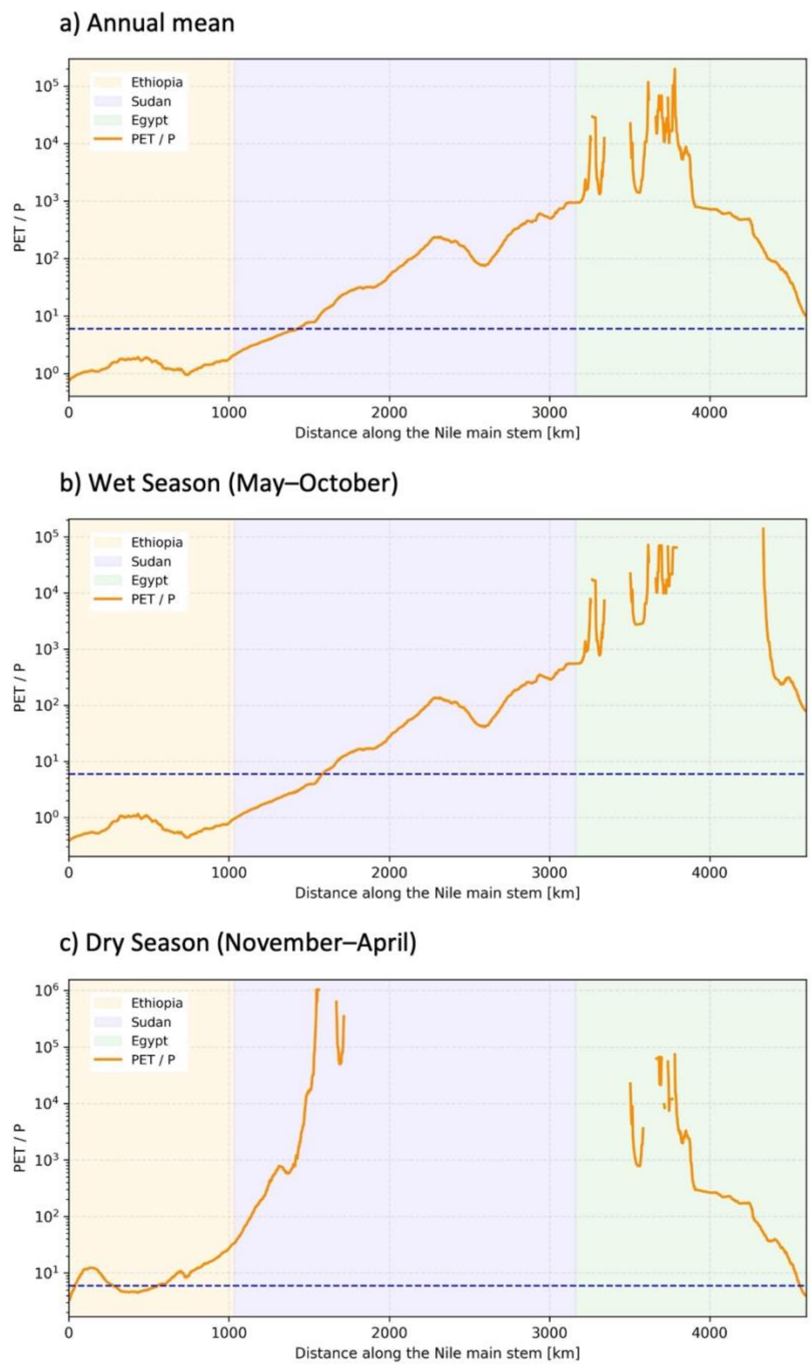

Figure 6. Dryness index along the Nile main stem for different time periods.
The dryness index, defined as the ratio of potential evapotranspiration (PET) to precipitation (P), is shown for (a) the annual mean, (b) the wet season (May–October), and (c) the dry season (November–April). Shaded backgrounds indicate the portions of the river flowing through Ethiopia, Sudan, and Egypt. The horizontal dashed line marks PET/P = 6, a threshold distinguishing natural irrigation regimes (PET/P ≥ 6) from natural drainage regimes (PET/P < 6).

Methods

We applied a two-step framework to the Nile and Ganges rivers, combining observed discharge records with high-resolution hydroclimatic datasets to first define reasonable use and then provide a basis for equitable flow allocation.

Hydroclimatic data

We extracted monthly precipitation (P), actual evapotranspiration (AET), and potential evapotranspiration (PET) for 1998–2018 from TerraClimate (Abatzoglou et al., 2018), a high-resolution (~4 km) global gridded climate dataset. TerraClimate employs climatologically-aided interpolation, blending monthly anomalies from CRU TS4.0 (Harris et al., 2020) and JRA-55 (Kobayashi et al., 2015) with WorldClim climatological normals (Fick & Hijmans, 2017), thereby producing an internally consistent suite of climate and water-balance variables. Basin-scale assessments of water availability were based solely on observed river discharge records. Long-term discharge data were compiled for two key stations: Nile (El Deim) and Ganges (Hardinge Bridge).

