# Climate controls how ecosystems size the root zone storage capacity at catchment scale

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**Abstract** The root zone moisture storage capacity ($S_R$) of terrestrial ecosystems is a buffer providing vegetation continuous access to water and a critical factor controlling land-atmospheric moisture exchange, hydrological response, and biogeochemical processes. However, it is impossible to observe directly at catchment scale. Here, using data from 300 diverse catchments, it was tested that, treating the root zone as a reservoir, the mass curve technique (MCT), an engineering method for reservoir design, can be used to estimate catchment-scale $S_R$ from effective rainfall and plant transpiration. Supporting the initial hypothesis, it was found that MCT-derived $S_R$ coincided with model-derived estimates. These estimates of parameter $S_R$ can be used to constrain hydrological, climate, and land surface models. Further, the study provides evidence that ecosystems dynamically design their root systems to bridge droughts with return periods of 10–40 years, controlled by climate and linked to aridity index, inter-storm duration, seasonality, and runoff ratio.

## 1. Introduction

The critical influence of vegetation on the water cycle was realized early [*Bates*, 1921; *Horton*, 1933] and is by now, together with its wider implications [*Seneviratne et al.*, 2013], well acknowledged [*Jenerette et al.*, 2012; *Rodriguez-Iturbe*, 2000; *Thompson et al.*, 2011]. It is also understood that water and vegetation interact in a co-evolutionary system toward establishing equilibrium conditions between vegetation and moisture availability in water-limited environments [*Donohue et al.*, 2007; *Eagleson,* 1978, 1982]. In other words, ecosystems tend to avoid water shortage [*Eagleson*, 1982; *Schenk*, 2008] and the associated negative effect on plants' carbon assimilation rates [*Porporato et al.*, 2004]. There is empirical and theoretical evidence that they do so by designing root systems that allow for the most efficient extraction of water from the substrate, thereby meeting the canopy water demand (or transpiration) while minimizing their costs in terms of carbon expenditure for root growth and maintenance [*Milly*, 1994; *Schymanski et al.*, 2008; *Troch et al.*, 2009].

In spite of a generally good understanding of how ecosystems and hydrology are interlinked, little is known about the detailed mechanisms controlling these connections, leaving many factors involved difficult to quantify. This is in particular true for the water holding capacity, or the plant available water storage capacity in the root zone ($S_R$), which is a key parameter for ecosystem function [*Milly and Dunne*, 1994; *Rodriguez-Iturbe et al.*, 2007; *Sayama et al.*, 2011]. It was suggested previously that changes in $S_R$ directly affect runoff [*Donohue et al.*, 2012], transpiration rates [*Milly and Dunne*, 1994] as well as, through its influence on transpiration and thus on latent heat exchange, land surface temperatures [*De Laat and Maurellis*, 2006; *Legates et al.*, 2011; *Seneviratne et al.*, 2013] and thus the fundamental hydrological response characteristics of natural systems [*Kleidon*, 2004; *Laio et al.*, 2001; *Porporato et al.*, 2004]. In spite of the understanding that soils, and thus also $S_R$, are manifestations of the combined and co-evolving influences of climate, biota, and geology [*Van Breemen*, 1993; *Phillips*, 2009], $S_R$ was in the past mostly estimated from soil characteristics or rooting depths [*Saxton and Rawls*, 2006; *Huang et al.*, 2013], disregarding the importance of climate. Thus, an approach to quantify $S_R$ accounting for feedback among the system components will facilitate a better understanding of how much sub-surface water can be accessed by root systems and is key for efficiently constraining hydrological and ecological predictions.

## 2. Hypothesis

Both, ecosystems and humans, need continuous access to water, requiring a buffer to balance the high variability of hydrological fluxes in the natural system. Where humans design reservoirs to store water to do

so, ecosystems dimension their root zones. A classical engineering method for designing the size of reservoirs is the mass curve technique (MCT; Figure S1a) and refinements thereof [*Hazen*, 1914; *Klemeš*, 1997; *Rippl*, 1883]. Using this technique, the reservoir size is estimated as a function of water demand, water input, and the length of dry periods. These factors show a striking resemblance with those that have been reported to control $S_R$: potential evaporation, precipitation, inter-storm duration, and seasonality [*Gentine et al.*, 2012; *Milly*, 1994]. Given these similarities and treating the root zone as a reservoir, we tested the hypothesis that the MCT can be used to estimate $S_R$ at the catchment scale, independently of point-scale root or soil observations, exclusively based on climate data (inflow and water demand) and to thereby establish a direct and quantifiable link between climate, ecosystem, and hydrology. Note that a catchment can consist of several ecosystems. Hereafter, however, $S_R$ of an ecosystem describes the integrated value of $S_R$ for all ecosystems in a catchment.

## 3. Methods

### 3.1. Estimation of Root Zone Storage Capacity ($S_R$)

#### 3.1.1. Mass Curve Technique (MCT)

The MCT is a method to estimate the reservoir storage based on the relationship between cumulative inflow and water demand (Figure S1a). To estimate $S_R$ (Figures S1b and S1c) first the average annual plant water demand $E_{ta}$ is determined from $E_{ta} = P_E - Q$, with $P_E = P - E_i$, where $P_E$ is the cumulative inflow, $P$ is precipitation, $E_i$ is interception, and $Q$ is runoff. Then water demand in dry seasons ($E_{td}$) is estimated using a linear relationship between $E_{ta}/E_{td}$ and the ratio of annual average to dry season average Normalized Difference Vegetation Index, i.e., $NDVI_a/NDVI_d$, assuming that transpiration is linearly related to the vegetation index and incoming radiation while being constrained by soil moisture [*Wang et al.*, 2007]. Finally, $P_E$ is plotted together with $E_{td}$. The required $S_R$ for each year is estimated based on the periods where the rate of water demand exceeds inflow (Figure S1). In other words, the vertical distance between the tangents to the accumulated $P_E$, parallel to $E_{td}$, at the beginning and the end of dry seasons yields the estimated $S_R$ of that year (Figure S1b).

