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Global assessment of the sensitivity of water storage to hydroclimatic variations

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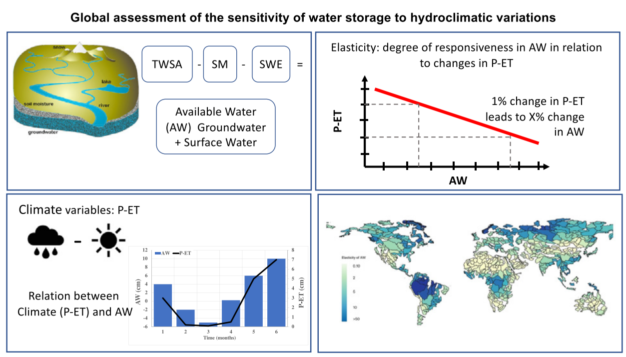
HIGHLIGHTS

- Global basin AW trends suggest that most basins exhibit significant changes in water stores.
- Observation-based available water storage changes demonstrate the effect of short-term climate changes on water resources.
- Hydroclimate elasticity of AW is influenced by seasonality and partitioning predictability as measured by the Budyko ratio.
- Elasticity magnitudes suggest that >1 billion people could experience large changes in AW driven by climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Observing basin water storage response due to hydroclimatic fluxes and human water use provides valuable insight to the sensitivity of water storage to climate change. Quantifying basin water storage changes due to climate and human water use is critical for water management yet remains a challenge globally. Observations from the Gravity Recovery and Climate Experiment (GRACE) mission are used to extract monthly available water (AW), representing the combined storage changes from groundwater and surface water stores. AW is combined with hydroclimatic fluxes, including precipitation (P) and evapotranspiration (ET) to quantify the hydroclimatic elasticity of AW for global basins. Our results detect consequential global water sensitivity to changes in hydroclimatic fluxes, where 25 % of land areas exhibit hydroclimatic elasticity of AW >10, implying that a 1 % change in monthly P-ET would result in a 10 % change in AW. Corroboration using a Budyko-derived metric substantiates our findings, demonstrating that basin water storage resilience to short-term water deficits is linked to basin partitioning predictability, and uniform seasonality of hydroclimatic fluxes. Our study demonstrates how small shifts in hydroclimate flux may affect available water storage potentially impacting billions globally.

1. Introduction

Terrestrial water response to the hydrologic cycle underpins water management challenges, whereby management in increasingly uncertain change must adapt to ensure sufficient resource availability to sustain societal needs and ecosystems. The outcome of hydrologic cycle intensification includes more frequent extreme weather events (Fowler et al., 2021a, 2021b) linked to the increased likelihood of amplification in the magnitude and severity of hydrologic extremes (i.e., floods and droughts) (Slater et al., 2021). A changing climate is expected to perturb the balance between precipitation (P) and the combination of evaporation and transpiration (hereafter lumped as ET) controlled, in part, by the thermodynamic principles whereby warmer air can hold more water vapor. Although hydrologic

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cycle intensification is expected through increased ET and P (Huntington, 2006), the unequal redistribution of water fluxes over terrestrial land remains unclear (Trenberth, 2011). The "dry gets drier, wet gets wetter" (DDWW) paradigm was advanced as a simplification of the complex climatological feedbacks that demarcate the divergence in hydrologic response to climate change. For example, studies documented that water-limited regions are more sensitive to climate change as compared to energy-limited regions (Kumar et al., 2010). Such climate-driven changes in the balance between P and ET transform water availability and have the potential to adversely impact water stress (Eckhardt and Ulbrich, 2003; Kundzewicz and Döll, 2009).

Recent attempts to monitor climate interactions with basin water storage applied remotely-sensed gravity data acquired by the Gravity Recovery and Climate Experiment (GRACE) mission (e.g., Rodell et al., 2018; Scanlon et al., 2021; Thomas and Famiglietti, 2019). Since launch in 2002, GRACE enabled important contributions to our global understanding of the hydrologic cycle (Rodell and Reager, 2023). Removal of modelled processes due to ocean dynamics, solid earth processes and isostatic glacial rebound result in a time varying signal representing integrated changes in water storage over land, termed Terrestrial Water Storage Anomalies (TWSA). Numerous GRACE studies have applied TWSA to address climate change (e.g., review by Tapley et al., 2019). Despite the contribution of GRACE to changes in the water cycle, characterization of basin water storage sensitivity that results from climate change, including anthropogenic influences driven by short-term water deficits, remains elusive.

