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Storage as a Metric of Catchment Comparison

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Abstract

The volume of water stored within a catchment, and its partitioning among groundwater, soil moisture, snowpack, vegetation, and surface water are the variables that ultimately characterize the state of the hydrologic system. Accordingly, storage may provide useful metrics for catchment comparison. Unfortunately, measuring and predicting the amount of water present in a catchment is seldom done; tracking the dynamics of these stores is even rarer. Storage moderates fluxes and exerts critical controls on a wide range of hydrologic and biologic functions of a catchment. While understanding runoff generation and other processes by which catchments *release* water will always be central to hydrologic science, it is equally essential to understand how catchments *retain* water. We have initiated a catchment comparison exercise to begin assessing the value of viewing catchments from the storage perspective. The exercise is based on existing data from five watersheds, no common experimental design, and no integrated modelling efforts. Rather, storage was estimated independently for each site. This briefing presents some initial results of the exercise, poses questions about the definitions and importance of storage and the storage perspective, and suggests future directions for ongoing activities. Copyright © 2011 John Wiley & Sons, Ltd.

Key Words storage; water balance; catchment comparison; soil water; groundwater

The Case for Storage

Further advances in catchment hydrology hinge on establishing meaningful metrics for catchment comparison across and within physiographically diverse regions (Robinson, 1993; Jones, 2005; McDonnell *et al.*, 2007; Wagener *et al.*, 2007). It is essential to synthesize the heterogeneous wealth of information generated from decades of case studies that document hydrological processes in individual catchments (e.g. Carey *et al.*, 2010). Several comparison metrics have been proposed in recent years. Some metrics focus on ratios of fluxes, i.e. streamflow/precipitation as a measure of catchment efficiency, or evapotranspiration/precipitation as a dryness index (Post and Jones, 2001), or streamflow characteristics (Lane and Lei, 1949; Olden and Poff, 2003; Poff *et al.*, 2006). More recent studies sought to use indices of hydrological functioning such as mean transit time (e.g. Tetzlaff *et al.*, 2009; Hrachowitz *et al.*, 2009). The premise of this briefing is that the volume of water stored within a catchment and its distribution among snowpack, vegetation, soil moisture, groundwater, and surface water are the variables that ultimately characterize the state of the hydrological system. Accordingly, catchment water storage may serve as insightful metrics for catchment comparison. Unfortunately, very few studies report storage measures. Recent work has demonstrated, or perhaps revived, a general interest in catchment water storage (Spence *et al.*, 2007, 2010; Kirchner, 2009; Soulsby *et al.*, 2009). However, the topic still receives relatively little attention, which may be due to the distributed nature of storage, the heterogeneity of storage architecture, or the general difficulty of site characterisation and storage measurements, particularly at catchment scales.

Table I. Summary of catchment and storage characteristics used within this catchment comparison (Mean storage: arithmetical average of daily storages; Min. storage: minimum of the daily storages modeled or observed (at driest day of summer) for the catchment. Max storage: maximum of the daily storages modelled or observed for the catchment. Total capacity: estimate of available active pore volume)

	Girnock Scotland	Gårdsjön Sweden	Reynolds Creek USA	Dry Creek USA	Panola USA
Storage Estimation Method	Input-output dynamics of natural tracers	Distributed measurements of soil moisture and groundwater	Coupled modelling and distributed measurements of soil moisture	Distributed measurements of soil moisture	Water balance
Area (km^2)	30	0·0063	0·38	0·02	0·41
Mean altitude (m)	405	133	2073	1500	222
Relief (m)	620	20	118	100	57
Dominant geology	Granite	Granodiorite	Basalt/Rhyolite	Granodiorite	Granodiorite
Mean soil depth (mm)	700	430	1230	459	1200
Annual precipitation (mm)	1000	1050	866	641	1250
Annual runoff (mm)	550	317	523	96	360
Mean storage (mm)	253	205	140	80	769
Min storage (mm)	222	140	5	39	240
Max storage (mm)	284	260	210	105	1168
Total storage capacity (mm)	280	300	460	207	1300
Storage range/Mean storage	0·24	0·59	1·46	0·83	1·21
Annual precipitation/Mean storage	8·01	5·12	3·95	6·19	1·63
Annual runoff/Mean storage	3·43	1·54	2·17	3·70	0·45