#### 3.1.2. Frequency Analysis

The Gumbel distribution [*Gumbel*, 1935], frequently used for estimating hydrological extremes, was used to standardize the frequency of drought occurrence (Figures S1d and S3). Here, Gumbel uses the reduced variate $y$ as a function of the return period $T$ of annual $S_R$ estimates ($y = -\ln(-\ln(1 - 1/T))$). Being a linear relationship, this allows the estimation of the $S_R$ required to overcome droughts with certain return periods, such as droughts with return periods of 10, 20, and 40 years ($S_{R10y}$, $S_{R20y}$, and $S_{R40y}$).

### 3.2. Root Zone Storage Capacity From Hydrological Models ($S_{uMax}$)

To test the MCT-derived values of $S_R$ for plausibility, a conceptual hydrological model was used to independently estimate the root zone storage capacity. It was developed based on the FLEX framework [*Fenicia et al.*, 2008]. As for most hydrological models its core is a dynamic buffer that moderates flows and retains tension water for plant use, essentially reflecting $S_R$ [*Fenicia et al.*, 2008; *Zhao and Liu*, 1995]. Here, the tension water storage capacity function of the Xinanjiang model [*Zhao and Liu*, 1995], controlled by parameter $S_{uMax}$, was adopted. The MOSCEM-UA [*Vrugt et al.*, 2003] algorithm was used for a multi-objective model calibration, based on the Kling-Gupta efficiency (KGE) [*Gupta et al.*, 2009] of flow, logarithmic flow, and the flow duration curve. All pareto-optimal parameter sets were retained as feasible and used for further analysis (in Figures 2, S1d, and S3 only the median values of $S_{uMax}$ are shown for clarity). The description of the model is available in the Supplement (Figure S4 and Table S1). The MCT-derived $S_R$ was then evaluated against the model-derived values of $S_{uMax}$.

## 4. Data Sets

For an initial analysis, data from six catchments in Thailand, with catchment areas between 452 and 3858 km$^2$, were used (Table S2, Dataset S1). These catchments are characterized by tropical savanna climate (Köppen-Geiger group Aw) with average annual precipitation and runoff of 1174 and 268 mm yr$^{-1}$. Land use is dominated by evergreen and deciduous forest (Figure 1d). Further, data from 323 in the United States catchments, with areas between 67 and 10,329 km$^2$, data records >30 years, and limited anthropogenic influence, available through the Model Parameter Estimation Experiment [*Schaake et al.*, 2006] were used.
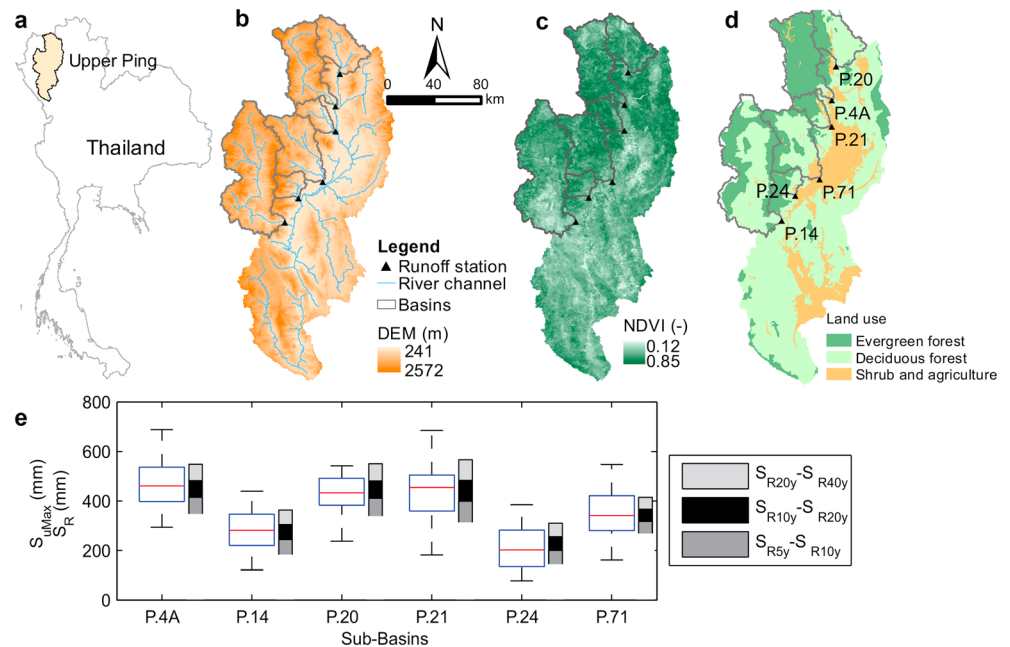
**Figure 1.** Upper Ping River catchment maps: (a) context; (b) elevation; (c) average annual Normalized Difference Vegetation Index (NDVI); (d) land use. Figure 1e compares the values of mass curve technique (MCT)-derived $S_R$ for different return periods (grey boxes) with the range of feasible calibrated values of $S_{uMax}$ from the hydrological model (red lines indicate the medians, boxes the 25/75th, and whiskers the 5/95th quantiles).