An observation-based assessment which captures temporal basin water storage change can provide valuable insight to understand fundamental changes in water stores that result from hydroclimatic and anthropogenic factors. Previous studies investigating hydroclimatic sensitivity (Chiew, 2006; Jiang et al., 2014; Sankarasubramanian et al., 2001; Yang et al., 2014a) assumed long-term steady-state basin storage conditions where elasticity of runoff (Q) was estimated in response to precipitation (i.e., P = ET + Q). Global-scale studies (Berghuijs et al., 2017; Berghuijs and Woods, 2016) applied sensitivity assessments at annual timescales, finding that hydrologic elasticities are a function of aridity (e.g., high elasticity in dryland and low elasticity in humid regions). A focus on sensitivity of runoff neglects the role of vital management resources, including groundwater, lakes and reservoirs (Sankarasubramanian et al., 2020; Avanzi et al., 2020), and fails to account for basin stores which often fulfill water demands. For example, surface water reservoirs represent an important component of management schemes, where >70 % of global annual discharge is stored (Döll et al., 2009; Lehner et al., 2011; Zhou et al., 2016). Likewise, groundwater reserves are seen as vital buffers against climate change (Famiglietti, 2014) serving as the primary source for billions of people, and accounting for nearly half of water use for agricultural irrigation globally (Famiglietti, 2014; Siebert et al., 2010). An observation-based water storage sensitivity is valuable to quantify a measure of the change in water stores readily available to fulfill human water demands. A sensitivity analysis using the GRACE satellite observations combined with auxiliary hydroclimate variables is investigated to quantify water storage sensitivity. We focus here on the sensitivity of monthly GRACE-derived water storage changes representing groundwater and surface water stores, defined by Castle et al. (2014) as available water (AW). In our analysis, we assume that water management schemes implemented to mitigate AW deficits are captured at short (i.e., monthly) timescales (Thomas and Famiglietti, 2019; Wang et al., 2011) and that water balance changes are governed by changes in P and ET. Interpretation of our GRACE-based elasticity is aided with a Budyko-derived elasticity metric (Creed et al., 2014). We envisage our results will contribute to robust frameworks to assess future changes in water availability driven by changes in climate and human-environment interactions.

2. Materials and methods

For this study, 431 large (>100,000 km^2) global basins from the Hydrosheds dataset (Level 4; Lehner et al., 2011) are used to constrain basin-scale storage responses as a function of hydroclimatic drivers. Changes in hydroclimatic drivers were examined for each basin using 0.25-deg gridded precipitation (P) and potential evapotranspiration (PET) datasets (CRU TS v4.05; Harris et al., 2020) over the period 2002–2017. The Climate Research Unit (CRU) data has been successfully used to apply the Budyko framework (Chen et al., 2022; Jaramillo et al., 2018; Xu et al., 2013) and is applied here as an internally consistent dataset. Given the lack of a consistent gridded estimate of evapotranspiration (ET), we estimate ET by constraining PET as a function of P applying the Turc-Pike equation (Dooge, 1992) where

$$ET = \frac{P}{\sqrt{1 + \left(\frac{P}{PET}\right)^2}} \tag{1}$$

Gridded hydroclimatic drivers (P, PET and ET) were spatially averaged over each basin while accounting for latitudinal changes in grid areas. Seasonal Mann-Kendall trend tests (Kendall, 1938; Mann, 1945) were applied to test trend significance (given $\propto = 0.05$) for all hydroclimatic time series, while the Sen slope estimator was applied to estimate slope magnitude (Sen, 1968). Calendar-year seasonality of the difference between P and ET (i.e., P-ET) was calculated applying a non-parametric estimator termed the apportionment entropy (AE) (Konapala et al., 2020) given by

$$AE = -\Sigma_{i=1}^{12}\left(x_i/\sum_{j=1}^{12} x_j\right)\, log_2\left(x_i/\sum_{j=1}^{12} x_j\right) \tag{2}$$

where x in Eq. (2) represents a monthly net balance (P-ET). Here, we apply AE to represent uniform seasonality, where an AE value of $\log_2(12)$ reflects homogeneous P-ET over a year while a value nearer 0 reflects high seasonal variability. In general, the higher the value of AE, the less variable P-ET over a calendar year.

The Budyko framework characterizes partitioning of P into ET and runoff as a function of the balance of water and energy on land (Budyko, 1974). The relationship ET/P, the evaporation ratio, and PET/P, the dryness index, is represented as

$$\left(\frac{ET}{P}\right) = \left(1 + \left(\frac{PET}{P}\right)^n\right)^{-\left(\frac{1}{n}\right)} \tag{3}$$

In our analysis, we wish to apply a theoretical Budyko curve across all 431 global basins, and thus have applied a value of $n = 2.6$ (Zhang et al., 2004) in Eq. (3). It is widely recognized that a single landscape parameter (n) cannot capture variability in catchment dynamics (Liu et al., 2021; Liu and You, 2021). However, application of a theoretical Budyko curve complements our proposed interpretive metric. Creed et al. (2014) introduced a measure of elasticity derived from annual variability in basin behavior using a ratio given by the range of dryness over the evaporative index within the Budyko framework. We simplified the metric introduced by Creed et al. (2014) to capture deviation from the theoretical Budyko curve given as

$$\frac{\Delta\left(PET/P\right)\big|_{Budyko}^{Basin}}{\Delta\left(ET/P\right)\big|_{Budyko}^{Basin}} \tag{4}$$

where Δ represents the difference between the theoretical Budyko curve and the estimated basin location within the Budyko plot. The ratio estimated in Eq. (4) is referred to here as the Budyko ratio to distinguish it from previous work (Creed et al., 2014; Domínguez-Tuda and Gutiérrez-Jurado, 2021).

