Opinion paper: Modelling catchments as living organisms

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Abstract

Catchment-scale hydrological models frequently miss essential characteristics of what determines the functioning of catchments. The most important active agent in catchments is the ecosystem. It manipulates and partitions moisture in a way that it supports the essential functions of survival and productivity: infiltration of water, retention of moisture, mobilization and retention of nutrients, and drainage. Ecosystems do this in the most efficient way, establishing a continuous, ever-evolving feedback loop with the landscape and climatic drivers. In brief, our hydrological system is alive and has a strong capacity to adjust itself to prevailing and changing environmental conditions. Although most models take Newtonian theory at heart, as best they can, what they generally miss is Darwinian theory on how an ecosystem evolves and adjusts its environment to maintain crucial hydrological functions. Through a Darwinian approach, we can determine the root zone storage capacity of ecosystems, as a crucial component of hydrological models, determining the partitioning of fluxes and the conservation of moisture to bridge periods of drought. Another crucial element of physical systems is the evolution of drainage patterns, both on and below the surface. Models that do not account for these patterns are not physical. The parameters in the equations may be adjusted to compensate for the lack of patterns, but this involves scale-dependent calibration.

In contrast to what is widely believed, relatively simple conceptual models can accommodate these physical processes very efficiently. The parameters of catchment-scale conceptual models, even if they represent physical parameters, such as time scales, thresholds and reservoir sizes, require calibration or estimation on the basis of observations. Fortunately, we see the emergence of new observation systems from space that permit independent estimation of these parameters. As a result, it will become more and more practical to calibrate well-structured conceptual models, even in poorly gauged catchments.

1. Introduction

“The whole is greater than the sum of the parts” and “Everything changes and nothing remains still […]” are quotes commonly attributed to the Greek philosophers Aristotle (384-322 BC) and Heraclitus (535-475 BC). More recently, but still before Darwin developed his theory on evolution, Alexander von Humboldt (1769-1859) considered nature and its processes as an inseparable entity, where all forces of nature are connected and mutually dependent (Wulf, 2015). Although these concepts were not formulated specifically to describe the movement of water through the natural environment, they very pointedly summarize what controls hydrological functioning at the catchment scale.

Ironically, state-of-the-art catchment-scale hydrological models do, for varying reasons depending on the model under consideration, frequently a poor job in addressing overall system behaviour emerging from the characteristics above. This results in many models being inadequate representations of real-world systems, haunted by large model and/or parameter uncertainties and unreliable predictions.

There has now for several decades been an on-going controversy about the individual benefits and flaws of top-down (i.e. conceptual) versus bottom-up (i.e. physically-based) modelling strategies. Beven (1989), for instance, argued that the so-called "physically-based" models fail to use a proper theory of up-scaling, cannot deal adequately with heterogeneity, and suffer from the curse of dimensionality and the sheer impossibility of parameter calibration. These problems have now, almost 3 decades later, not been overcome and still pose limitations to modelling efforts, as recently highlighted by Zehe et al., (2014). Much of the ongoing discussion concentrates on data uncertainty and availability. This is, without doubt, an important and well-justified aspect of the discussion as it helps to improve current modelling practice. Yet, largely not questioning the validity of model concepts themselves, it ignores that a significant proportion of uncertainty in current-generation catchment-scale hydrological models -- both conceptual and physically based -- can be directly linked to the fact that our conceptual understanding of two of the critical aspects of the system, i.e. internal organization and the capacity of the ecosystem to manipulate the system in response to the temporal dynamics of the atmospheric drivers, as encapsulated in the above two quotes, is only insufficiently or often not at all accounted for in these models. One reason for that is the common absence of observations at the modelling scale of interest and our resulting inability to meaningfully characterize natural heterogeneity in the model domain. This leads to the largely indispensable need for model calibration (for both, conceptual and physically based models), which in turn exacerbates our problem to meaningfully parameterize, test and constrain models.

McDonnell et al (2007), motivated by Dooge's (1986) paper on "Looking for hydrologic laws", concluded that: "In order to make continued progress in watershed hydrology and to bring greater coherence to the science, we need to move beyond the status quo of having to explicitly characterize or prescribe landscape heterogeneity in our (highly calibrated) models and in this way reproduce process complexity but instead explore the set of organizing principles that might underlie the heterogeneity and complexity."; suggesting that we need to find the organising principles underlying the apparent simplicity we can observe in system behaviour.