While understanding processes by which catchments *release* water will always be central to hydrologic science, it is equally essential to understand how catchments *retain* water. For example, in relatively dry environments seasonal soil moisture storage deficits must be exceeded before runoff or groundwater recharge can occur (Seyfried *et al*., 2009). Similarly, in temperate and tropical environments storage thresholds occur on shorter inter-storm timescales for landscapes ranging from hillslope to catchment scales (e.g. Noguchi *et al*., 1997; Tani, 1997; Western and Grayson, 1998; Peters *et al*., 2003; Tromp-van Meerveld and McDonnell, 2006; Zehe *et al*., 2007). In both environments, strong relationships exist between subsurface storage and stream flow, a concept that has a long history in engineering hydrology (e.g. Nash, 1957; Wittenberg, 1999). Additionally, storage as snow imposes time lags on precipitation/runoff relationships, and the ability of soil to store water in seasonally dry regions makes winter precipitation available for summer plant growth. Virtually all plant growth is influenced by either not enough or too much storage. Storage is critical for biogeochemical processes, many of which depend on, among other things, concentration gradients and time of exposure (time and amount of storage). Standard practice in spatially distributed hydrologic modelling is to estimate numerous model parameters based on fairly well measured inputs, but output measured only at the catchment outlet. Validation of hydrologic models only by stream flow is complicated by the notion that hydrograph models can simulate runoff while misrepresenting the processes that generate the runoff (e.g. Kirchner, 2006). Given the centrality of storage in catchment functions, efforts directed towards internal storage will help constrain such models by providing a better understanding of the processes inside catchments.

We have initiated a comparison exercise to begin assessing the value of viewing catchments from the storage perspective. Investigators from each of five contributing sites (Table I) across a range of spatial scales and climate, geological, and soil conditions estimated storage volumes by whatever means were available to them including direct measurements, indirect water balances, environmental tracers, hydrologic modelling, or a combination of the above. The exercise is based on existing data, no common experimental design, and no integrated modelling efforts. Rather, storage was estimated independently for each site, without common instructions–unavoidable for such initial inter-site comparisons where data were measured for different reasons and research objectives. It is not our intention to propose a new methodology for storage-based comparison. Rather, our intent is to highlight an essential component of catchment hydrology that is currently underappreciated in order to inspire new measurement strategies and modelling approaches to assess storage.

We highlight four lessons learned from this initial exercise. First, there is a need for clear definitions of storage with respect to new discoveries in understanding the residence time of catchment water. Second, the various methods to assess storage must be reconciled to determine if storage from one method is the same as storage from another. Third, appropriate metrics for storage comparison must be selected. Fourth, a community framework for organising existing data, as well as plans for future integrated measurement and modelling campaigns, will facilitate further comparison efforts.

Defining Storage

Catchment comparisons based on storage must use a common vocabulary. Storage in the context of this briefing is the quantity of water that exists at an instant within a control *volume*, which is constrained by the topographically defined catchment *area* that directs flow to a common stream outlet. Depth transforms catchment area to volume. Defining the depth of stored water in a catchment is challenging and raises the question of what is *active* versus *total* storage. Active storage refers to 'zones' that fill and release water on time scales relevant to annual input and output fluxes. The depth of active water is not necessarily correlated with physical depth, but active and inactive zones can be distributed throughout the porous continuum from deep groundwater to near surface soil moisture depending on edaphic, topographic, and biological controls. Nevertheless, many studies have shown that streamflow (Hrachowitz *et al*., 2010) and evapotranspiration (e.g. Dawson, 1996; Jackson *et al*., 2000, Brooks *et al*., 2009) are composed of stored water of widely varying ages in the vadose and saturated zones, confusing the distinction between active and inactive stores.