The Center for Space Research (CSR) mascon data (Save et al., 2016) for the period 04/2002–05/2017 was used to compute basin average TWSA in equivalent water height to negate the use of scaling factors usually applied to redistribute water mass changes (Watkins et al., 2015). Linear interpolation was applied to fill temporal data gaps and rectify to a continuous monthly TWSA time series. Available water (AW), representing the combined storage changes attributed to surface water stores (i.e., lakes and reservoirs) and groundwater storage were calculated using a mass balance approach (Castle et al., 2014). AW was extracted from TWSA by removing snow water equivalent (SWE) and soil moisture (SM) by

$$\Delta AW_t = TWSA_t - \Delta SWE_t - \Delta SM_t \quad (5)$$

where Δ denotes a variation for the time mean. The Global Land Data Assimilation System (GLDAS) land water content dataset (https://grace.jpl.nasa.gov) is provided to GRACE users as an independent simulation of land water storage changes. Here, basin average SM and SWE were extracted from GLDAS using the 0.25-degree NOAH output (Chen et al., 1996). Hydrologic output from NOAH is applied for simplicity due to a lack of large-scale observations studies for both SWE and SM in addition to the adherence of the GLDAS water level content database. SM and SWE time series anomalies were estimated by removing the mean over the period 2004–2009 to be consistent with GRACE processing.

To measure the sensitivity of AW to hydroclimatic variables, the concept of elasticity is applied. Elasticity is defined by the proportional change of a variable, here as AW, divided by the proportional change in P-ET. For interpretation, a 1 % change in P-ET would result in a % change in AW as defined by the magnitude of elasticity. Elasticity may be estimated using various formulations (Sankarasubramanian et al., 2001). A bivariate hydroclimatic estimator is applied to calculate elasticity, Ɛ, as

$$\varepsilon_{P-ET} = \rho_x \frac{CV_{AW}}{CV_{P-ET}} \quad (6)$$

where ρ_x represents the cross-correlation between AW and P-ET and CV is the coefficient of variation. Given the nature of groundwater storage and lake/reservoir response to climate (Jasechko et al., 2014), a lag is expected between AW and P-ET. A seasonal lag of up to 3 months was applied to calculate a maximum absolute value of ρ_x. Lognormal distribution estimators were used to calculate the mean and standard deviation of P-ET. The absolute values of mean AW were applied for CV_{AW} given that CV represents the variability of the data around the mean and thus has no meaning if negative.

3. Results

3.1. Trends in P-ET and AW

The hydroclimatic metric, P-ET, deviates from dryness as defined in previous studies (Greve and Seneviratne, 2015) due to positive ET constraints (Eq. (1)) and instead represents initial water availability, i.e., the water that remains within the terrestrial environment. Trend magnitude in P-ET (Fig. 1a) were generally small (median of $7.7e^{-6}$ mm/a), reflective of ET constraints as a function of P. Approximately a quarter of global basins exhibited significant trends in P-ET ($n = 82$). Negative trends were noted in the eastern Amazon and Orinoco basins in South America, while positive trends were noted in northern Canadian basins and sub-basins of the Congo River in Central Africa. Significant trends in P-ET are attributed to prolonged drought (e.g., Australia) or notable changes in precipitations (e.g., northern Canada) (Rodell et al., 2018). Greve and Seneviratne (2015) equated P-ET to account for water availability, finding that 25 % of global land area exhibited significant P-ET trends for the period 1980–1999. Although the study applied their analysis to 0.5-degree grids, the basin-scale trends presented here document 18 % of land areas to exhibit significant P-ET trends.

Trends in AW imply a change in groundwater storage and/or a change in reservoir/lake storage. In comparison to Fig. 1a, trends in AW (Fig. 1b)

