We highly appreciate the time and effort that the Reviewer has dedicated to providing feedback on our manuscript and are grateful for the insightful comments on our manuscript. Please find below our detailed replies to the individual comments.

Major comments:

(1) Reviewer Comment:

The abstract is unnecessarily long and contains repetitive statements. I suggest making it more concise.

Reply:

We completely agree with this suggestion. We will therefore reformulate concisely our abstract to make it shorter in the revised manuscript.

(2) Reviewer Comment:

I am confused by the use of the terminologies "transpiration," "evaporation," and "transpiration" in certain contexts. For example, in Lines 198-205, Equation 5 should represent the overall water balance in a watershed, thus Er_bar should indicate total evapotranspiration rather than just transpiration. In Line 203, author used "potential evaporation", "evaporation". These make me lost.

Reply:

Thank you for pointing this out. In Equation 5: $\overline{E_r} = \overline{P_e} - \overline{Q_O}$, Where $\overline{P}_e$ (mm d⁻¹) is the long-term mean effective precipitation which is estimated by Equation 2: $P_e(t) = P(t) - E_i(t) - dS_i/dt$, where the volume of effective precipitation P_e (mm d⁻¹) represents the fraction of the total precipitation (P) that actually reaches the soil after accounting for canopy interception and the associated interception evaporation Ei (Figure FR1). Interception evaporation Ei is here (Eq. 3) assumed to be equivalent to EP, as evaporation of water intercepted at the surface of leaves is effectively "open water evaporation", i.e. EP. Therefore, Er_bar in Equation 5 represents just transpiration excluding interception evaporation (Ei). Also note that, for brevity, although Er is referred to as transpiration throughout this paper, it also contains soil evaporation, which is comparatively minor (e.g. Brutsaert, 2014) and thus not individually accounted for here. In line 203, we clarified the estimation method of the daily transpiration (Er) based on "potential evaporation (EP)" and "interception evaporation (Figure FR1)", but we will make it clearer in the revised manuscript.
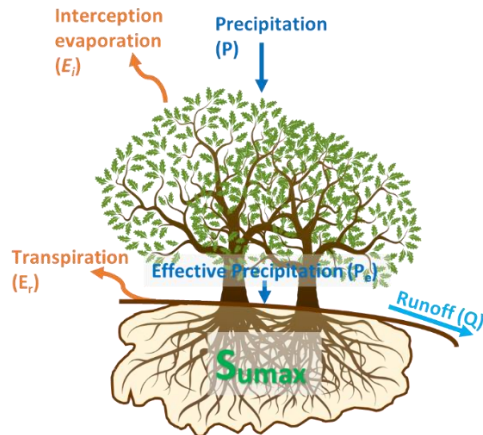
Figure FR1. The concept figure of water-balance method to estimate root zone storage capacity (Sumax).

(3) Reviewer Comment:

Somehow, I am unable to access the data and model in the Code and Data Availability section. Although HESS does not mandate the openness of data/code/user-guides like the Geoscientific Model Development does, I encourage the author to make these accessible to enable readers to replicate or advance the work, thus expanding its impact.

Reply:

Thank you for pointing this out. We agree, and we will upload the model code to an open access repository. All hydrological data are available via open access databases as explicitly highlighted in text and the Data availability section.

(4) Reviewer Comment:

I question the solid physical meaning of the Sumax. Firstly, Sumax is not a directly measurable feature using devices; it seems to be derived from known variables (precipitation, ET, streamflow). Such derivations generally should have a clear meaning, indicating their driving factors. Hence, the question arises: what are the driving factors determining the value of Sumax? Can it be measured without long-term climate data or model calibration? The equations 1-8 calculate Srd.n rather than derive Sumax. The concept of Sumax seems more akin to a feature in a conceptual model, derived from data. Unlike field or laboratory measurable parameters like conductivity in soil flux calculations via Darcy's Law, Sumax cannot be directly measured or validated experimentally.