1.1. The whole is greater than the sum of the parts

Observations from a wide range of natural systems strongly suggest that whenever one medium flows through another medium as a result of a gradient, patterns appear (Savenije, 2009). On the surface, such patterns facilitate infiltration or drainage with limited soil loss; in the unsaturated zone, patterns facilitate efficient replenishment of moisture deficits and preferential drainage when there is excess moisture; in the groundwater, patterns facilitate the efficient and gradual drainage of groundwater, resulting in linear reservoir recession. In the surface drainage network, patterns facilitate the efficient transport of water and sediments (e.g. Rodriguez-Iturbe and Rinaldo, 2001). A clear analogy with drainage patterns is water flowing through a leaf or blood flowing through a body in a system of veins, providing efficient supply of, for example, water and oxygen, to all parts of the organism (e.g. West et al., 1997). But there are also examples from places afar, such as ice melting on Mars forming similar drainage patterns as in landscapes on Earth. Most conceptual models already implicitly account for such structures by the use of modelling components that represent some sort of preferential flow paths and which are controlled by calibrated parameters, effective at the modelling scale. On the one hand, these parameters integrate the natural heterogeneity of flow resistances, i.e. hydraulic conductivities, of the entire model domain. On the other hand, they also characterize spatial distribution functions that describe connectivity patterns of these flow paths in a spatially heterogeneous domain. In contrast, despite the increasing use of conceptual formulations of preferential flow paths based on dual- or multi-domain flow in newest-generation physically based models (Zehe et al., 2001; Kollet and Maxwell, 2006; Sudicky et al., 2008), many others rely on simple and straightforward aggregation of processes from the lab-scale to the catchment scale, assuming that there is no structure and organization in the system as the modelling scale increases from the grid scale to the full domain of the model application. In both cases a suitable description of the emerging patterns and self-organization which is characteristic for many natural systems (e.g. Bak, 1996) is in addition hindered by the typically elevated number of calibration parameters and the associated equifinality or insufficient description of spatial heterogeneity when using direct observations. Thus, according to these models, the only place in nature where there are no drainage patterns is in the subsurface, i.e. in the root zone, in the unsaturated zone below it, and in the groundwater. This is conceptually wrong, because subsurface drainage patterns, manifest as preferential flow paths and created by diverse biological, physical and chemical processes, do appear at a wide range of spatial and temporal scales. Patterns are created by, for example, animal burrows (e.g. earth worms; Zehe and Flühler, 2001; Schaik et al., 2014), former root channels, soil cracks, rock interfaces, and fissures, which are further reinforced by internal chemical and physical erosion processes. Typically characterized by convergent flow, reduced flow resistance and higher flow velocities, these patterns, as manifestations of organization, provide efficient drainage as well as transport capacity for dissolved or suspended substances. When zooming out to the macroscale, the time dynamic connectivity of these structures frequently emerges as simple functional relationships with system wetness (e.g. Detty and McGuire, 2010; Penna et al., 2011).

1.2. Everything changes and nothing remains still

But the problem is not only the absence of patterns. These pattern result from evolution over time. Evolution of climate and landscape have the potential to cause systemic change within catchments. Such a systemic change is unlikely to be picked up at time scales smaller than the calibration period with current model formulations, as the typically constant model parameters define time-invariant functional relationships emerging at the scale of the model domain. Only, and only if the system could be broken down into its smaller, more detailed building blocks and accounting for the relevant physical, chemical and biological processes involved, such a systemic change would emerge from a model. Yet, this is problematic, if not impossible given current-day observation technology and our incomplete understanding of the underlying mechanisms. As an illustrative example, consider the change of the interception pattern over time after the conversion of grassland into forest. If detailed parameterizations of vegetation growth dynamics across the model domain were part of the model, changes in canopy and sub-canopy, and thus in interception pattern over time, would naturally emerge from the model. Given our lack of observations and process knowledge, this is, however, not feasible at scales of actual interest. Rather, functional relationships of the process emerging at larger scales and at lower levels of process detail have to be used. This, however, typically entails that potentially dynamic small-scale processes are lumped into constant parameters, preventing the emergence of a time-variant pattern. It is therefore of critical importance to realize and acknowledge that the hydrological system is not merely a dead configuration of earth material through which water flows. It is the foundation of a living ecosystem that manipulates and adapts the environment so as to facilitate its own survival and reproduction. Ecosystems clearly do not do this in a conscious way with an objective in mind. Rather, the mere fact that they have survived past conditions in competition with other species is proof that they have done so efficiently. The current state of an ecosystem is then the manifestation of its development over the past. This trajectory and not the current structure controls system response. This is Darwinian thinking, alien to the purely mechanistic philosophy on which much of our state-of-the-art modelling concepts are based.