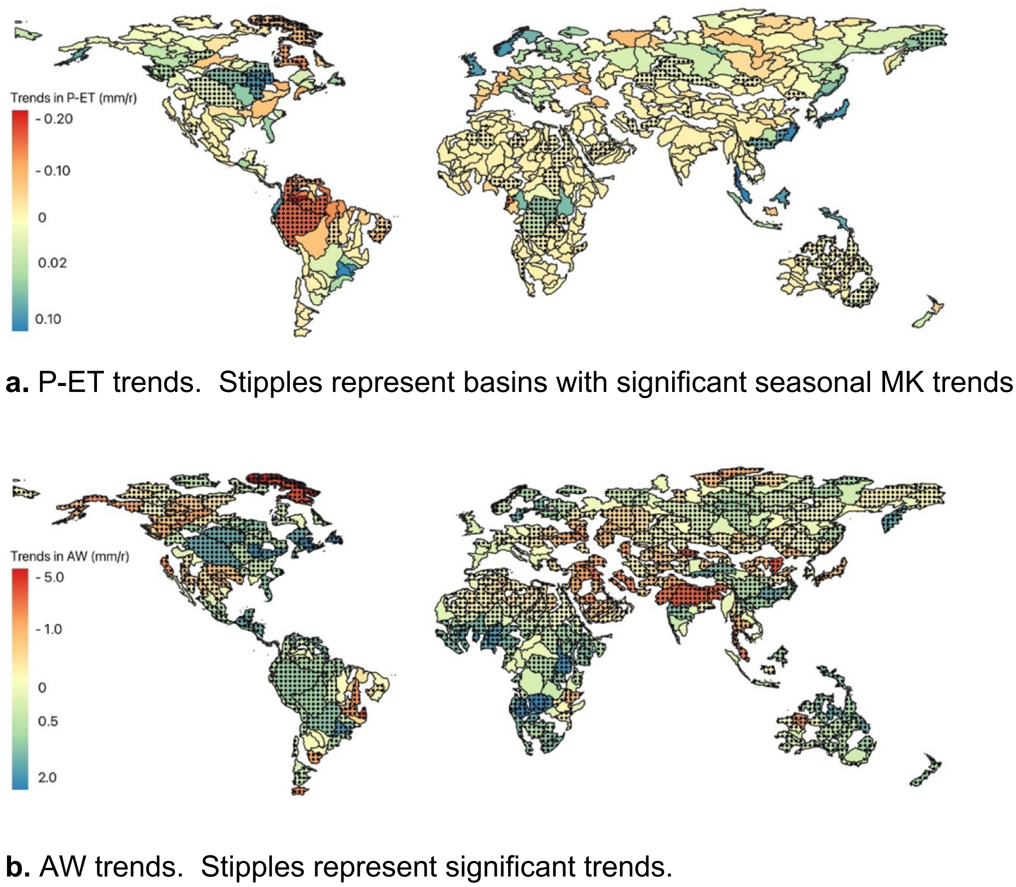

Fig. 1. a. P-ET trends. Stipples represent basins with significant seasonal MK trends.
b. AW trends. Stipples represent significant trends.

were significant for most basins ($n = 362$), approximately half of which exhibit significant positive trends ($n = 184$). Basins in sub-Saharan Africa, central North America and central South America, Australia and northern Asia documented significant positive AW trends. Similarities in AW trends (Fig. 1b) and TWSA trends documented by Rodell et al. (2018) highlight the influence of terrestrial storage capacity (Reager and Famiglietti, 2009), especially given low trend magnitudes in SM and SWE extracted from NOAH (Supplemental, Figs. S1 and S2). Significant trends in 84 % of land areas are documented in AW (Fig. 1b). The land area disparity between significant trends in P-ET and AW are attributed to the role of terrestrial storage capacity, whereby terrestrial storage capacity controls the retention of additional hydroclimatic input (e.g., P-ET) (Reager and Famiglietti, 2009).

P-ET trends in Fig. 1a reflect results applying CRU datasets for both P and PET and use of Eq. (1) to calculate ET. Our use of NOAH to extract hydrologic budget components (Eq. (5)) assumes that hydroclimatic variables are consistent between NOAH and CRU and thus effectively constrain simulated SM and SWE. A comparison between CRU-based estimates of P-ET and P-ET as extracted from NOAH forcing data and model output are presented in Fig. 2. Fig. 2a documents that CRU-based estimate of P-ET systematically underestimate P-ET extracted from NOAH. However, correlation remains high ($\rho = 0.93, pval < 0.001$)) suggesting synchrony between the time series. Additionally, trends in P-ET from both datasets compared well (Fig. 2b), with high correlation ($\rho = 0.89, pval < 0.001$)) although a bias towards underestimation of P-ET trends from CRU as compared to NOAH datasets are noted.

3.2. Elasticity

Global hydroclimatic elasticity of AW was examined across large basins to capture basin water storage change attributed to short-term water demands and water deficits created by P-ET. Our approach assumes that hydroclimate conditions reflected by changes in P-ET lead to observable changes in AW. Results depicted in Fig. 3 present the magnitude of the hydroclimate elasticity of AW, where the value denotes a percent change in monthly AW that would occur due to a 1 % change in monthly P-ET.

Humid, tropical basins (e.g., Amazon and Congo) exhibit relatively high elasticity, where the magnitude of hydroclimatic elasticity of AW is generally >20. These elasticity magnitudes are attributed to monthly deviations in P, as these basins exhibit greater seasonal variability in P versus ET (Figs. S3-S5). Our findings corroborate those of Milly and Dunne (2002) who focused on sensitivity of runoff to P, suggesting that relations between P and net radiation amplify basin sensitivity. High latitude basins in Asia and Europe exhibit similarly large elasticity magnitudes caused by the seasonal nature of precipitation, where winter precipitation is primarily snow. Sankarasubramanian et al. (2001) documented negative correlations between snow pack and runoff elasticity, attributed to the hypothesis that snow pack buffers runoff via changes in runoff timing. Conversely, Rasouli et al. (2022) identified a positive relation between precipitation elasticity and annual runoff in snow-dominated catchments, connecting runoff sensitivity to a function of elevation and precipitation change. Although snowpack is deemed to be removed from TWSA as SWE in the extraction of AW (Eq. (5)), seasonal meltwaters may represent some component of the sensitivity of storage change as captured by elasticity of AW (e.g., meltwater runoff filling reservoir storage). Additionally, high latitude basins exhibit low standard deviations in P with high standard deviations in temperature, suggesting that small shifts in temperature-driven ET can perturb the P-ET balance, resulting in magnified changes in AW (Myers-Smith and Myers, 2018).