Different methods to determine the depth of stored water are used throughout the hydrologic research community, and different interpretations of *active* storage depth *versus total* storage depth challenge comparison efforts. Combining multiple methods such as natural conservative tracers (e.g. water isotopes or chloride) and traditional hydrometric methods, however, may provide greater insight into distinctions between active and total catchment storage (Soulsby *et al*., 2009) and should be explored further. For example, classic hydrological theory implies a relationship between the mean transit time of water (MTT) and storage (S) whereby $S = MTTi$ when i is the water flux. MTT of water molecules in catchments can be estimated from tracers (McGuire and McDonnell, 2006). Hydrometric and tracer-derived storage estimates at Gårdsjön, Sweden (Table I) produce similar results, while at Girnock, Scotland, the two estimates are very different. Transit times at Gårdsjön derived from ^{18}O data correspond to a mean storage of 186 mm during the year-long study period (Rodhe *et al*., 1996), compared to the hydrometrically determined storage of 205 mm. However, for the Girnock catchment in Scotland, ^{18}O-based MTT estimates of 580 days (with an uncertainty ±310 days) equate to catchment storage of 1051 (±561) mm (Soulsby *et al*., 2009). This contrasts with soil moisture monitoring which implies storage changes of <50 mm between the wet and dry seasons (Haria and Price, 2000) whilst catchment-scale modelling implies a dynamic storage of around 100 mm implying groundwater influence (Birkel *et al*., 2010a). However, the much greater storage implied by tracers strongly infers large stores of deep ground water, which mixes with precipitation inputs and damps tracer variations. These contrasting studies may indicate the increasing role that stored groundwater plays at larger catchment scales. Examples like these highlight the need to reconcile various storage definitions and estimation methods.

Estimating Storage

While point measurements of many storage values are commonplace, spatially distributed catchment-scale storage estimates are rare. Storage variables in Table I were estimated independently for each site using previously collected data from diverse methods. Here, we describe the methods used as well as introduce each site with respect to the water balance.

The Treeline site (0·02 km^2) in the Dry Creek Experimental Watershed, herein called Dry Creek, is on the northern edge of the Snake River Basin in the semi-arid non-glaciated southwest of Idaho at a mean elevation of 1610 m. The site trends northwest to southeast, the total relief of site is 70 m and it contains surface slopes of 20–40° over mostly concave and convex angles. Soils are derived from weathering of the Idaho Batholith, a biotite granodiorite intrusion 75–85 million years in age. Soils are gravelly sandy-loam, depth ranges from 0·25 to 1·2 m and averages 0·45 m. (Williams *et al*., 2009). The primary vegetation includes sagebrush, forbs, grasses, and scattered trees (Pinus ponderosa; Pseudotsuga menziesii). An ephemeral stream flows from approximately late November through early May. An annual time series of soil water storage in Treeline was estimated by multiplying the depth of soil and the hourly volumetric water content. Water content was measured with continuously logging time domain reflectometry (TDR) at several depths in one soil pit and periodic measurements of near-surface soil moisture at 57 locations in the catchment (McNamara *et al*., 2005; Williams *et al*., 2009). Soil depth at each location was measured by driving a steel rod to the point of refusal. Representative areas were calculated for each point using a polygon method to produce a weighted average catchment storage. Storage statistics (Table I) were taken as appropriate values from this one-year time series. This estimate of storage does not account for storage in the snowpack which, although a very important storage mechanism in this catchment, is not used in this comparison.

Reynolds Mountain (0·38 km^2) is in the Reynolds Creek Experiment Watershed, herein called Reynolds Creek, on the southern edge of the Snake River basin, approximately 100 km south of Dry Creek. Elevations range from 2020 to 2140 m. Soils in the Reynolds Creek were formed on slopes ranging from nearly level to 40% and have textures ranging from loam to clay with widely varying coarse fragment contents that generally increase with depth and proximity to bedrock. Soil depths range from extremely shallow (rock outcrops in places) to greater than 3 m. Parent material consists of shallow surficial loess deposits over basalt and latite. Vegetation at the Reynolds Creek is dominated by mountain big sagebrush (*Artemesia tridentata vaseyana*), either in dense stands with snowberry (*Symphoricarpos oreophilus*) or sparse stands without snowberry. Rocky ridges have little or no vegetation surrounded by a sparse coverage of low sagebrush (*Artemesia arbuscula*) with mixed grasses and forbs. Dry meadows are dominated by grasses and forbs. Groves of quaking aspen (*Populus tremuloides*) are found either under or immediately downslope of snow drifts in upland areas, or associated with willows in riparian areas. There are also small areas of conifers, dominated by Douglas fir (*Pseudotsuga menziesii*) in protected, non-drift areas. In this study, the storage referred to is soil water. The estimates are based on a combination of measurements and simulations (Grant *et al*., 2004; Seyfried *et al*., 2009). The field measurements were made at 20 different neutron access tube locations over a 2-year period; data were collected periodically to bedrock, usually ≤ 1 m depth. Measured storage at the end of a very dry summer was regarded as a threshold between inactive and active stored water. This state corresponds to cessation of stream flow. In order to generalize these results, a soil water balance model was parameterized using the measured soil water data, soil maps, and vegetation patterns. This model, run in conjunction with ISNOBAL (a snow accumulation and melt model; Marks *et al*., 1999), was used to estimate soil water storage throughout the catchment on a daily time step. Over a two-year period we compared measured and simulated soil water storage at a variety of measurement sites for a total of 26 site-years. In general, the simulated dynamics of storage followed those measured quite closely. The average difference between the measured and simulated values was less than 1·6 cm of water. The overall R^2 was greater than 0·92 with a slope near 1 and y-intercept near zero.