Hydrological systems, at all spatial scales, from the plot to the catchment scale, therefore may be understood as meta-organisms (e.g. Bosch and Miller, 2016), i.e. systems of living biological entities, that occupy an ecological niche and that interact mutually but also with their inanimate environment. The current appearance and characteristic of these systems is clearly not the endpoint of their trajectories. Ecosystems, and hence hydrological systems, continuously and dynamically evolve over a wide range of temporal and spatial scales. Yet, current generation models are mostly built on the foundations of time-invariant system descriptors. This modelling strategy provides us with system characterizations that are only snapshots in time and that deprive us of developing a better understanding of what drives change and of the systems' future trajectories.

2. The crucial elements of a hydrological model

Any hydrological model that claims to be physical has to properly reflect key elements of hydrological systems. The first key element is the proper reflection of the partitioning points that the ecosystem creates to optimise system functions: infiltration, retention, and drainage. The second key element is that in the landscape patterns emerge, on and below the surface, that facilitate efficient ways of drainage and infiltration.

2.1. Representation of partitioning points

In a hydrological system we can identify two major partitioning zones controlling how and where precipitation is partitioned into different upward, downward or lateral fluxes. The first partitioning zone is located at the (near-) land surface, where precipitation is split into: (1) direct feedback to the atmosphere from canopy interception, ground interception, and open water; (2) infiltration into the root zone; and (3) surface runoff (Hortonian infiltration excess overland flow and Dunne saturation excess overland flow). Water infiltrating into the soil eventually reaches the second partitioning zone, the root zone, which splits the incoming moisture into: (4) transpiration by vegetation; (5) soil evaporation; (6) subsurface saturation and/or infiltration excess flow, e.g. the fill-and-spill theory and/or rapid sub-surface flow through preferential drainage structures within and below the root zone; and (7) percolation to the groundwater.

If one wants to describe the hydrological functioning of a hydrological unit or catchment, an accurate description critically hinges on a meaningful definition of this partitioning and the residence times of the moisture in the two system partitioning zones. What characterizes and shapes these two partitioning zones and thereby controls their respective functioning, are largely the biotic components of the ecosystem, i.e. vegetation, animals and microorganisms living in a given landscape. In fact, over the past, the ecosystem actively has manipulated (and continues to do so) water fluxes and residence times in a way that the landscape provided the functions that allowed the ecosystem's development to reach its current state. These functions are: (1) facilitating infiltration so as to efficiently recharge root zone soil moisture and to optimise subsurface drainage; (2) retention of sufficient moisture for vegetation to overcome critical periods of drought; (3) efficient drainage of excess water, to ensure sufficient oxygen supply for roots; and (4) maintenance of a healthy substrate with an adequate availability of nutrients. The latter implies the prevention of excessive erosion and leaching of valuable nutrients. If, and only if the current ecosystem manages to modify the substrate so as to satisfy all these functions, it will safeguard long-term survival. It will have to do so efficiently, otherwise, due to an excessive allocation of scarce resources to, for instance, the growth and maintenance of the root system, insufficient resources for surface growth will be available. As a consequence, an inefficient species will experience a disadvantage in the competition with species that are more adapted to the environmental conditions at a given location. They will eventually be replaced by the better adapted species, changing the dynamics and pattern not only of the plant community at that location but also affecting the entire ecosystem around it and thereby its influence on the hydrological functioning. These changes can include for example changes to the root system, the canopy or the animal and microorganism communities in the area. All of which can result in changes to the pathways of water (and nutrients) through the system and eventually affect how the system stores and releases water and nutrients.