MOPEX catchments with more than 20% of precipitation falling as snow were excluded from the analysis since neither the MCT nor the model account for snow dynamics. Likewise, catchments in very arid climates ($I_A > 2$, $I_A = E_P/P$, $E_p$ is potential evaporation) were excluded as vegetation in such regions may favor different survival strategies such as increased water storage in the plants themselves. Catchment average precipitation was calculated with inverse distance weighting. Potential evaporation was estimated using the Hargreaves equation [*Hargreaves and Samani*, 1982]. The interception threshold $E_i$ to estimate $P_E$ was set to $2\,mm\,d^{-1}$. Catchment average annual and dry season mean NDVI values were obtained from the MODIS13Q1 product (2002–2012; LP DAAC) by using the average of all cells within the catchment over the required period.

## 5. Results and Discussions

Depending on dry season characteristics in individual years (Figure S2), the six Thai study catchments exhibited considerable fluctuations in MCT-derived $S_R$ needed in the individual years to satisfy dry period plant water demand, with overall values across all six catchments from ~100 to ~450 mm (Figure S3). In the individual catchments the range between the minimum and the maximum values for annual $S_R$ was on average ~200 mm. To generalize these results, the required $S_R$ for drought return periods of 5, 10, 20, 40, 60, and 100 years were estimated using the Gumbel distribution (Figure S3).

Calibrating the hydrological model to stream flow observations for these six study catchments showed that the ranges of calibrated $S_{uMax}$ correspond surprisingly well with the values of MCT-derived $S_R$ (Figure 1e). In fact, values of $S_R$ required to cover canopy water demand for droughts with return periods from 10 to 20 years coincided with the median of calibrated $S_{uMax}$ in each catchment, with some vegetation-related variation: the results suggest that catchments with higher values of annual catchment average NDVI (P.4A, NDVI = 0.69; P.21, NDVI = 0.70) and thus higher canopy water demand develop larger $S_{R20y}$ of 447 and 439 mm, respectively, than those with lower canopy water demand (P.14, NDVI = 0.64, $S_{R20y}$ = 280 mm; P.24, NDVI = 0.66, and $S_{R20y}$ = 219 mm). In other words, ecosystems in these catchments have developed root zone that allows them to overcome droughts with return periods of 10–20 years. These results suggest that plants "design" their root-accessible water storage according to a cost minimization strategy [*Milly*, 1994], i.e., to meet canopy water demand with minimal carbon allocation to roots. It could be observed in these six
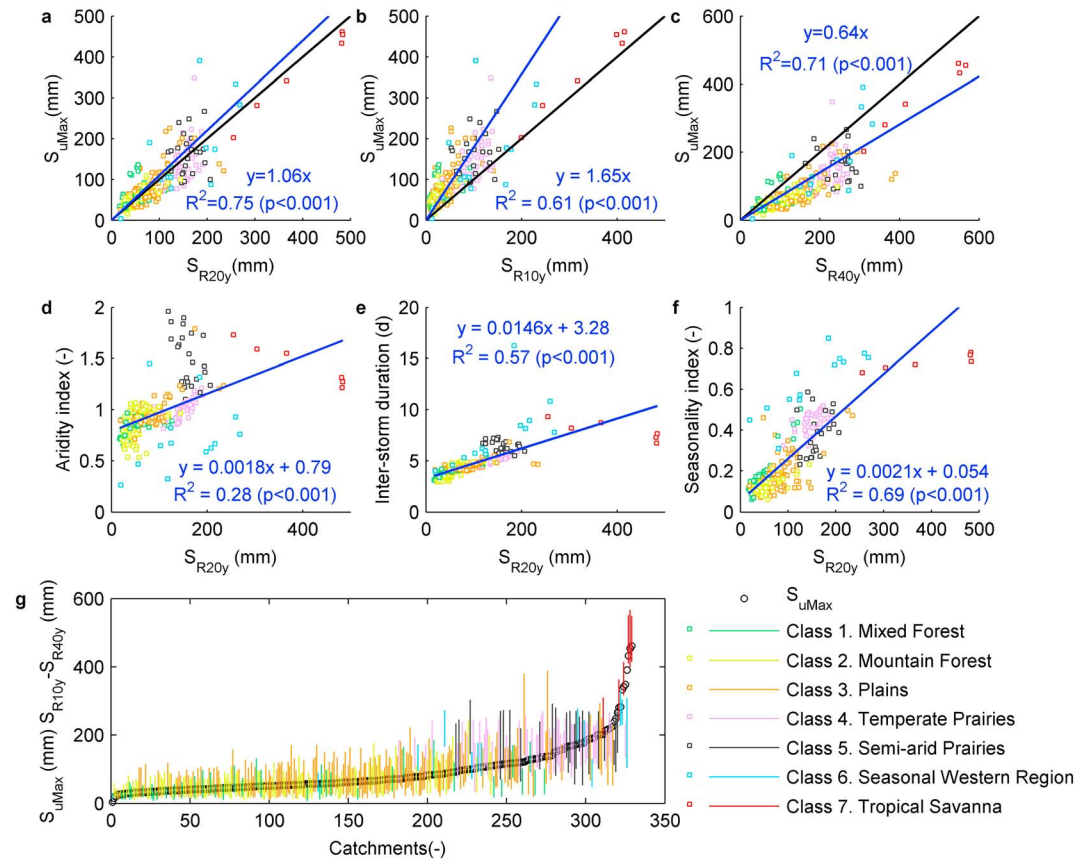
**Figure 2.** Relationships between $S_R$, $S_{uMax}$, and climate indices for the 329 study catchments. (a) $S_{uMax}$ vs. $S_{R20y}$ (storage capacity with 20 years return periods); (b) $S_{uMax}$ vs. $S_{R10y}$; (c) $S_{uMax}$ vs. $S_{R40y}$; (d) $S_{R20y}$ vs. aridity index ($I_A$); (e) $S_{R20y}$ vs. inter-storm duration ($I_{ISD}$); (f) $S_{R20y}$ vs. seasonality index ($I_S$); (g) $S_{uMax}$ (black circles) and ranges of $S_R$ between 10 and 40 year return periods ($S_{R10y}$–$S_{R40y}$), sorted by increasing $S_{uMax}$. Colors indicate ecoregion classes, based on simplified CEC Level II ecoregions.