In contrast, arid/semi-arid basins exhibited small (e.g., <3) elasticity magnitudes, suggesting that incremental changes in P-ET do not proportionally amplify changes in AW. These water-limited basins are coerced to exhibit little seasonal variability in P-ET (Eq. (1)). Additionally, these basins are characterized as having low storage capacity (Reager and Famiglietti, 2009) and generally decreasing water storage trends (Rodell et al., 2018). Similarly, arid basins were found to exhibit a reduced tendency for high hydrologic response to climate variability (Domínguez-Tuda and Gutiérrez-Jurado, 2021).

Regionally important basins (e.g., Missouri, Danube, Rhine and Ganges) exhibit hydroclimate elasticities between 3 and 5, meaning that small shifts in P-ET have the potential to result in salient changes to AW stores. In these regionally important basins, the potential contribution to AW resulting from reservoir storage is low, where the equivalent water thickness of large reservoir capacities (Lehner et al., 2011) was small in comparison to the monthly climatology amplitude (Fig. S6). Estimated groundwater withdrawals (Döll et al., 2014) highlight greater potential influence, where equivalent water thickness of abstraction volumes represented 12 %, 7 %, 29 % and 10 % of the monthly climatology amplitude for the Missouri, Danube, Rhine and Ganges, respectively (Fig. S7). A shift in P-ET, representing a water deficit, could potentially trigger an increase in short-duration groundwater abstraction (Famiglietti, 2014), thus influencing observed AW changes (Thomas and Famiglietti, 2019).

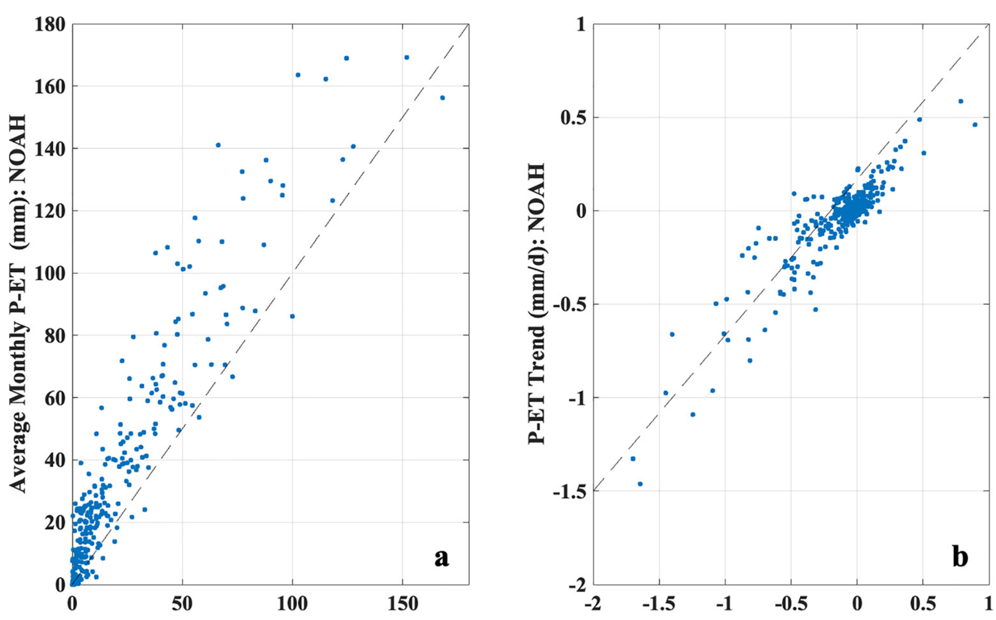

Fig. 2. Hydroclimatology comparisons between CRU datasets used within our elasticity metric and NOAH forcing and model output.

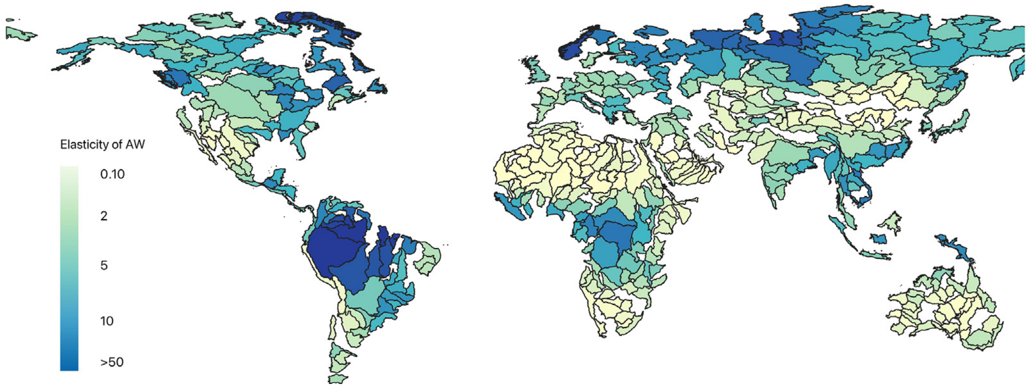

Fig. 3. Hydroclimate elasticity of AW. Colors represents hydroclimatic elasticity of AW magnitude.