Reply:

This is indeed a very interesting point. Sumax [mm] is here and in a wide range of previous analyses (Kleidon et al., 2004; Gentine et al., 2012; Gao et al., 2014; Wang-Erlandsson et al., 2016; Nijzink et al., 2016; Singh et al., 2020; Dralle et al., 2021; Hrachowitz et al., 2021; McCormick et al., 2021; Giardina et al., 2023; Stocker et al., 2023; Hahm et al., 2024) defined as the **maximum subsurface water volume between permanent wilting point and field capacity that is within the reach of roots and therefore accessible to plants for transpiration**. As such it is an inherently scale-independent real system property and model parameter. We fully agree that it is currently not directly observable at larger scales. However,

its controlled by the interaction between water and energy supply and the eventual adaptation of vegetation root-systems to satisfy the plant water demand that arises from that interaction. More specifically, it is the amplitudes and the phase lags between peak seasonal precipitation and solar radiation reflect this vegetation accessible subsurface water volume Sumax (e.g. Gentine et al., 2012; Stocker et al., 2023). The interaction between the amplitudes and phase lags is implicit in Eqs. 1 − 8 that underlie the estimation of Sumax (see also in the references provided above).

To put this method into a wider context, let us also consider the physical background of the root zone storage capacity Sumax. To survive dry periods, vegetation needs continuous access to water stored in the subsurface and accessible to roots to satisfy its canopy water demand. As a consequence, the vegetation present at any moment, and in particular its active root system, reflects its successful adaptation to the prevalent climatic conditions in a region (Laio et al., 2001; Schenk and Jackson, 2002; Rodriguez-Iturbe et al., 2007; Donohue et al., 2007; Gentine et al., 2012; Liancourt et al., 2012). Irrespective of geometry, distribution or structure of root systems, **Sumax [mm] and thus the maximum vegetation-accessible water storage volume in the unsaturated root zone of the subsurface**, represents the hydrologically relevant information of root systems (Rodriguez-Iturbe et al., 2007; Nijzink et al., 2016a; Savenije and Hrachowitz, 2017; Gao et al., 2024). Therefore, **the value of Sumax is directly affected by the root depth and root distributions of plants**. In response to a changing environment, the root systems of vegetation continuously adapt to allow the most efficient use of available energy and resources for surviving. The driving factors for roots adaptation are also the driving factors for Sumax, as Sumax inherently represents adaptations of the root system (i.e., the climatic factors, the soil texture, the landscape).

Based on the definition of Sumax, if our research only focuses on one plant or point study, we can estimate Sumax based on the measurements of soil porosity, root depth and root density, without long-term climate data or model calibration (see e.g. de Boer-Euser et al., 2016). However, our study focuses on a large catchment scale. It is not possible to collect the root information for each plant in our catchment, nor do we have sufficiently accurate data on soil properties. It is therefore necessary to adopt a Darwinian perspective (Harman and Troch, 2014) and to estimate effective values of Sumax to reflect the collective and adaptive behaviour of all individual plants within our catchment. Then we choose two common methods which have been used in many previous studies to estimate Sumax. From Eqs. 1 − 8 we then indeed compute the maximum water storage deficits (Srd.n). Then the estimation of the Sumax is based on the Gumble extreme distribution. Previous studies suggested that vegetation develops root zone storage capacities large enough to survive in dry spells with return periods of ~ 20 − 40 years (Gao et al., 2014; deBoer-Euser et al., 2016; Wang-Erlandsson et al., 2016; Hrachowitz et al., 2021). Therefore, we define Sumax,WB here as the maximum storage deficit in a 40-year period so that Sumax,WB=Srd,40yr.

(5) Reviewer Comment:

Sumax is derived from the differences between effective precipitation and transpiration. The calibrated values of Sumax (Sumax,cal) are computed using outputs from the FLEX model, which is calibrated by streamflow. This suggests that the streamflow simulations are reliable within the FLEX model but may not imply the reliability of ET calculations (PET, AET, evaporation, transpiration, etc.). I would like to hear your thoughts on this challenge.