catchments that ecosystems develop storage capacities $S_R$ that are mainly controlled by atmospheric moisture supply and canopy demand dynamics, which supports earlier studies that documented the importance of canopy water demand and environmental conditions for $S_R$ [*Field et al.*, 1992; *Milly and Dunne*, 1994; *Gentine et al.*, 2012] and the hypothesis that ecosystems adapt their root zones [*Schenk*, 2006] by lateral or vertical growth [*Schenk and Jackson*, 2002a] to access the necessary soil water volume.

The hypothesis of climate and canopy water demand being dominant controls on $S_R$ and the existence of a link between $S_R$ and $S_{uMax}$ were further tested by applying the same methodology as above to additional 323 very diverse catchments across the US. Based on all 329 study catchments (Thailand and US), statistically highly significant relationships between calibrated $S_{uMax}$ and MCT-derived $S_R$ for drought return periods of 10–40 years ($R^2_{10yrs} = 0.61$, $R^2_{20yrs} = 0.75$, $R^2_{40yrs} = 0.71$; $p < 0.001$; Figures 2a–2c) suggest that across the contrasting environmental conditions in these catchments, ecosystems design their $S_R$ according to similar, simple, first order principles. Figure 2g displays the full range of $S_{R10y}$ – $S_{R40y}$, compared to $S_{uMax}$ values for all study catchments, showing that the majority of catchments' $S_{uMax}$ plots within the $S_{R10y}$ – $S_{R40y}$ range.

## 5.1. Links Between Climate, Vegetation and $S_R$

The results indicate that at the catchment scale the plant available storage capacity is controlled by catchment wetness characteristics: when plotting $S_{R20y}$ for the individual catchments against their respective aridity indices ($I_A$) ($R^2 = 0.28$; $p < 0.001$) or the mean inter-storm durations ($I_{ISD}$), a proxy for dry period durations ($R^2 = 0.57$; $p < 0.001$), it was found that the lowest $S_R$ (<100 mm) are required in wet climates (Figure 2d) with shortest inter-storm durations (Figure 2e), while larger $S_R$ are required in regions with higher aridity and longer dry period durations. Another determining factor for $S_R$ was found to be the seasonality of
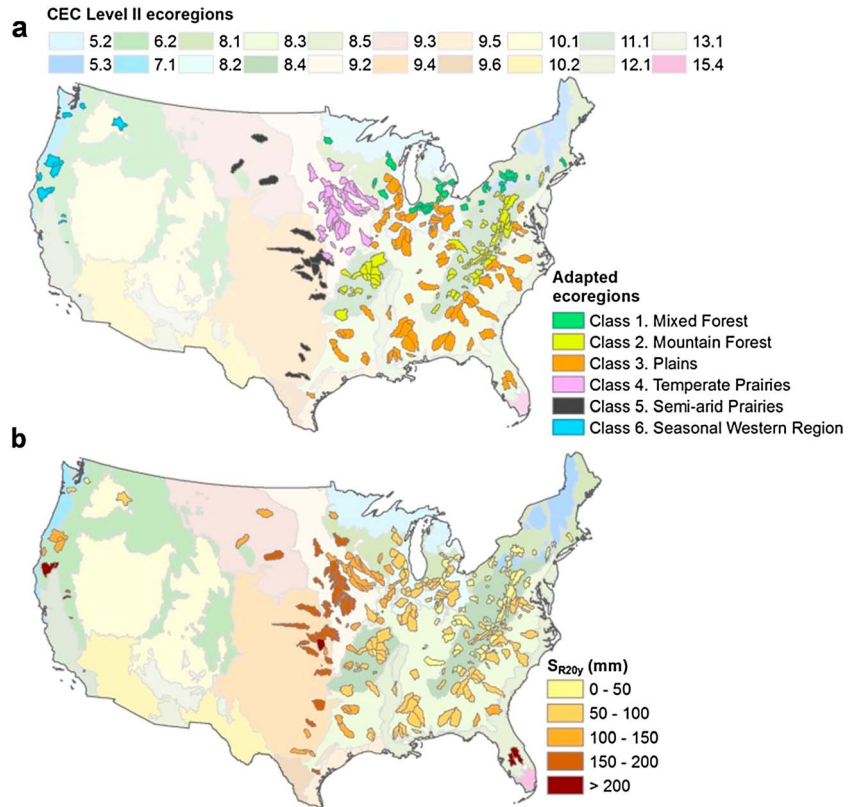
**Figure 3.** CEC North American Level II ecoregions in the US overlain by (a) the MOPEX study catchments classified based on the simplified CEC North American Level II ecoregions and (b) the $S_{R20y}$ for the MOPEX study catchments. The horizontal color bar applies to the background in both figures; the individual vertical color bars apply to the catchments in the respective sub-panels.