The Panola Mountain Research Watershed (0·41 km^2), herein called Panola, is a relatively undisturbed forested catchment in the Piedmont Province of Georgia, USA. PMRW contains 10% exposed bedrock outcrops and the remainder of the catchment is covered with a mixed deciduous and coniferous forest dominated by hickory, oak, tulip poplar, and loblolly pine. PMRW is predominantly underlain by granodiorite bedrock. The regolith is thin (<1 m) on hillslopes and thick (≤ 5 m) in the riparian zone. Soils generally are well drained and weathered bedrock underlying variable-depth soil on a trenched hillslope is relatively permeable (144 mm/day). Storage was estimated by a water balance approach. The storage-discharge (SD) relation (in the following section) targets the catchment water storage during baseflow and was derived from cumulative daily precipitation minus daily runoff when ET is a minimum, i.e. from the beginning of senescence in the autumn (15 October) to the end of winter (15 March), and the daily baseflow, i.e. daily flow for non-rain days and for at least 4 days after the last rainfall. The results were combined from each water year (WY: October through September) from 1986 to 2008 and initial storage was optimized to reduce the RMS error of the relation ($R^2 = 0{\cdot}96$ for a semi-log relation between storage (cumulative precipitation) and streamflow). The mean storage was computed from the SD relation and mean baseflow (average of the 7-day minimum streamflow). The minimum storage was the amount of soil water at the wilting point for a 1·2 m average depth soil. The maximum storage was computed from the SD relationship and the maximum 7-day minimum streamflow for WY1986-WY2008, which is essentially the maximum baseflow during the wettest of the wet seasons. The maximum daily streamflow from which this relation was derived was 3 mm/day. Consequently, the storage for streamflow >3 mm/day is extrapolated.

The Gårdsjön Covered Catchment (0·0063 km^2), herein called Gårdsjön, is located on the Swedish west coast. The bedrock is of gneissic granodiorite, and the dominant vegetation is an 80–100-year-old stand of Norway Spruce (*Picea abies*). The topography is characterized by a 100-m-long valley extending along the catchment, with steep flanks (10–30°), and an elevation range from 123 to 143 m. The shallow podzol soils developed in a till overburden with a mean depth of 43 cm over the bedrock which is assumed to be impermeable. The well-drained podzols of the flanks give way to moister soils in the valley bottom where there are local areas of peat. The detailed physical soil properties have been investigated in four profiles in G1 and three profiles in nearby catchments. The daily dynamics of the spatial distribution of soil water and groundwater storage were simulated with a model based on groundwater level observations, soil properties, soil moisture measurements, and an assumption of hydrological equilibrium above the water table (Bishop *et al*., 1998). A Monte-Carlo analysis of uncertainty estimated that the model had an uncertainty of less than 10%. In each of the four soil profiles used to observe the total water storage in the till soil, a set of Time Doman Reflectometry (TDR) probes were installed and left in place and measured fortnightly from June 1991 to September 1993. The deepest measurement level in profiles varied from 32 to 82 cm. The upper 30 cm of soil accounts for almost half the total catchment soil volume. For the remainder of the soil volume below 30 cm, the permanent TDR profiles were used to estimate water content, thus making it possible to convert these TDR maps into estimates of total catchment soil water storage. Soil depth determines the dimensions of the reservoir for water storage within the catchment. The depth of the soil profile to bedrock was gauged with a steel probe at 240 regularly spaced points on a 5 × 5 m grid across the catchment. The thickness of the humus layer (LFH) was measured at another 124 regularly distributed points, and the thickness of the O-, A_e-, B-, and C-horizons were also measured at 60 of those points. Groundwater levels in the surficial material (soil and till) were the key to water storage dynamics in this study. These wells were constructed of 2·5 cm diameter, perforated, PVC tubes inserted down to the till-bedrock interface. Water level was monitored at three locations with pressure transducers recorded every 30 min for three years starting in April 1990. For a more extensive measure of the spatial variation in groundwater level, manual measurements were made fortnightly in another 34 groundwater tubes between April 1990 and September 1993. As part of the experimental study on acidification recovery, the natural precipitation was intercepted by a roof and replaced with less acid irrigation water (Bishop and Hultberg, 1995). This created a step-shift in the ^{18}O of the precipitation that was utilized to determine the distribution of water residence times in the catchment (Rodhe *et al.*, 1996).