Reply:

Thank you for pointing this out. This is a very interesting observation. Streamflow and evaporation are the most important fluxes in hydrological system. Exactly, it is necessary to make sure both of them reliable. Indeed, we calibrated our model to streamflow observations to make the modelled streamflow reliable. **Firstly, the daily potential evaporation EP** (mm d−1) was estimated using the Hargreaves equation based on the observed daily maximum and minimum temperature, which has been used in many previous studies and shown to be among the most reliable methods (Oudin et al., 2005). **Secondly, for the estimation of actual evaporation**, we used Figure 2b to check if the estimation of actual evaporation is reliable based on our model. Based on the observed long-term data of precipitation and stream flow, we calculate the long-term average actual evaporation Ea by closing the water balance Ea = P − Q, shown as evaporative index: I_E = Ea/P= 1-Q/P = 0.57 (see table 2 in the manuscript) for the entire time period. The total Ea over that time period estimated from our observations is ~ 35.000 mm After calibrating our model based on the entire time period from 1953-2022, we showed the total modelled actual evaporation over 70 years is also ~35.000 mm, which means that that modelled long-term evaporation is consistent with the observations. **Finally,** we used equations 5-6 to estimate **the transpiration (Er)**, which is one part of the actual evaporation (Ea = Ei + Er), based on the long -term effective precipitation (Pe) and observed streamflow (Qo). To make the estimation of transpiration reliable, we need to make sure to have a plausible estimate of effective precipitation, which is the amount of precipitation that really reaches the soil after interception evaporation (Ei). Effective precipitation (Pe), here, is estimated by solving the water balance of an interception storage (Si) with maximum interception storage capacity (Simax; here taken as 2.0 mm). As Sumax is not very sensitive to the choice of Simax as previously shown by e.g. Hrachowitz et al., (2021) and Bouaziz et al. (2022), we used here an value of Simax = 2.0 mm, which was previously also used by de Boer-Euser et al. (2016) and Bouaziz et al. (2022).

We will clarify that in the revised manuscript.

(6) Reviewer Comment:

If Sumax can be derived from observed precipitation, ET, etc., what is the necessity for model calibration? Consider a hypothetical experiment: if someone sets the Sumax value in the FLEX model based on observed data and then calibrates the model using streamflow, would this experiment yield comparable performance metrics (e.g., NSE) to those obtained from the model/simulation? I know you already test the model output via fixed Sumax, but did not focus on the NSE performances.

Reply:

This is indeed an important and interesting comment. On the one hand, as you observed, the Sumax can be estimated by the water-balance method based on observed hydrological data, on the other hand, as parameter in hydrological model, Sumax can also be derived by the calibration of a hydrological model. Both of these two different methods can estimate the value of Sumax. The two methods are largely independent of each other. If therefore the values of Sumax (and their evolution over time) derived from these two methods do not conflict, but instead remain consistent, this is evidence that the estimated values of Sumax from both methods reflect at least to some degree its real-world value.

We agree that replacing the calibrated Sumax with a fixed value does result in very similar model performances without recalibration of the model. From, extensive prior model testing we found that additional calibration of the other parameters while keeping Sumax fixed does only slightly improve the model performance. This was therefore not further explored here.

In any case, we will, for completeness, add the performance metrics of the model for both cases: calibrated and fixed (i.e. water balance-derived Sumax) in Table S3 in the Supplementary Material in the revised manuscript.

(7) Reviewer Comment:

An opinion paper by Gao et al. (2023) (10.5194/hess-27-2607-2023) discusses concepts that may connect to the soil features or arguments presented in this manuscript. I am neutral on the opinions expressed in Gao et al. (2023), but I am curious whether there are links between the Sumax concept and the points made in this paper.

Reply:

This is a very interesting comment. Gao et al. (2023) pointed that the traditional understanding of the high importance of soil may to some extent mislead the understanding of hydrological processes and the development of hydrological model. And they suggest that we need to consider the terrestrial ecosystem structure to improve our understanding of hydrological processes and how the ecosystem can be survived and developed. Our research focuses on how the ecosystem adapts to climatic variability, reflected by the fluctuation of the Sumax values, and the effects on the long-term partitioning of drainage and evaporation and hydrological response. Therefore, there is indeed a link between Gao et al. (2023) and our research. The conclusions of Gao et al. (2023) somewhat support our research objectives and indicates that our research is meaningful. We will clarify that in the revised manuscript.