precipitation. The higher the rainfall seasonality index ($I_S = \frac{1}{\overline{P_a}} \sum_{m=1}^{m=12} \left| \overline{P_m} - \frac{\overline{P_a}}{12} \right|$, where $\overline{P_m}$ is the mean rainfall of month $m$, and $\overline{P_a}$ is the mean annual rainfall), the larger a $S_R$ is required ($R^2 = 0.69$; $p < 0.001$; Figure 2f). Stepwise multiple linear regression further showed that combining the three predictors $I_S$, $I_A$, and $I_{ISD}$ can explain 79% of the variance in $S_{R20y}$ ($S_{R20y} = 218I_S + 64I_A + 5I_{ISD} - 51$; $R^2_{adj} = 0.79$; $p < 0.001$; variance inflation factor $<4$). Furthermore, the US study catchments were classified according to the CEC North American Level II ecoregions (Table S3; Figure 3a) [*Wiken et al.*, 2011], with the 6 tropical catchments in Thailand constituting one additional class. Note that the CEC classification was simplified for clarity of the presentation, without overall impact on the interpretation. The classification indicates that, for example, in semi-arid Prairies (Table S3; Figures 3a and 3b) dominated by seasonal short and mix-grass Prairie vegetation, $S_{R20y}$ is around 150 – 200 mm, which is below the values of ~200 – 500 mm that would be expected for ecosystems with comparable aridity indices ($I_A$ ~1 – 2) but dominated by evergreen plants as indicated by the regression line in Figure 2d. By going dormant during the dry season, thereby minimizing transpiration, such ecosystems only need to access sufficient moisture to reach maturity during the growing season. In contrast, the results also suggest that ecosystems in environments with marked seasonality and out of phase precipitation and energy supply, such as West-coast ecoregions (Table S3 and Figures 3a and 3b), require higher $S_R$ than ecosystems with higher aridity indices in other climates (Figure 2d) to ensure sufficient access to water throughout the prolonged dry periods (Figure 2e). The here suggested concept of $S_R$ is conceptually different from rooting depth, as it accounts for the volume of water accessible to roots and thus rather reflects the average root density in a catchment. It was, however, observed that patterns of $S_R$ are broadly corresponding with observed rooting depths in previous studies. For example, some observations by *Schenk and Jackson* [2002b] include that Tropical Savanna ecosystems are characterized by, on average, deepest rooting depths, with a median value of 1.2 m. Similarly, they report elevated root depths (~0.8–2 m) in Mediterranean
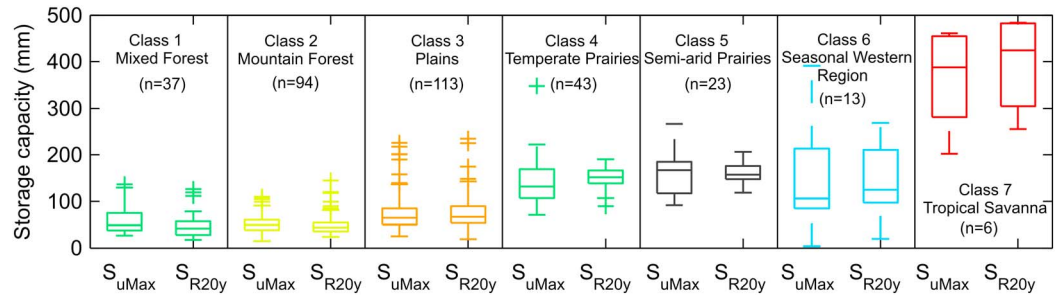
**Figure 4.** Distributions of $S_{uMax}$ and $S_{R20y}$ in the seven simplified ecoregion classes of the 329 study catchments.

climates as well as low and comparable root depths in temperate forests and grasslands. Our results (Figure 4) likewise suggest that the largest $S_R$ are required in Tropical Savanna systems (~400 mm) and, although wetter than Mediterranean climates, in the Seasonal Western Region (~100 – 200 mm), while forests and grasslands (Classes 1–3) exhibit low and comparable $S_R$ requirements.

### 5.2. Implications for the Hydrological Response and Beyond

Following these results, not only a spatial pattern of $S_{R20y}$ across the US emerges, following the precipitation and evaporative energy supply gradients (Figure 3b), but it could also be shown that the long-term annual catchment runoff coefficient ($C_R = Q/P$) exhibits a significant, negative correlation with $S_{R20y}$ ($R^2 = 0.48$; $p < 0.001$; Figure 5). This suggests that flow partitioning into runoff and evaporative fluxes, as shown in the Budyko framework [*Budyko and Miller*, 1974], is strongly controlled by $S_R$ [*Gentine et al.*, 2012]. While humid catchments are characterized by low $S_R$ and high $C_R$, vegetation in more arid catchments requires a higher $S_R$ to store more water, resulting in lower $C_R$ and thus in proportionally higher plant transpiration. This does not only underline the importance of $S_R$ for understanding the hydrological response, but it also emphasizes the role of co-evolution of vegetation and hydrology. Furthermore, the positive correlation between $S_{R20y}$ and rainfall seasonality implies a certain buffering of seasonality effects on the runoff ratio, resulting in only small deviations of catchments from the Budyko curve despite differences in climatic seasonality [*Williams et al.*, 2012].