There is increasing experimental (e.g. Brooks et al., 2010; Evaristo et al., 2015) and theoretical evidence (e.g. Hrachowitz et al., 2013; Van der Velde et al., 2015) for such an eco-hydrologically controlled partitioning that regulates these contrasting requirements of storage and drainage of water and nutrients, which has recently been comprehensively summarized in the two-water-worlds hypothesis (McDonnell, 2014; Good et al., 2015). Briefly, root systems extract water and nutrients mainly from the soil matrix, which is characterized by relatively small pore sizes. In contrast, larger pores, having lower specific surfaces and thus less adsorption capacity, only start to fill with increasing moisture content of the soil, when the small pores are increasingly saturated. The lower flow resistances in these larger subsurface features provide less buffer but rather allow for higher flow velocities. They thereby provide an efficient mechanism for water to bypass the soil matrix with little interaction and to drain excess water through a network of preferential channels when the system is in a wet state. Although not independent of each other, water stored in the matrix for transpiration and water in preferential features, generating stream flow, are therefore characterized by distinct age signatures, effectively constituting distinct pools of water (e.g. Hrachowitz et al., 2015). This dual system, satisfying the contrasting hydrological functions of sufficient storage (of water and nutrients) and efficient drainage required by an ecosystem, has developed through co-evolution of climate and hydrology with the ecosystem in a Darwinian process (e.g. Sivapalan et al., 2011; Blöschl et al., 2013). Being in a dynamic equilibrium, the state of such a system at any given time is a manifestation of its past trajectory and reflects the conditions for survival at that time.

2.2. The emergence of patterns and their properties

Implicit in relatively simple models with little spatial discretization (i.e. mostly lumped or semi-distributed conceptual models) is that there is an underlying process of maximum efficiency that leads to self-organisation (e.g. Zehe et al, 2013). The Earth system is continuously receiving solar energy. This energy needs to be dissipated in an efficient way to produce entropy (e.g, Michaelian, 2012). According to Kleidon (2016), the process of energy conversion corresponds with maximum power or maximum entropy production, close to the Carnot limit, leading to the evolution of patterns of efficient transport of erosion products. Eventually this self-reinforcing mechanism, i.e. positive feedback loop, creates an organised system of drainage (Kleidon et al., 2013).

As argued by Dooge (1986), catchments are "complex systems with some degree of organisation"; in other words, it is "organised complexity" (Dooge, 2005). This organisation is dominated by the ecosystem, which is not static but very much alive and continuously evolving. Given the strong evidence for the interactions between hydrological functioning, climate and ecosystem (e.g. Milly, 1994; Rodriguez-Iturbe and Porporato, 2007; Alila et al., 2009; Gao et al., 2014a; Nijzink et al., 2016), it is inconceivable that the hydrological system remains unaltered under climate or land-use change. It is rather adjusting in response to changing environmental conditions and thereby actively and continuously adjusting the partitioning zones at a wide range of spatial and temporal scales. The dominant ecosystem that emerges will, in a Darwinian sense, then tend to maximum efficiency for survival.

The ecosystem shapes the hydrological system in a way that it converges towards a dynamic equilibrium between infiltration, retention, drainage and limitation of erosion, thereby creating conditions that facilitate its own survival. In a feedback, hydrology on its own term then similarly shapes the ecosystem. If we want to model such systems, we have to realise that our models need to reflect this dynamic and continuous feedback loop. In other words, our models need to be organic and alive, just as natural systems are. Yet, to do this, there is little need to describe the sub-surface partitioning zone, i.e. the unsaturated root zone, in multiple layers with different properties and using root depth estimates. Such data is rarely available at the level of required detail and if it is, it has mostly been obtained from one-time sampling campaigns with no information about their respective temporal trajectories.