The Girnock Burn (31 km^2), herein called Girnock, is located in NE Scotland. Precipitation falls mainly as rain evenly distributed throughout the year. Altitude ranges from 230 m to 862 m and the mean slope is 9·4°. The bedrock, low permeability igneous and metamorphic rocks, has generally poor aquifer characteristics, and fracture flow is probably the main mechanism of bedrock groundwater storage and movement. At most sites, superficial drifts cover much of the solid geology (Soulsby *et al.*, 2007). In valley bottom areas, the drifts are fine textured with significant water storage but relatively low fluxes (Malcolm *et al.*, 2004). As a result, soil cover is dominated by histosols and gleysols on the lower catchment slopes close to the river channel. These soils have particularly high storage capacity in their organic surface horizons. More freely draining podzols dominate the steeper upper slopes, with shallow regosols occurring at higher altitudes. Land use is dominated by heather (*Calluna vulgaris*) moorland with small patches of forest. Insight into storage dynamics at Girnock Burn has been gained by multiple approaches. Although direct soil moisture measurements have not been carried out in the catchment, they have been carried out in the same region using neutron probes in soils with similar geology and climate (e.g. Haria and Price, 2000). A typical podzol or gley soil (70 cm deep) would have around 400–450 mm of storage capacity, mostly in the highly retentive organic surface horizons. Moreover, evenly distributed precipitation and low summer ET typically result in soil moisture deficits of $<$100 mm (typically ca. 50 mm). Direct measurements of shallow groundwater dynamics in similar environments are sparse, but can exceed over 1m in a year though field determination of resulting storage change is unavailable (Soulsby *et al.*, 1998). Estimates of catchment-scale water storage dynamics were obtained using a tracer-aided conceptual rainfall-runoff model (Birkel *et al.*, 2010b for details). This showed maximum annual storage change of ca. 100 mm, split between the soil and groundwater zones, which is broadly consistent with the insights from hydrometric measurements. Input-output dynamics for natural tracers have also been used to provide valuable insight into catchment-scale storage (Soulsby *et al.*, 2009).

Storage Comparison Metrics

Meaningful storage comparisons rely on meaningful storage metrics. Whereas the storage values presented in Table I hold little meaning on their own, storage magnitudes with respect to other water balance components show patterns (Table I). The mean depth of active storage (S) increases with total annual precipitation (P) (Figure 1(a)). Interestingly, P/S decreases with P (Figure 1(b)) suggesting that the mean storage in the wetter catchments increases more rapidly than does the precipitation. One explanation is that in the semiarid catchments (DCEW and RCEW), the soil water storage reservoirs are completely depleted in summer with very low minimum storage values. Despite the strong relationship between P and S, the relationship between discharge (Q) and P is not strong (Figure 1(a)), possibly because while storage reservoirs fill in direct response to precipitation, storage mechanisms partly regulate discharge. Indeed, the storage-discharge (SD) relationship has been the proposed as a significant descriptor of catchment behaviour (Spence, 2007; Kirchner, 2009; Spence, 2010).