Limitations of MCT method include its dependence on the availability of water inflow and demand data. This restricts the possibility to estimate $S_R$ for individual ecosystems or a grid-based spatial distribution within a catchment. Further, $S_R$ estimates are currently based on constant water demand estimates and may benefit from allowing for seasonal variations. Additional research is also required to determine at which scales the method is applicable.
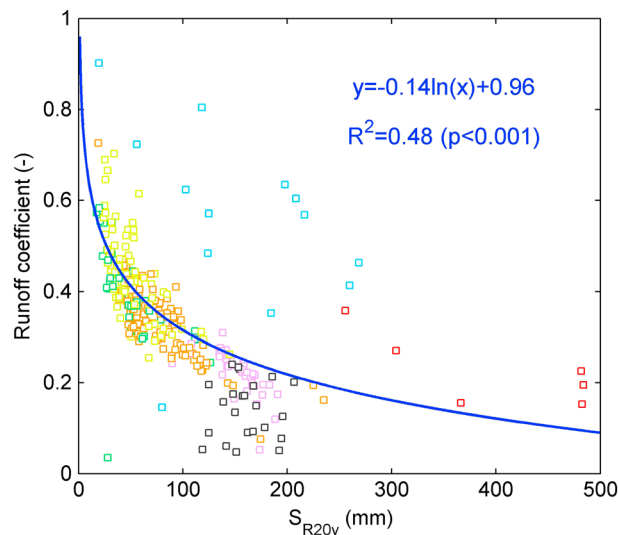
The root zone storage is the core of hydrological models as it controls the partitioning of available water for plant use and flow generation. The estimation of this parameter from independently observed data can reduce the number of calibration parameters and the associated parameter uncertainty in hydrological models, in particular for predictions in ungauged basins [*Blöschl et al.*, 2013; *Hrachowitz et al.*, 2013]. Similarly, estimates of $S_R$, as a controlling factor of soil moisture, are potentially useful for a range of geophysical applications: (1) in ecology, estimates of $S_R$ may be valuable for understanding factors controlling primary production and growth as well as ecosystem development and survival strategies [*Kolb et al.*, 1990; *Briggs and Knapp*, 1995; *Breshears and Barnes*, 1999]. (2) In land surface



$$y = -0.14\ln(x) + 0.96$$
$$R^2 = 0.48 \ (p < 0.001)$$

**Figure 5.** Relationship between $S_{R20y}$ and the mean annual runoff coefficient for the 329 study catchments.

schemes and climate models [*Dirmeyer et al.*, 2006; *Niu et al.*, 2011; *Seneviratne et al.*, 2013], estimates of $S_R$ can help define land-atmosphere exchange processes of water and energy, thereby potentially improving the models' predictive ability. (3) $S_R$ also plays a key role in biogeochemical studies. Controlling soil moisture dynamics and it establishes the physico-chemical environment for cycling of nutrients and solutes, such as nitrogen [*Pastor and Post*, 1986; *Agehara and Warncke*, 2005] or carbon [*Howard and Howard*, 1993; *Kurc and Small*, 2007]. Linking transport, plant uptake, and chemical processes, $S_R$ estimates may improve the understanding of these processes and their representation in models. (4) Through its link to vegetation and its influence on soil saturation and overland flow generation, $S_R$ estimates may also prove beneficial for the understanding and quantification of erosion and mass movement processes [*Seeger et al.*, 2004; *Ray and Jacobs*, 2007].

The dependency of $S_R$ on climate and ecosystems/land cover further entails that $S_R$ cannot be treated as static as it varies depending on changes in any of these. This potentially offers a simple way to account, to some extent, for a temporally evolving system, which is a step from Newtonian toward Darwinian modeling strategies [*Harman and Troch*, 2014; *Harte*, 2002; *Hrachowitz et al.*, 2013; *Kumar and Ruddell*, 2010].

## 6. Conclusions

Using data for more than 300 diverse catchments in Thailand and the US, the presented results support the hypothesis that, at catchment scale, ecosystems dynamically and optimally adjust their root systems to their environment [*Milly*, 1994; *Kleidon and Heimann*, 1998] in a way that the plant available water storage capacity is controlled by the precipitation regime, canopy water demand, and land cover. It was shown that many ecosystems develop root systems that can tap sufficient water to overcome droughts with 10–40 year return periods but no more than that, as it is increasingly expensive in terms of carbon allocation to roots. It was shown that the root zone storage capacity can be calculated, independent of point-scale observations, using a simple, water-balance based method. The results strongly highlight the importance of the dynamic co-evolution of climate, ecosystems, and hydrology. With this approach we have established a climate and land cover driven technique to estimate the storage capacity of the root zone at catchment scale, a crucial parameter of the water cycle at the interface of hydrological, ecological, and atmospheric sciences.

## References

Agehara, S., and D. D. Warncke (2005), Soil moisture and temperature effects on nitrogen release from organic nitrogen sources, *Soil Sci. Soc. Am. J.*, 69(6), 1844–1855.

Bates, C. G. (1921), First results in the streamflow experiment, Wagon Wheel Gap, Colorado, *J. For.*, 19(4), 402–408.

Blöschl, G., M. Sivapalan, T. Wagener, A. Viglione, and H. Savenije (2013), Runoff prediction in ungauged basins: Synthesis across processes, places and scales, Cambridge Univ. Press, Cambridge, U. K.

Breshears, D. D., and F. J. Barnes (1999), Interrelationships between plant functional types and soil moisture heterogeneity for semiarid landscapes within the grassland/forest continuum: A unified conceptual model, *Landscape Ecol.*, 14(5), 465–478.

Briggs, J. M., and A. K. Knapp (1995), Interannual variability in primary production in tallgrass prairie: Climate, soil moisture, topographic position, and fire as determinants of aboveground biomass, *Am. J. Bot.*, 82, 1024–1030.