3.3. Budyko and role of partitioning

Within GRACE studies, the Budyko curve (Budyko, 1974) has been applied to define hydroclimatic influences on terrestrial water stores (e.g., Sankarasubramanian et al., 2020; Gudmundsson et al., 2016; Xu et al., 2013). Here, the Budyko framework is applied as an empirical organizing principle (Schaefli et al., 2011) to interpret hydroclimatic elasticity of AW. An important supposition in our analysis is that the Budyko ratio (Eq. (4)) adheres to the partitioning predictability hypothesis advanced by Creed et al. (2014). Adherence to the hypothesis suggests that points nearer the theoretical Budyko curve reflect idealized partitioning of water within the catchment, where P is partitioned into PET and Q. Points further away from the theoretical Budyko curve reflect deviations from idealized partitioning, thought to reflect the influence of human action within the catchment (Sivapalan et al., 2011, 2012). Application of the CRU dataset combines observation-based P and derived PET, and thus does not account for catchment Q. However, within the Dunne framework, P, PET and ET reflect drivers of runoff mechanisms and thus serve as proxies for catchment partitioning (Trancoso et al., 2016). Thus, although Q is not explicit, the Budyko ratio infers hydroclimatic controls that regulate catchment water flux.

The hydroclimatic elasticity of AW is differentiated within the Budyko framework as a function of aridity. As illustrated in Fig. 4a, energy-limited catchments tend to exhibit high elasticity magnitudes, whereas water-limited catchments are characterized by lower (e.g., >5) elasticity magnitudes. Our findings generally support modeling-based results of Kumar et al. (2010) who found that water-limited regions are more sensitive to climate change. A comparison of the Budyko ratio and intra-annual variability in P-ET, as measured by AE (Eq. (2)) is depicted in Fig. 4b. Divergence of elasticity magnitudes is notable, where high elasticity basins are characterized by uniform seasonality (i.e., high AE) and small deviations from the Budyko curve (i.e., low Budyko ratios). Conversely, basins with low annual uniformity in P-ET and large deviations from the theoretical Budyko curve tend to exhibit low elasticity magnitudes. The

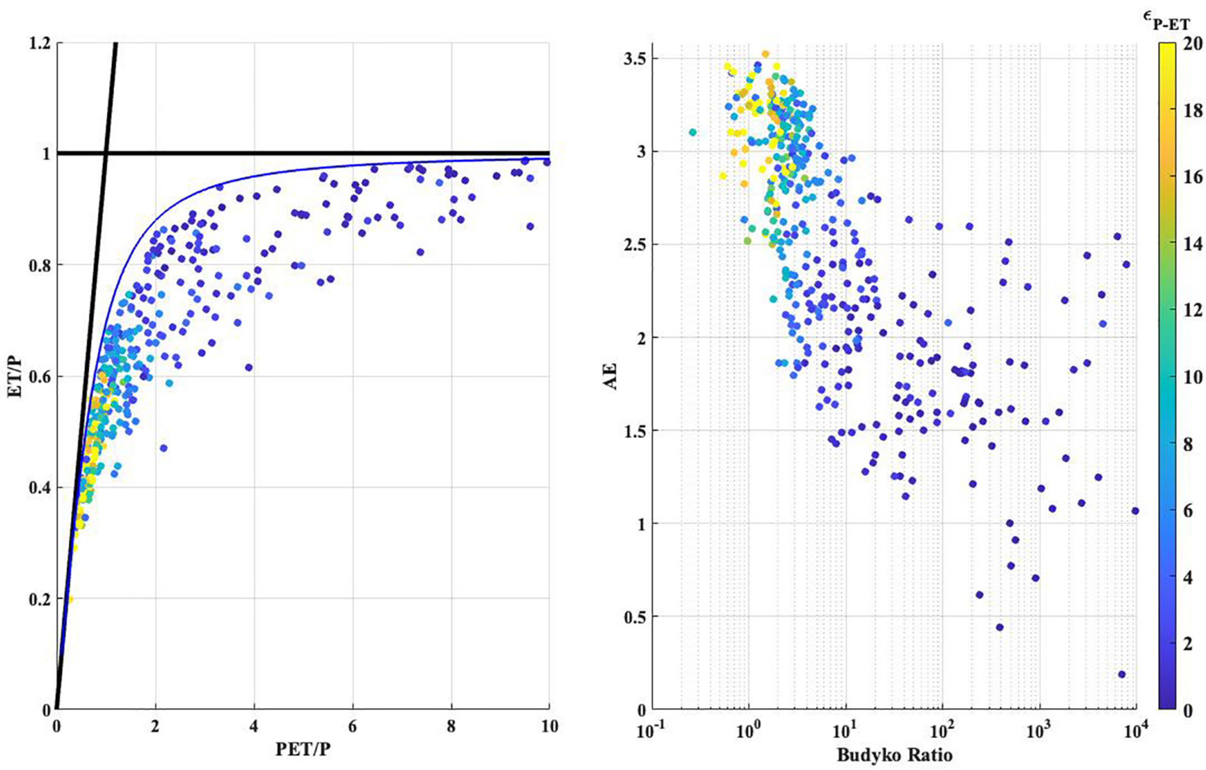

Fig. 4. (left) a. Location of basins within the Budyko plot as a function of elasticity. (right) b. Differentiation of basin elasticities as a function of seasonality (as AE) and distance from the theoretical Budyko curve.