The SD relationship illustrates how changes in storage are manifested in discharge. The SD relationship captures the empirical relationships between streamflow dynamics that we can measure and characterize, and the storage properties, which are less well known. SD relationships were constructed by estimating active storage depths in each catchment at prescribed discharge values (Figure 2). The catchments are similar with respect to flow generation in that the runoff in each catchment demonstrates a non-linear response with respect to catchment wetness. Each SD curve is well-explained by a power function, and with one exception they display similar storage ranges. Interestingly, as the basins become more 'full' relative to their maximum storage, there is less of a relationship with discharge (Figure 3), suggesting that storage regulates discharge more significantly in relatively dry conditions. This happens at different degrees of relative storage in different catchments, possibly reflecting the various soil water retention capacities among the catchments. For example, Dry Creek soils are coarse gravelly sands that do not sustain moisture contents above field capacity for very long (McNamara et *al.*, 2005) leading to a relatively flat SD relationship.

Published literature for each site gives insight into potential controls on the shapes of the SD relationships. At Gårdsjön, increases in catchment runoff were

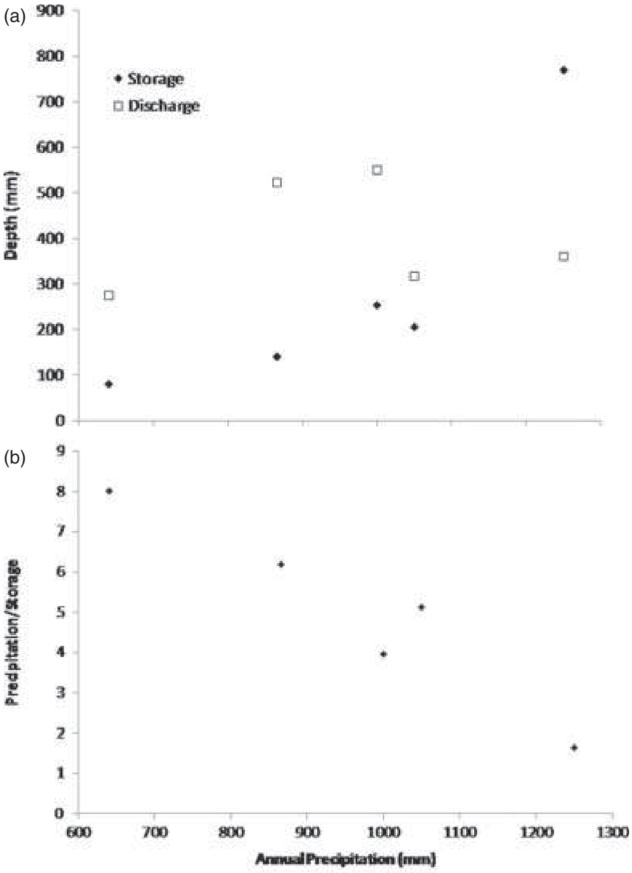

Figure 1. Relationships between annual precipitation and (a) mean storage (diamonds) and discharge (squares), and (b) the annual precipitation/storage ratio

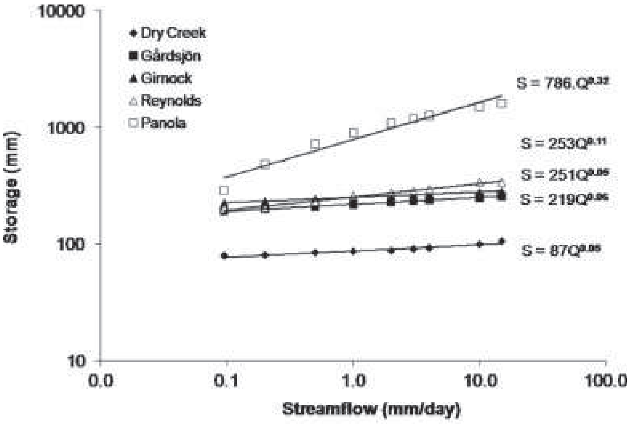

Figure 2. Storage-discharge functions for each of the five sites expressed as power functions. The curves were constructed by determining storage volumes for predetermined discharge values, both normalized to drainage area