Budyko Framework Application

For each of the two river basins (Nile and Ganges), we selected a single representative main stem for analysis. Hydroclimatic variables (P, AET, PET) were extracted from TerraClimate (1998–2018) at 4 km intervals along each river, with values averaged across the surrounding 5×5 grid cells (∼16 km × 16 km) to smooth local variability and capture broader spatial patterns (see Supplementary Figures 1 and 2). The dryness and evaporative indices were then derived at each interval. Grid cells were classified as natural drainage (DI < 6) or natural irrigation (otherwise). This classification was applied consistently across annual, wet-season (May–October), and dry-season (November–April) scales, enabling functional classification of drainage- and irrigation-dominated regimes.

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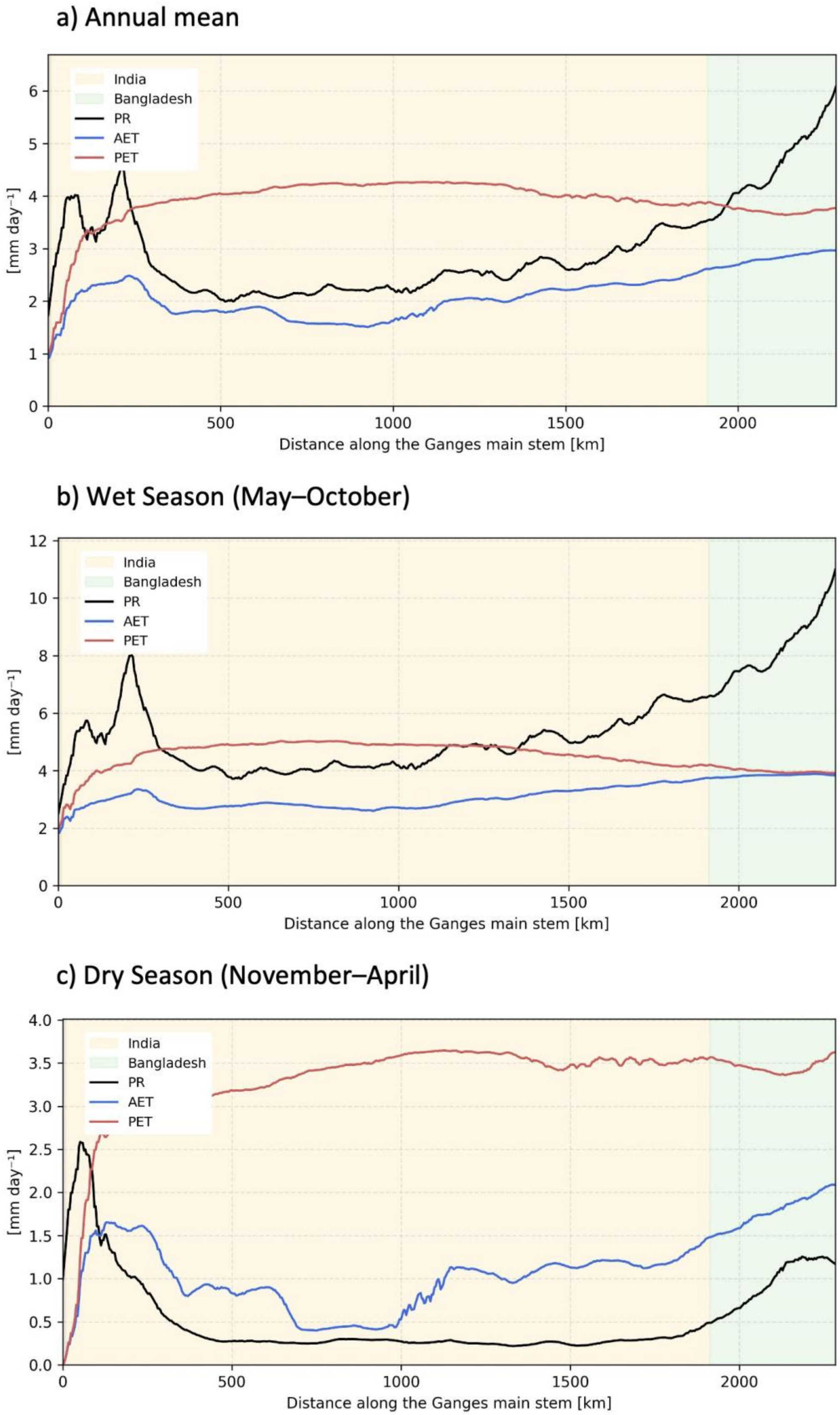
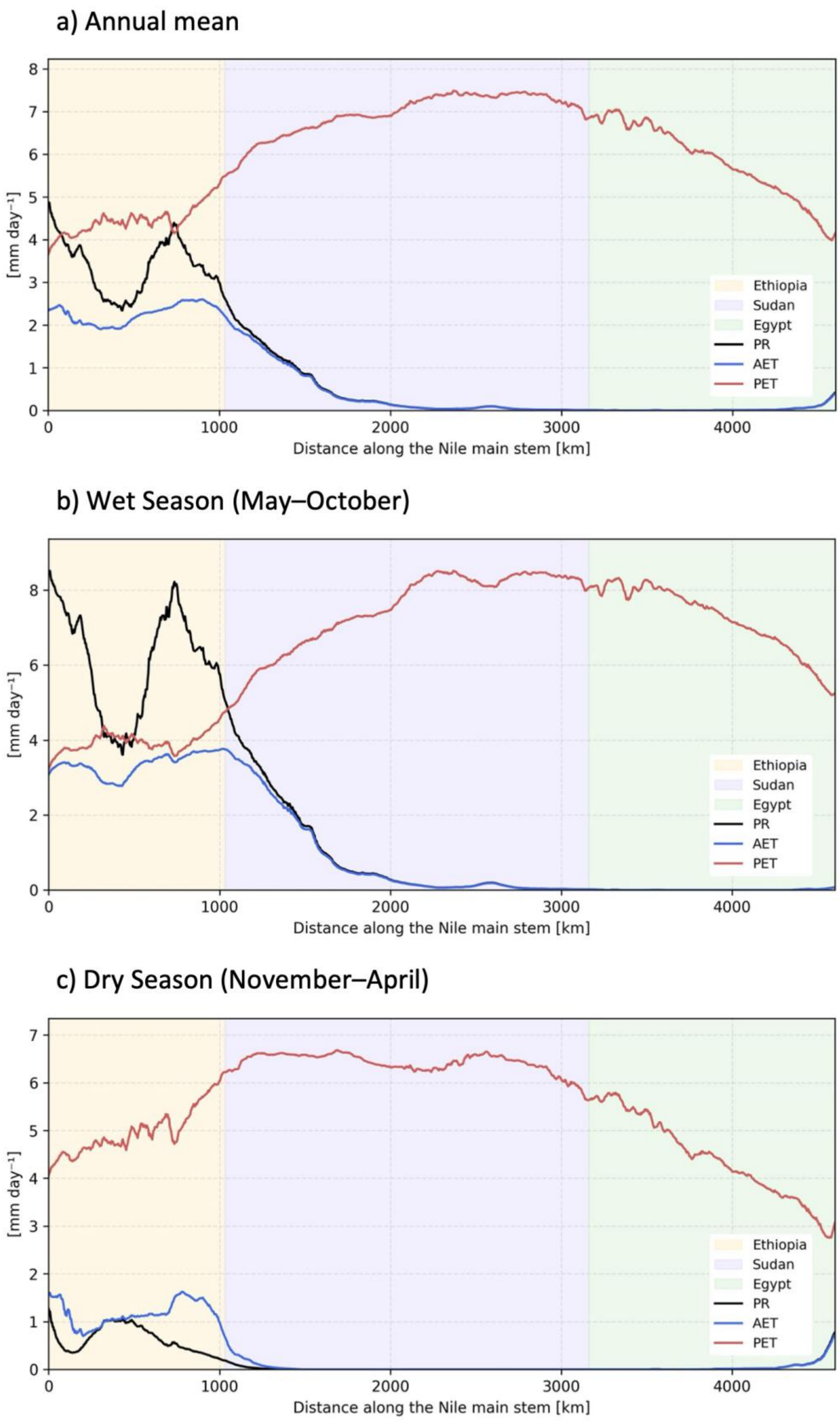