Budyko, M. I., and D. H. Miller (1974), *Climate and Life*, Academic Press, London.

De Laat, A. T. J., and A. N. Maurellis (2006), Evidence for influence of anthropogenic surface processes on lower tropospheric and surface temperature trends, *Int. J. Climatol.*, 26(7), 897–913.

Dirmeyer, P. A., R. D. Koster, and Z. Guo (2006), Do global models properly represent the feedback between land and atmosphere?, *J. Hydrometeorol.*, 7(6), 1177–1198

Donohue, R. J., M. L. Roderick, and T. R. McVicar (2007), On the importance of including vegetation dynamics in Budyko's hydrological model, *Hydrol. Earth Syst. Sci.*, 11(2), 983–995.

Donohue, R. J., M. L. Roderick, and T. R. McVicar (2012), Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko's hydrological model, *J. Hydrol.*, 436–437(0), 35–50.

Eagleson, P. S. (1978), Climate, soil, and vegetation: 6. Dynamics of the annual water balance, *Water Resour. Res.*, 14(5), 749–764.

Eagleson, P. S. (1982), Ecological optimality in water-limited natural soil-vegetation systems: 1. Theory and hypothesis, *Water Resour. Res.*, 18(2), 325–340.

Fenicia, F., J. J. McDonnell, and H. H. G. Savenije (2008), Learning from model improvement: On the contribution of complementary data to process understanding, *Water Resour. Res.*, 44, W06419, doi:10.1029/2007WR006386.

Field, C. B., F. S. Chapin, P. A. Matson, and H. A. Mooney (1992), Responses of terrestrial ecosystems to the changing atmosphere: A resource-based approach, *Annu. Rev. Ecol. Syst.*, 23, 201–235.

Gentine, P., P. D'Odorico, B. R. Lintner, G. Sivandran, and G. Salvucci (2012), Interdependence of climate, soil, and vegetation as constrained by the Budyko curve, *Geophys. Res. Lett.*, 39, L19404, doi:10.1029/2012GL053492.

Gumbel, E. J. (1935), Les valeurs extrêmes des distributions statistiques, *Annales de l'institut Henri Poincaré*, 5(2), 115–158.

Gupta, H. V., H. Kling, K. K. Yilmaz, and G. F. Martinez (2009), Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, *J. Hydrol.*, 377(1–2), 80–91.

Hargreaves, G. H., and Z. A. Samani (1982), Estimating potential evapotranspiration, *J. Irrig. Drain. Div.*, 108(3), 225–230.

Harman, C., and P. A. Troch (2014), What makes Darwinian hydrology "Darwinian"? Asking a different kind of question about landscapes, *Hydrol. Earth Syst. Sci.*, *18*(2), 417–433.

Harte, J. (2002), Toward a synthesis of the Newtonian and Darwinian worldviews, *Phys. Today*, *55*(10), 29–34.

Hazen, A. (1914), Storage to be provided in impounded reservoirs for municipal water supply, *Trans. Am. Soc. Civil Eng.*, *77*, 1539–1640.

Horton, R. E. (1933), The Rôle of infiltration in the hydrologic cycle, *Eos Trans. AGU*, *14*(1), 446–460.

Howard, D. M., and P. J. A. Howard (1993), Relationships between CO ~ 2 evolution, moisture content and temperature for a range of soil types, *Soil Biol. Biochem.*, *25*, 1537–1537.

Hrachowitz, M., et al. (2013), A decade of Predictions in Ungauged Basins (PUB)—A review, *Hydrol. Sci. J.*, *58*(6), 1198–1255.

Huang, M., S. L. Barbour, A. Elshorbagy, J. Zettl, and B. C. Si (2013), Effects of variably layered coarse textured soils on plant available water and forest productivity, *Procedia Environ. Sci.*, *19*, 148–157.

Jenerette, G. D., G. A. Barron-Gafford, A. J. Guswa, J. J. McDonnell, and J. C. Villegas (2012), Organization of complexity in water limited ecohydrology, *Ecohydrology*, *5*(2), 184–199.

Kleidon, A. (2004), Global datasets of rooting zone depth inferred from inverse methods, *J. Clim.*, *17*(13), 2714–2722.

Kleidon, A., and M. Heimann (1998), A method of determining rooting depth from a terrestrial biosphere model and its impacts on the global water and carbon cycle, *Global Change Biol.*, *4*(3), 275–286.

Klemeš, V. (1997), Water storage: Source of inspiration and desperation, in *Reflections on Hydrology: Science and Practice*, edited by N. Buras, pp. 286–314, AGU, Washington D. C.

Kolb, T. E., K. C. Steiner, L. H. McCormick, and T. W. Bowersox (1990), Growth response of northern red-oak and yellow-poplar seedlings to light, soil moisture and nutrients in relation to ecological strategy, *For. Ecol. Manage.*, *38*(1), 65–78.

Kumar, P., and B. L. Ruddell (2010), Information driven ecohydrologic self-organization, *Entropy*, *12*(10), 2085–2096.

Kurc, S. A., and E. E. Small (2007), Soil moisture variations and ecosystem-scale fluxes of water and carbon in semiarid grassland and shrubland, *Water Resour. Res.*, *43*, W06416, doi:10.1029/2006WR005011.

Laio, F., A. Porporato, L. Ridolfi, and I. Rodriguez-Iturbe (2001), Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress: II. Probabilistic soil moisture dynamics, *Adv. Water Resour.*, *24*(7), 707–723.