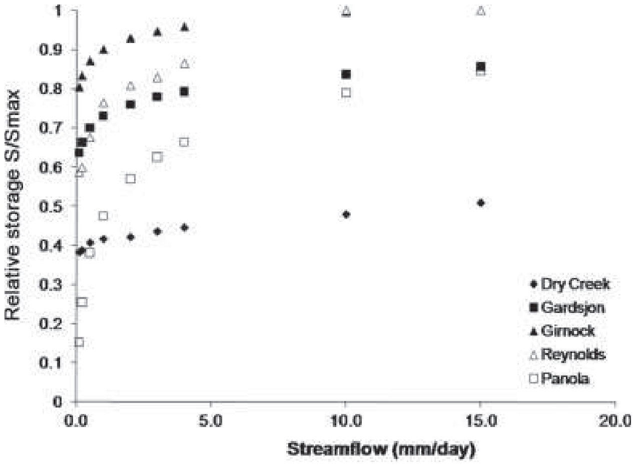

Figure 3. Storage-discharge functions for each site normalized to maximum available storage

marked above a threshold ground water level (Bishop *et al*., 1998). At Panola, stormflow water yields (Q/P) are linearly related to soil moisture content above a soil moisture threshold, above which maximum ground water levels were linearly related to soil moisture and stormflow water yields (Peters *et al*., 2003). At Girnock, the extent of the wetted area associated with peaty soils adjacent to the stream is associated with runoff. Field mapping of the area has revealed a non-linear response dependent on precipitation and antecedent conditions (Birkel *et al*., 2010). For the two snowmelt-dominated Idaho catchments, whole-slope hydraulic connectivity is established when the deeper soils become wetted above field capacity and upland soils are directly connected to the stream

(McNamara *et al*., 2005; Seyfried *et al*., 2009). Although the presence of thresholds is common among these catchments, each catchment likely has a unique spatial pattern with respect to hydrological connectivity, depending on key-runoff generating areas, that produces the SD relationships illustrated in Figures 2 and 3 (Bracken and Croke, 2007).

Dry Creek and Gårdsjön are perhaps the most comparable in terms of size and methods used. Both catchments are drained by ephemeral streams with similar soil depths, but are located in very different climates, with different relative magnitudes of water balance components. The active storage leading to streamflow generation at Treeline is quite limited resulting in a relatively low power function exponent likely due to the rapidly draining coarse soils and lack of connection to deep groundwater. Conversely, the wetter Gårdsjön catchment shows a large range of active storage, perhaps due to the presence of saturated groundwater. The drainage areas of Reynolds Creek and Panola are also similar, but with different SD properties. The mean annual storage is half the annual runoff at Panola, whereas the mean annual storage is only a quarter of the annual runoff at Reynolds Creek. Panola accesses the largest range of storage, likely due to its sustained connection between the stream and deep groundwater. The SD relationship at Girnock is similar to other sites despite the fact that the catchment is much larger than the others and the methods used to calculate storage were quite different.

While the similarities and differences in SD relationships among the sites inspire intriguing ideas on possible underlying principles governing drainage, they may also be due to differences in the way storage is estimated, or even the way storage is defined. Further, the runoff generation context embodied in the SD relationship illustrates just one component of the complex controls that storage can have on catchment functions. It does not distinguish the type and spatial variability of storage, nor does it capture the important part of stored water that survives 'flushing' that is essential to drought-sensitive ecohydrological processes. Both these problems require further refinement of active and total storage concepts.

Future Directions

Within the constraints of the loosely organized grassroots comparison exercise presented here, we suggest that understanding how catchments store water can yield important insights into how catchments release water. Comparative investigations of catchments across a wider range of environments using standardized methods, error assessments, and definitions will yield further insights into the relationships between storage dynamics and catchment processes.

Environmental observation networks are challenged with describing essential processes and capturing the uniqueness of place while at the same time elucidating generalities across regions. Integrated modelling and field campaigns specifically designed to understand storage and its role in regulating catchment functions should be a priority in future observation strategies. In the meantime, we encourage continued grassroots comparison efforts making use of experimental catchments worldwide. The efforts can be greatly enhanced by community-driven data sharing through systems such as the CUAHSI Hydrologic Information System. With new geophysical methods, like microgravity, we have additional ways to evaluate water storage. Furthermore, the GRACE satellite provides rough estimates (at coarse spatial and temporal resolution) of water storage across the entire globe. Further developing these estimates will require combining traditional measurements such as groundwater levels and soil moisture with new geophysical techniques. Expanding the number of experimental basins and including other methods for estimating catchment water storage should be useful in providing a collection of tools to compare and contrast catchments.

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