a) Annual mean
India
Bangladesh
PR
AET
PET
[mm day⁻¹]
Distance along the Ganges main stem [km]
b) Wet Season (May–October)
India
Bangladesh
PR
AET
PET
[mm day⁻¹]
Distance along the Ganges main stem [km]
c) Dry Season (November–April)
India
Bangladesh
PR
AET
PET
[mm day⁻¹]
Distance along the Ganges main stem [km]

Supplementary Figure 1. Spatial variations of precipitation (P), actual evapotranspiration (AET), and potential evapotranspiration (PET) along the Ganges main stem for (a) annual mean, (b) wet season (May–October), and (c) dry season (November–April). Shaded background colors indicate the countries through which the river flows (India and Bangladesh).


a) Annual mean
[mm day⁻¹]
Distance along the Nile main stem [km]
Ethiopia
Sudan
Egypt
PR
AET
PET
b) Wet Season (May–October)
[mm day⁻¹]
Distance along the Nile main stem [km]
Ethiopia
Sudan
Egypt
PR
AET
PET
c) Dry Season (November–April)
[mm day⁻¹]
Distance along the Nile main stem [km]
Ethiopia
Sudan
Egypt
PR
AET
PET

Supplementary Figure 2. Spatial variations of precipitation (P), actual evapotranspiration (AET), and potential evapotranspiration (PET) along the Nile main stem for (a) annual mean, (b) wet season (May–October), and (c) dry season (November–April). Shaded background colors indicate the countries through which the river flows (Ethiopia, Sudan, and Egypt).