Consider, as a thought experiment, the case of a plant species in a humid climate at a location with a relatively poorly drained soil such as loam. From experiments with individual plants of that species an estimate of average root depth at that location can be obtained. Together with estimates of soil porosity, the water storage capacity in the root zone of that *specific location* can be readily determined. Firstly, this approach ignores that root systems can and do adapt to temporal variability in environmental conditions at time scales relevant for hydrological applications. But moreover, considering that plants of the same species have common limits of operation such as water and nutrient requirements, it is implausible to use the same root depth estimates for the same plant growing in a drier climate and/or at a different location with well-drained, coarser soils, such as sand. The estimated storage capacity of water accessible to plants will be considerably underestimated and will merely reflect the differences in soil properties. However, if the same species survived in a different climate or on that different soil, this implies that it had sufficient access to water and nutrients. In other words, the plant developed a different, i.e. deeper and/or denser, root system that could ensure access to the same volume of water as in the first location (cf. Gao et al., 2014a; DeBoer-Euser et al., 2016; Nijzink et al., 2016). Thus, ecosystems control the hydrological functioning of the root zone in a way that *continuously* optimizes the functions of infiltration, moisture retention, drainage and limitation of erosion.

The result of such a co-evolution between climate, ecosystem, substrate and hydrological functioning typically exhibits surprisingly simple patterns emerging at larger scales in spite of the complex and highly heterogeneous combination of soils, geology, topography and climate and their mutual interactions at smaller scales. Thus, even relatively simple lumped or semi-distributed conceptual models have in the past shown considerable skill in reproducing hydrological functioning in a wide variety of landscapes and climates. In fact, it is highly likely that these models' relatively simple closure relations, based on simple system descriptions that permit the integration of natural heterogeneity over the model domain, using functional, emergent relationships, are manifestations of energetic optimality, most likely at a state of maximum power (e.g. Kleidon, 2016).

Apparently, ecosystems are capable of creating resilience against variability and, in that process, create predictable behaviour within an otherwise complex environment. Hence, mere upscaling from the lab-scale to the landscape scale is insufficient if the ecosystem is not included as an active agent creating resilience against the variability of nature.

3. Why can simple conceptual models meaningfully represent these system properties?

Several hydrologists have remarked on the paradox that instead of more complexity, simplicity emerges in catchment behaviour as more processes come into play (e.g. Sivapalan 2003a). This happens at a scale where the hydrological unit has sufficient size to achieve a certain level of organisation. Self-organisation leads to less complexity (Dooge, 2005). Conceptual models, being a configuration of relatively simple relationships, seem therefore adequate to deal with systems that have reached some degree of organisation. But it is not merely the simplicity.

Let us consider a conceptual model that consists of three main stores: the surface reservoir, the root zone reservoir and the groundwater reservoir. The surface reservoir represents the retention of moisture by canopy and ground interception, which has a relatively small storage capacity from which the moisture can evaporate directly back to the atmosphere. Above the capacity threshold the moisture is split into infiltration and surface runoff, depending on a threshold defined by the infiltration capacity. There is nothing non-physical about this. The key lies in the infiltration function, but this is not particular for conceptual models.

The unsaturated root zone storage in a conceptual model can be brought in tune with the storage requirement of the vegetation. This can be derived in a Darwinian sense and can lead to scale-independent estimates of root zone storage capacity for given ecosystems (Gao et al., 2014a; Nijzink et al., 2016; Wang-Erlandsson, 2016). This is a fully physical storage capacity. When the store is full, sub-surface runoff and recharge is generated. At aggregate scale there is spatial heterogeneity in the landscape, which leads to a distribution of thresholds above which runoff is generated, describing the connectivity pattern of that system. This can be done by using any suitable distribution function, such as in the Xinangjiang (Zhao & Liu, 1995) or VIC model (e.g. Liang et al., 1994). If the runoff mechanism is sub-surface flow, the threshold is sub-surface saturation above a less permeable layer (e.g. McDonnell, 2009); if the mechanism is saturation excess overland flow, it describes the increasing saturated area of a catchment (Dunne & Black, 1970). Again, this is purely physical, as long as the right runoff mechanism is applied to the appropriate landscape: sub-surface (McDonnell) flow on hillslopes and Dunne overland flow on landscapes where groundwater can reach the surface (wetlands and riparian zones). The routing of the flow toward the stream network can be done by simple transfer functions, linear reservoirs or cascades. This is just a matter of routing and does not affect the partitioning or the water balance.