(8) Reviewer Comment:

The paper attempts to establish a connection between Sumax and vegetation adaptation to climate. However, I do not see any analysis on vegetation adaptation, except for the use of omega in the Budyko method. Moreover, the ET is an output from the model, not an observation linked to vegetation-specific features. Given these uncertainties, I believe the current findings are sufficient for publication and recommend not expanding them to include vegetation adaptation.

Reply:

We acknowledge that our description of the link between Sumax and vegetation adaptation in the original manuscript was not sufficiently clear. Related to the reply to comment (4), the definition of Sumax is the maximum vegetation-accessible water storage volume in the unsaturated root zone of the subsurface. Therefore, the value of Sumax is directly linked with vegetation as it defines the water volume accessible to roots and thus, by extension, the size and structure of the root system. To survive, vegetation continuously adapts to the changing environment by adapting the root depth or root density, which both

directly affect the values of Sumax. Therefore, changes in Sumax over time explicitly reflect the adaptation of vegetation root-zones to changing hydro-climatic conditions.

Concerning ET, please note that in water-balance method, we estimated ET based on observed data of precipitation and stream flow, by closing the long-term water balance. This method then requires the rationale that the surplus water resulting from long-term average P-Q needs to have been evaporated/transpired in the past. However, this can only be the case with a sufficiently large vegetation accessible storage volume Sumax – otherwise, vegetation would not have access to sufficient water in dry periods to transpire the observed water volumes.

We will further clarify that in the revised manuscript.

(9) Reviewer Comment:

I encourage the author to disclose all the calibrated parameter values from the model. These values indicate both the performance of the model and the characteristics of the watersheds.

Reply:

We completely agree with this suggestion. We will add all the calibrated parameter values from the model into the revised supplement.

(10) Reviewer Comment:

Figure S1: The groundwater storage (Ss) in the figure implies a seasonal variation. What factors cause the seasonal variation of groundwater storage? The variation of groundwater storage implies the variation of baseflow, but it did not affect the total streamflow (Q). Is there any data/analysis support the groundwater storage and baseflow? There are two more reservoirs (unsaturated fast) in the model. Could you show the outputs about them?

Reply:

Thank you for pointing this out. Here note that the groundwater storage (Ss) in our model indicates the *active* groundwater storage, not including the passive, hydrologically inactive groundwater storage, which is estimated by Wang et al. (2023), about 4000mm. The total groundwater storage including active and passive parts does not vary so much during one year. When we return to the groundwater storage (active groundwater) which is showed in Figure S1, indeed, there is a seasonal variation. The driving factors can be precipitation which is the primary input source of the groundwater recharge. In this particular case, the lower winter groundwater levels are related to the groundwater depletion during the preceding summer/autumn period and to periods of snow cover in winter, when groundwater is not (or only at low rates) being recharged. Seasonal changes in precipitation directly impact groundwater levels, with wet seasons often leading to increased groundwater recharge (Figure FR2). As you said, the slow streamflow from this component in our model structure (Figure 5 in the original manuscript) is often synonymous with baseflow, which is part of the total streamflow.

In any case, we will also show the seasonal fluctuation of storage in the unsaturated storage component in the revised supplement.
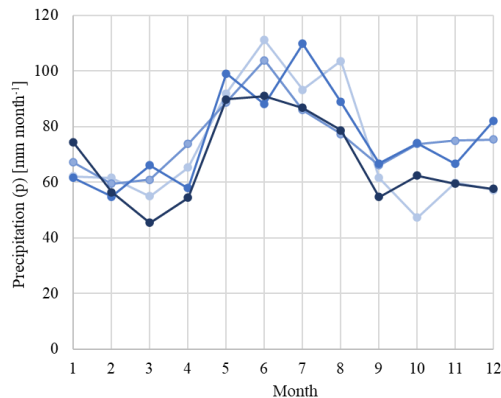

Figure FR2. The concept figure of water-balance method to estimate root zone storage capacity (Sumax).