differentiation in Fig. 4b suggest that seasonality is an important factor in our estimate of elasticity, where basins with typically uniform monthly P-ET reflect the highest calculated elasticity magnitudes. Creed et al. (2014) identified their Budyko elasticity was influenced by seasonality, similar to seasonal influences in the hydroclimate elasticity of AW identified in humid, tropical basins (Fig. 2). Williams et al. (2012) similarly related hydrological surplus and dryness indices to influence water partitioning, thus dictating basin placement in the Budyko framework. Yang et al. (2014a) suggest that deviation from the theoretical Budyko curve reflects influence of anthropogenic changes, thus possibly reflecting interventions based on management schemes during periods of water stress.

To corroborate our interpretation of the Budyko ratio as reflective of anthropogenic influence, we extracted irrigation water withdrawal in equivalent water height from WaterGAP (Herbert and Döll, 2019) to reflect human water use. Irrigation influences, whereby groundwater or surface water abstractions are applied to crops, will result in a direct and observable change in AW. Further, indirect changes could result in P-ET where supplemental irrigation would increase ET without effect to P. Additionally, higher P would reduce the need for irrigation application as soil moisture reserves may fulfill agricultural water demands. The relations between the Budyko ratio and extracted irrigation water withdrawals are depicted in Fig. 5. Data depicted in Fig. 5 suggest that basin elasticity magnitudes do not generally correlate with simulated irrigation water withdrawals. The lack of correlation is attributed to multivariate factors that lead to changes in AW that may not be fully captured by comparison with irrigation water withdrawals.

4. Discussion

The GRACE-based elasticity metric provides a new perspective to assess the covariance between an observation of water stores that integrates both surface and subsurface storage and climate change. Our elasticity methodology provides a foundation to appraise transformational changes in available water (AW, Eq. (1)) and the effects of climate. Our assessment of hydroclimatic elasticity of AW provides a quantitative measure of the sensitivity of monthly water stores readily available to fulfill water demands caused by changes in the net difference between precipitation (P) and evapotranspiration (ET) represented as P-ET. Whereas numerous studies evaluated the sensitivity of runoff, often focusing on precipitation (Berghuijs et al., 2017; Chiew, 2006; Domínguez-Tuda and Gutiérrez-Jurado, 2021; Dooge, 1992; Rasouli et al., 2022; Sankarasubramanian et al., 2001), our analysis captures changes in monthly AW as observed by GRACE attributable to monthly P-ET. Our methods broaden understanding of climate and terrestrial water responses that only address groundwater stores (Mohamed et al., 2022; Ouatiki et al., 2022; Scanlon et al., 2022) by combining novel estimates of AW with established sensitivity metrics.

In its original construction, the partitioning predictability hypothesis proposed that climatic points nearer the theoretical Budyko curve reflect idealized basin partitioning of P into ET and runoff (Q). Notably, numerous factors can cause deviation from the theoretical Budyko curve, including poor representation of hydroclimatic variables (e.g., P, PET, ET) which dictate the location of points in the Budyko framework. In our analysis, we use a single hydroclimatic dataset, CRU (Harris et al., 2020), for both P and PET to mitigate the influence of hydroclimatic variable uncertainty. Additionally, truncation of Budyko theory using a first-order approximation may amplify point location errors due to changes in climatic variables over time (Yang et al., 2014b). Finally, our use of a constant landscape parameter (n) and the Fu equation ignores the potential influence of factors including soil moisture (Gu et al., 2019), climate seasonality (Ning et al., 2017) and land use change (Jaramillo and Destouni, 2015). Our assessment applied the theoretical Budyko curve, and constrained $n = 2.6$ to depict an idealized Budyko relationship. Our specific interest in applying a consistent Budyko relation across all study basins is linked to our interpretation of elasticity magnitudes through the partitioning predictability hypothesis, and we thus assume that the myriad of factors that are linked to the landscape parameter are captured in the Budyko ratio (Eq. (4)). Further, our estimate of ET constrained by P and PET may fail to capture agricultural ET that alters partitioning in addition to withdrawal effects to AW.