Finally, data from catchments worldwide suggest that groundwater systems at the catchment-scale function in many cases as linear reservoirs in natural catchments, manifest in the frequently observed exponential recession of the hydrograph during rainless periods, in particular in lower order, upland streams where time lags introduced by channel routing are limited compared to the modelling time scale. Why the dynamic part of the groundwater is organised in this simple way is still one of the fundamental questions in hydrology, but the answer is likely to be found in the theory of maximum power or maximum entropy production. Whether or not the answer to this question will be found sooner or later does not affect the viewpoint that the exponential depletion of groundwater is physical and real. The linear reservoir is not more or less physical than Darcy's equation.

In spite of their rather low level of detail, conceptual models are quite capable of representing these processes in a simple and adequate way, provided we account for differences in landscape, ecosystem and land cover. If there is considerable heterogeneity in the climatic drivers (precipitation and energy) and if these drivers are available at grid-scale, then the stocks of the conceptual models can be distributed spatially, so as to account for the spatial heterogeneity of the moisture states. Conceptual models do not have to be lumped, as long as the system descriptors reflect the processes at the hydrological unit scale at which they emerge.

4. What are the practical consequences?

Ironically, the above implies that bringing in more physics -- i.e. the right kind of physics -- into our models makes them simpler. Apparently, simplicity -- that is to say the right kind of simplicity -- enhances the physics of our hydrological models. If a model is complex, yet fails to reproduce patterns emerging at the macroscale that characterize real-world systems as a result of the evolution of the system over the past, that may be an indication of a lack of physics, or of the wrong application of physics. In other words, zooming out to the macroscale allows to focus on the pattern and processes emerging at that scale, which are, due to the ever improving remote sensing technology, increasingly observable at the actual modelling scale (see Figure 1). This offers opportunities for prediction in ungauged basins. As emphasized by Sivapalan et al. (2003b), our limited ability to predict hydrological behaviour is an indication of our lack of understanding of *essential* physical processes at the *macroscale*. This is of particular importance the scarcer detailed observations at suitable spatial resolutions and scales are. In fact, it was this inability that was the main trigger for the PUB science decade (2003-2012).

There is already a wide range of remotely sensed data available that allow modellers to directly exploit spatial patterns emerging at the macroscale for use in models. For example, as different parts of the landscape can be associated with different dominant hydrological processes, topographical indicators extracted from globally available digital elevation models, such as the topographic wetness index (TWI; Beven and Kirkby, 1979; Ambroise et al., 1996; Freer et al., 2004) or more recently the height above the nearest drainage (HAND; Rennó et al., 2008; Savenije, 2010; Nobre et al., 2011; Gharari et al., 2011) have proven highly valuable for model development, as illustrated by the example of a landscape-informed semi-distributed formulation of a conceptual model in Figure 2. Similarly, increased detail in land cover maps, including also products such as leaf area index, allows to account for the effect spatial pattern of different vegetation types (e.g. Cuo et al., 2009; Li et al., 2009; Samaniego et al., 2010), while the higher temporal resolution of snow cover maps permits an improved representation of spatial patterns of snow accumulation and depletion (e.g. Rodell and Houser, 2004; Andreadis and Lettenmaier, 2006; Nester et al., 2012). As shown by a range of recent studies, these information sources can serve as efficient tools to constrain spatially explicit or semi-distributed models (both conceptual and physically based) while ensuring a meaningful representation of spatial patterns (e.g. Gao et al., 2014b,2016).

A further example that illustrates the value of remote sensing data to identify and quantify pattern emerging at the macroscale are spatially distributed estimates of precipitation and evaporation. Recent work suggests that the catchment-scale moisture retention capacity in the unsaturated root zone, one of the most important parameters in terrestrial hydrological systems, can be estimated based on a Darwinian theory. If an ecosystem has been able to survive critical periods of drought, where the evaporation E was larger than the precipitation P, then apparently it had sufficient storage to overcome this drought. By simulating the storage variation resulting from P and E time series, the root zone storage capacity that the ecosystem designed can be estimated (e.g. Gao et al., 2014a; De Boer-Euser et al., 2016; Nijzink et al., 2016; Wang-Erlandsson et al., 2016; Figure 3). With this method, the root zone storage capacity of each landscape element can in principle be determined at any scale where information on E and P is available.