(11) Reviewer Comment:

Let's conceptualize an ideal watershed based on your presented data. When the maximum water deficit in the root zone (Sumax) is about 120 mm (your results), and the maximum groundwater storage is approximately 4 mm (Figure S1), assuming typical porosities for the two layers (p_root = 0.4 and p_gw = 0.2), the calculated depth of the average hydrological-response aquifer would be 120/0.4+4/0.2=320 mm. This value represents the aquifer depth necessary for the hydrological response in this watershed. However, this formulation does not account for the unsaturated and fast reservoirs, as these are not detailed in the manuscript. I wish to highlight two concerns: (1) the calculated 320 mm depth for the hydrological-response aquifer seems unreasonable; (2) there is a need for information and analysis concerning the unsaturated and faster reservoirs to better understand the watershed dynamics and model structure.

Reply:

Thank you for pointing this out and we will try to clarify this in the following. Related to the reply to comment (10), here, the slow response storage (Ss) is only the active groundwater, not including the passive groundwater. The difference between the two is that only the active groundwater generates hydraulic heads (ha>0) and thus flow (i.e. it is the water stored in aquifers above stream water levels). Groundwater below stream water levels cannot generate hydraulic head (hp=0) and are therefore hydrologically inactive, i.e. assuming an impermeable bedrock boundary condition, they always store the same volume of water so that dS/dt = 0, as indicated in the sketch provided in FR3 below. For further details, we would like to refer you to Zuber (1986; and in particular Figure 1 therein) and Hrachowitz et al. (2016). As we estimated passive groundwater in Wang et al. (2023), the value is ~4000mm. Considering the larger hydrologically inactive, passive part of the groundwater then the estimated value of groundwater storage increases from 320mm to be ~ 20320mm which is reasonable for hydrological response.

We agree that any unsaturated zone below the root zone is not accounted for in this type of model. The reason is that with no roots present below the root zone, water cannot be extracted from these deeper layers of the subsurface by evaporation/transpiration. As a result, the soil moisture of this zone will not

go below capacity as water is held against gravity in the pores and cannot drain. After a rainfall event, the infiltrating wetting front will pass through this unsaturated zone. But as it is already at filed capacity, no additional water can be stored there and the total water volume that has entered the unsaturated zone below the root zone with the precipitation event will eventually recharge the groundwater with a few days of delay, depending on the depth of the groundwater and the soil permeability. As such, the unsaturated zone below the root zone does only temporarily store water for a few days before being released into the groundwater. It does therefore, at the much longer time-scales that regulate Sumax, not have any discernible effect. This is also the reason why standard, state-of-the-art conceptual hydrological models do not consider this additional zone (e.g. Perrin et al., 2003; Fenicia et al., 2006; Clark et al., 2008; Samaniego et al., 2010; Gharari et al., 2013; Newman et al., 2017; Seibert et al., 2022). The same applies for the consideration of passive groundwater storage as described above, which is only needed for tracer and water quality studies but not water quantity studies as in detail described by Hrachowitz et al. (2016), due to the difference in water flow velocities and celerities as described in detail by and McDonnell and Beven (2014).
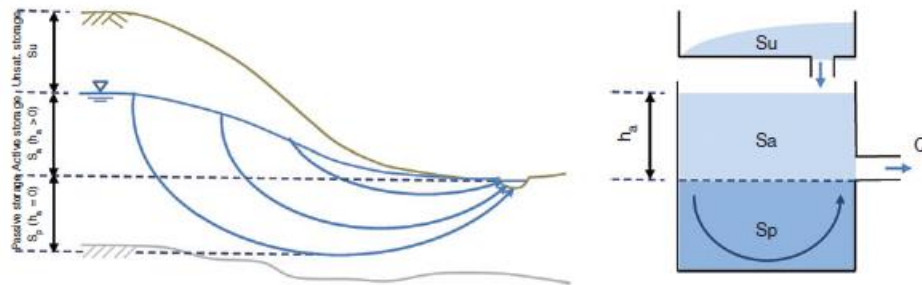

Figure FR3. Sketch of the definition of hydraulically and hydrologically active (Sa) and passive (Sp) groundwater storage in a hillslope cross-section and the respective representation thereof in hydrological models (after Hrachowitz et al., 2016).