The relation between the Budyko ratio and seasonality of P-ET with respect to the hydroclimatic elasticity (Fig. 4b) illustrates a strong covariance between climate and AW. Basins with a combination of high AE and low Budyko ratio tend to exhibit high elasticity magnitudes, meaning that significant changes in monthly AW will occur due to a shift in monthly P-ET. Conversely, basins with low seasonality and high Budyko ratios exhibit low elasticity magnitudes. In these basins, irregularity in AW and deviations in P-ET are commonplace, and thus monthly changes in AW due to P-ET represent normal conditions, leading to low elasticities. Humid basins tended to exhibit higher elasticity magnitudes. In India, previous work (Asoka et al., 2017) related variability in groundwater abstraction and changes in precipitation. In monsoonal-influenced basins, high elasticity would be anticipated given nonuniform seasonality in P-ET (Fig. 4). Li and Quiring (2021) similarly found P to be the dominant driver of hydrological change. However, in their analysis, Li and Quiring ignore the role of basin water storage to meet short-term water demands created by deficits in P. Here, we capture the influence of climate variability in water storage (as AW) by assuming that water balance changes are governed by changes in P-ET and that these changes are captured by GRACE (Thomas and Famiglietti, 2019). A comparison of irrigation water withdrawals, Budyko ratio and elasticity (Fig. 5) failed to identify relations between irrigation water withdrawals and elasticity. The lack of relation can be attributed to numerous factors. For example, in arid regions with uniform seasonality in P-ET, groundwater abstractions may have reached a quasi-steady state condition and thus may not be observable using GRACE (Alley and Konikow, 2015; Thomas and Famiglietti, 2019). Our comparison in Fig. 5 neglects surface water management not directly related to agriculture, including flood management, hydropower and streamflow regulation. The comparison, however, is likely to be impacted by lumping data over the study period, and thus would fail to capture monthly change deemed important in our elasticity analysis.

Within the context of the DDWW paradigm, one would anticipate drier basins to exhibit low elasticity. In this scenario, small changes in P-ET would be negligible given that PET in arid basins is often much larger than P. This assertion is documented in Fig. 3, where arid basins were found to have lower magnitudes in hydroclimate elasticity of AW. The interpretation, however, is likely influenced given ET constraints by P (Eq. (1)). Additionally, precipitation events in arid basins tend to be episodic, leading to low seasonality (Fig. S3). In arid basins, the variability in groundwater abstractions further complicates interpretation. Long-term

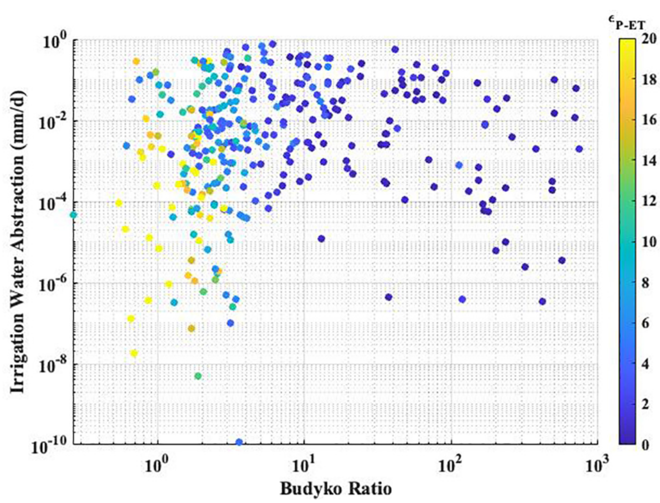

Fig. 5. Irrigation water abstraction (from WaterGAP) compared to Budyko ratio (Eq. (4)). A lack of clear relationship between the degree of irrigation water abstraction and Budyko ratio suggests a complex interaction between AW elasticity and climate change.

groundwater abstractions result in a quasi-steady-state conditions, thus limiting our ability to observe a change in groundwater storage given that GRACE only observes a mass change and not 3-dimensional groundwater flow (Alley and Konikow, 2015; Thomas and Famiglietti, 2019). Thus, we assume that rapid changes in groundwater abstractions are unlikely in arid and hyper-arid basins given the monthly imbalance between P-ET, where groundwater abstraction rates are presumably constant to fulfill water demands.

The risk of water stress in basins that exhibit large elasticity magnitudes is uncertain. However, our results document that basins with large elasticity magnitudes may lack long-term resilience due to rapid changes in AW stores attributed to combination of climate and water use. AW captures two water stores, groundwater and surface water (i.e., reservoirs and lakes), each with discrete residence time and replenishment rates. Adaptation measures and water management schemes could be regulated to alleviate diminishing AW reserves to mitigate depletion of stores with longer residence times (i.e., groundwater) (Konikow and Kendy, 2005). The role of integrated water management may be applied to minimize tradeoffs between terrestrial water storage change, including groundwater and surface water (Huggins et al., 2022). In our analysis, we focus on the combined storage readily available to fulfill water demands and thus are unable to distinguish between groundwater and surface water storage change. Nonetheless, our results provide a metric to evaluate water resources responses to climate, particularly perturbations of the land surface energy balance represented as P-ET.

The elasticity framework allows for monitoring of water storage changes driven by climate. Our evaluation does not account for basin characteristics that may influence elasticity magnitudes which, when combined with the GRACE-based approach described here, offers potential for water availability forecasting. Ultimately, our evaluation of climate and water resources readily available to fulfill human water demands holds important implications of water availably given covariable changes in climate and water resources.

CRediT authorship contribution statement

B.F.T. designed and performed research. B.F.T. and J.N. analyzed data and wrote paper.

Data availability

Data used to produce all figures have been deposited in GitHub: https://github.com/wateq101/AW_Elasticity (after review). All data including GRACE data used in this study are publicly available from PODAAC at https://podaac.jpl.nasa.gov/GRACE. The GLDAS land surface model results are from https://ldas.gsfc.nasa.gov/gldas. Hydroclimate data (P and PET) are from https://catalogue.ceda.ac.uk. All other study data are included in the article and/or SI Appendix.

Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162958.

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