Similarly, time series of remotely sensed gravity anomalies can be related to spatio-temporally varying water storage patterns i.e. GRACE (e.g. Wahr et al., 2004). This information was in the past already successfully used to evaluate or constrain hydrological models (e.g. Winsemius et al., 2006; Krakauer and Temimi, 2011; Milzow et al. 2011; Xie et al., 2012; Reager et al., 2014). However, spatial organization allows to take this even a step further. The stream flow recession during dry periods, when the root zone is disconnected from groundwater (e.g. McDonnell, 2014) and stream flow is sustained exclusively by the groundwater, is characterized by an exponential decrease (i.e. linear reservoir) emerging at the macroscale in many catchments worldwide. During such periods, the water balance reduces to a relation between the groundwater storage S_g and the groundwater dominated outflow Q_g, which are assumed to be linearly related by a recession time scale k_g:

$$\frac{dS_g}{dt} = -Q_g = -\frac{S_g}{k_g} \qquad (1)$$

GRACE provides estimates of changes of the total water equivalent storage W, which is the sum of all water stores (surface, unsaturated and saturated zones). During the dry season, when there is a disconnect between the (sub-)surface and the groundwater, the temporal gradient of the surface and sub-surface stores can be replaced by (P-E). If we subtract (P-E) from the temporal gradient of W ($\mathrm{d}W/\mathrm{d}t$), we thus obtain the recession of the groundwater storage ($\mathrm{d}S_g/\mathrm{d}t$, see Figure 4):

$$\frac{dS_g}{dt} = \frac{dW}{dt} + (E - P) = -\frac{S_g}{k_g} \qquad (2)$$

The temporal recession of S_g obeys the same exponential function as the recession in the drainage network during dry periods, acting as a linear reservoir, implying that the time scale of the recession k_g reflects the recession parameter at the scale of the model application.

4.4 Can we predict runoff without ground stations? [1]

Thus already with the present remote sensing-based tools, we can derive crucial hydrological parameters from pattern and organization identified through independent data sources (see Figure 2): the root zone storage capacity $S_{u,max}$ for different vegetation classes from E and P products; and the recession time scale k from gravity observations. If subsequently we estimate interception capacities S_i from land cover information, which can be done with reasonable accuracy (e.g. Samaniego et al., 2010), then there are, when using a conceptual model, only few parameters left to calibrate, such as the exponent β of the spatial distribution function describing the connectivity of fast flow paths (e.g. preferential flow), a splitter D describing the connectivity of preferential recharge, and the fast recession time scales k_f. Because in the above we have not yet simulated the entire time series, what one could do next is to drive a simple conceptual model with P and calibrate on the time series of E and W (e.g. Winsemius et al., 2009). This would allow estimation of the remaining three parameters.

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[1] based on the poster presented at the symposium in honour of Eric Wood (Princeton 3 June 2016)

At the present level of technology there is still considerable uncertainty in the estimation of *E*, *P* and *W* time series. But the quality of these products is gradually improving. In addition, we have more and more access to accurate altimetry, which could in the future allow meaningful calibration on water levels, making use of hydraulic equations. Already now, calibration on lake levels is possible, and a few studies even already ventured in using altimetry for the determination of accurate river geometry, river levels and, using hydraulic equations, calibration of runoff on water levels (e.g. Sun et al., 2012, 2015).

5. Conclusions

As hydrological scientists, we would like all our models to be based on solid physics. On this issue we do not disagree. What we sometimes disagree on, is what type of physics we need to include. It is clear that both model concepts, whether "top down" conceptual, or "bottom-up" physically-based, have an important role to play in discovering the physics of underlying pattern formation. But for both concepts applies that if a model does not contain the pattern and characteristics of an active organising agent, i.e. the ecosystem, then the model cannot claim to be physical as this active agent organises moisture retention, infiltration and preferential drainage.

If we realise that our physical system is organised, following some form of optimality, whether we call it maximum entropy production or maximum power, then our hydrological world becomes simpler and even more predictable. In recent years, the focus on small-scale physics and the believe in the ever-increasing computer power, have prevented us from developing holistic modelling strategies that provide plausible descriptions of how nature really works at the macro scale (e.g. Savenije, 2001) and which can be encapsulated in already relatively simple formulations of conceptual models.

The good news is that these holistic approaches match very well with the newly arising remote sensing-based tools that are increasingly getting better. The chances are not remote that the global ambition of the PUB decade to predict runoff in ungauged basins at acceptable levels of certainty will be reached in the not too distant future. This is of course, provided we use the right physics.