Legates, D. R., R. Mahmood, D. F. Levia, T. L. DeLiberty, S. M. Quiring, C. Houser, and F. E. Nelson (2011), Soil moisture: A central and unifying theme in physical geography, *Prog. Phys. Geogr.*, *35*(1), 65–86.

Milly, P. C. D. (1994), Climate, soil water storage, and the average annual water balance, *Water Resour. Res.*, *30*(7), 2143–2156.

Milly, P. C. D., and K. A. Dunne (1994), Sensitivity of the global water cycle to the water-holding capacity of land, *J. Clim.*, *7*(4), 506–526.

Niu, G.-Y., et al. (2011), The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements, *J. Geophys. Res.*, *116*, D12109, doi:10.1029/2010JD015139.

Pastor, J., and W. M. Post (1986), Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles, *Biogeochemistry*, *2*(1), 3–27.

Phillips, J. D. (2009), Soils as extended composite phenotypes, *Geoderma*, *149*(1), 143–151.

Porporato, A., E. Daly, and I. Rodriguez-Iturbe (2004), Soil water balance and ecosystem response to climate change, *Am. Nat.*, *164*(5), 625–632.

Ray, R. L., and J. M. Jacobs (2007), Relationships among remotely sensed soil moisture, precipitation and landslide events, *Nat. Hazards*, *43*(2), 211–222.

Rippl, W. (1883), The capacity of storage reservoirs for water supply, *Minutes Proc. Inst. Civil Eng.*, *71*, 270–278.

Rodriguez-Iturbe, I. (2000), Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamies, *Water Resour. Res.*, *36*(1), 3–9.

Rodriguez-Iturbe, I., P. D'Odorico, F. Laio, L. Ridolfi, and S. Tamea (2007), Challenges in humid land ecohydrology: Interactions of water table and unsaturated zone with climate, soil, and vegetation, *Water Resour. Res.*, *43*, W09301, doi:10.1029/2007WR006073.

Saxton, K. E., and W. J. Rawls (2006), Soil water characteristic estimates by texture and organic matter for hydrologic solutions, *Soil Sci. Soc. Am. J.*, *70*(5), 1569–1578.

Sayama, T., J. J. McDonnell, A. Dhakal, and K. Sullivan (2011), How much water can a watershed store?, *Hydrol. Process.*, *25*(25), 3899–3908.

Schaake, J., S. Cong, and Q. Duan (2006), The US MOPEX data set, *IAHS Publ.*, *307*, 9.

Schenk, H. J. (2006), Vertical vegetation structure below ground: Scaling from root to globe, in *Progress in Botany*, edited by K. Esser et al., pp. 341–373, Springer, Heidelberg, Germany.

Schenk, H. J. (2008), The shallowest possible water extraction profile: A null model for global root distributions, *Vadose Zone J.*, *7*(3), 1119–1124.

Schenk, H. J., and R. B. Jackson (2002a), Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems, *J. Ecol.*, *90*(3), 480–494.

Schenk, H. J., and R. B. Jackson (2002b), The global biogeography of roots, *Ecol. Monogr.*, *72*(3), 311–328.

Schymanski, S. J., M. Sivapalan, M. L. Roderick, J. Beringer, and L. B. Hutley (2008), An optimality-based model of the coupled soil moisture and root dynamics, *Hydrol. Earth Syst. Sci.*, *12*(3), 913–932.

Seeger, M., M. P. Errea, S. Begueria, J. Arnaez, C. Marti, and J. M. Garcia-Ruiz (2004), Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees, *J. Hydrol.*, *288*(3), 299–311.

Seneviratne, S. I., et al. (2013), Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment, *Geophys. Res. Lett.*, *40*, 5212–5217, doi:10.1002/grl.50956.

Thompson, S. E., C. J. Harman, A. G. Konings, M. Sivapalan, A. Neal, and P. A. Troch (2011), Comparative hydrology across AmeriFlux sites: The variable roles of climate, vegetation, and groundwater, *Water Resour. Res.*, *47*, W00J07, doi:10.1029/2010WR009797.

Troch, P. A., G. F. Martinez, V. R. N. Pauwels, M. Durcik, M. Sivapalan, C. Harman, P. D. Brooks, H. Gupta, and T. Huxman (2009), Climate and vegetation water use efficiency at catchment scales, *Hydrol. Process.*, *23*(16), 2409–2414.

Van Breemen, N. (1993), Soils as biotic constructs favouring net primary productivity, *Geoderma*, *57*(3), 183–211.

Vrugt, J. A., H. V. Gupta, L. A. Bastidas, W. Bouten, and S. Sorooshian (2003), Effective and efficient algorithm for multiobjective optimization of hydrologic models, *Water Resour. Res.*, *39*(8), 1214, doi:10.1029/2002WR001746.

Wang, K., P. Wang, Z. Li, M. Cribb, and M. Sparrow (2007), A simple method to estimate actual evapotranspiration from a combination of net radiation, vegetation index, and temperature, *J. Geophys. Res.*, *112*, D15107, doi:10.1029/2006JD008351.

Wiken, E., F. Jimenez Nava, and G. Griffith (2011), *North American Terrestrial Ecoregions-Level III*, edited by CfE Cooperation, Comm. for Environ. Coop., Montreal, Canada.

Williams, C. A., et al. (2012), Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers, *Water Resour. Res.*, *48*, W06523, doi:10.1029/2011WR011586.

Zhao, R. J., and X. R. Liu (1995), The Xinangjiang model, in *Computer Models of Watershed Hydrology*, edited by V. P. Singh, pp. 215–232, Water Resour. Publ., Colo.