Minor Comments

(12) Reviewer Comment:

What is the f(x) in equation 7?

Reply:

Thank you for pointing this out. *f(x)* in equation 7 indicates the following equations. We will clarify this clearly in the revised manuscript.

(13) Reviewer Comment:

Line205: what is the El-bar in your equation?

Reply:

Thank you for pointing this out. *El-bar here indicates the long term mean interception evaporation. We will add the statement of the meaning of El-bar in the revised manuscript.*

(14) Reviewer Comment:

Line219-221: citation is necessary.

Reply:

We completely agree with this suggestion. We will add the relevant references in the revised manuscript.

(15) Reviewer Comment:

Line790: I don't see the figure2(b) make any sense here. The accumulation of ET in such long period does not tell clear message here. The shaded areas for the t1-t4 are not very clear in these figures. I am not sure, but the maximum streamflow in figure 2d seems beyond of the y-axis-max and was crop out of the figure box.

Reply:

Thank you for pointing this out. We used Figure 2b to check and demonstrate that the estimation of actual evaporation is reliable based on our model. As your comment (5) said, we can not only make sure streamflow is reliable, but also make sure the estimated actual evaporation reliable. As another important fluxes except streamflow, the actual evaporation also needs to be checked after calibrating the hydrological model. Based on the long-term water balance, we calculate the actual evaporation should be around 35.000 mm. After calibrating our model based on the entire time period from 1953-2022, we showed the total modelled actual evaporation over the same 70 years is also about 35000 mm, which means that our model worked well for estimating the actual evaporation. We will clarify this more clearly in the revised manuscript.

(16) Reviewer Comment:

Table S3: I interpreted the values in the table, for example, "0.59(0.06-0.55)" in the first cell, as "mean/media (min – max)", but the value "mean" is out of range of min-max. Do I misunderstand the meanings of the value in the table?

Reply:

Thank you for pointing this out. In Table S3, we showed the performance metrics for the most balanced solution and the ranges of all performance metrics for all pareto optimal solutions for two calibration cases (Scenarios 1 – 2). So, for example, *"0.59(0.06-0.55)"* indicates "the most balanced solution (5% percentile- 95% percentile)", more specifically, *"0,59"* is the value of Nash–Sutcliffe efficiency (NSE) of streamflow based on the most balanced solution *(the largest DE based on our calibration, see the specific definition of DE in 4.3.2)*. And *"0.55"* indicates the 95% percentile, not the maximum value. We will clarify this clearly in the revised supplement.

(17) Reviewer Comment:

Line348: No section 4.1.2 in this manuscript.

Reply:

Indeed. We will correct that.

(18) Reviewer Comment:

Line 352: What is the p value here? They seem not the common p-values in statistics. I don't think the 4-sample analysis can tell any potential relationship between the two variables, let alone any convincing conclusions.

Reply:

We of course completely agree with the reviewer. A 4-sample analysis is statistically not very meaningful. We do not intend to use the relationship in any quantitative way but merely intend to use it to point out the corresponding temporal evolution of the Sumax estimates from the two independent methods. However, to avoid any misunderstandings, we will remove the value from Figure 9 in the revised manuscript.

(19) Reviewer Comment:

Line 471-472: "The catchment-scale root zone storage capacity (Sumax) is a critical factor affecting the moisture exchange between land and atmosphere as well as the hydrological response in terrestrial hydrological systems". The "affect" may not the right word, "reflect" may be.

Reply:

Agreed. We will correct that.

(20) Reviewer Comment:

Figure S1: I cannot find the gray shades in the figure. Or are they fully overlapped with green shades?

Reply:

Right. Gray shades derived based on scenario 1 with time-invariant Sumax are almost fully covered by green shades derived by scenario 2 with time-variant Sumax. We will make this clearer in the revised version.

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