References:

Alila, Y., Kuraś, P. K., Schnorbus, M., & Hudson, R. (2009). Forests and floods: A new paradigm sheds light on age‐old controversies. Water Resources Research, 45(8).

Ambroise, B., Beven, K., & Freer, J. (1996). Toward a generalization of the TOPMODEL concepts: Topographic indices of hydrological similarity. Water Resources Research, 32(7), 2135-2145.

Andreadis, K.M., & Lettenmaier, D.P. (2006). Assimilating remotely sensed snow observations into a macroscale hydrology model. Advances in water resources, 29(6), 872-886.

Bak, P. (1996). How nature works: the science of self-organized criticality. Springer, New York.

Beven, K. (1989) "Changing ideas in hydrology—the case of physically-based models." Journal of hydrology 105,1-2, pp.157-172.

Beven, K. J., & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology, Hydrological Sciences Journal, 24(1), 43-69.

Blöschl, G., M. Sivapalan, T. Wagener, A. Viglione and H. Savenije, 2013. Run-off Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales. Cambridge University Press.

Bosch, T. C., & Miller, D. J. (2016). The Holobiont Imperative: Perspectives from Early Emerging Animals. Springer.

Brooks, J. R., Barnard, H. R., Coulombe, R., & McDonnell, J. J. (2010). Ecohydrologic separation of water between trees and streams in a Mediterranean climate. *Nature Geoscience*, *3*(2), 100-104.

Cuo, L., Lettenmaier, D. P., Alberti, M., & Richey, J. E. (2009). Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrological Processes, 23(6), 907-933.

De Boer‐Euser, T., McMillan, H. K., Hrachowitz, M., Winsemius, H. C., & Savenije, H. H. (2016). Influence of soil and climate on root zone storage capacity. *Water Resources Research*.

Detty, J. M., & McGuire, K. J. (2010). Threshold changes in storm runoff generation at a till ‐ mantled headwater catchment. Water Resources Research, 46(7).

Dooge, J. C. I. (1986). Looking for hydrologic laws. *Water Resources Research*, *22*(9S).

Dooge, J.C.I. (1997). Searching for simplicity in hydrology. Surveys in Geophysics 18, 5, pp. 511-534.

Dooge, J.C.I. (2005). Bringing it all together, Hydrol. Earth Syst. Sci., 9, 3-14, doi:10.5194/hess-9-3-2005.

Dunne, T., & Black, R. D. (1970). Partial area contributions to storm runoff in a small New England watershed. *Water resources research*, *6*(5), 1296-1311.

Evaristo, J., Jasechko, S., & McDonnell, J. J. (2015). Global separation of plant transpiration from groundwater and streamflow. *Nature*, *525*(7567), 91-94.

Fenicia, F., H. H. G. Savenije, P. Matgen, and L. Pfister, 2006. Is the groundwater reservoir linear? Learning from data in hydrological modelling. Hydrology and Earth System Sciences, Vol. 10: 139–150.

Freer, J. E., McMillan, H., McDonnell, J. J., & Beven, K. J. (2004). Constraining dynamic TOPMODEL responses for imprecise water table information using fuzzy rule based performance measures. Journal of Hydrology, 291(3), 254-277.

Gao, H., M. Hrachowitz, S.J. Schymanski, F. Fenicia, N. Sriwongsitanon, H.H.G. Savenije, 2014a. Climate controls how ecosystems size the root zone storage capacity at catchment scale, *Geophysical Research Letters*, 41, 7916-7923, doi: 10.1002/2014GL061668.

Gao, H., M. Hrachowitz, F. Fenicia, S. Gharari, and H. H. G. Savenije, 2014b. Testing the realism of a topography driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China, *Hydrol. Earth Syst. Sci.*, 18, 1895-1915, 2014.

Gao, H., Hrachowitz, M., Sriwongsitanon, N., Fenicia, F., Gharari, S., & Savenije, H. H. (2016). Accounting for the influence of vegetation and landscape improves model transferability in a tropical savannah region. Water Resources Research, 52(10), 7999-8022.

Gharari, S., M. Hrachowitz, F. Fenicia, and H. H. G. Savenije, 2011. Hydrological landscape classification: investigating the performance of HAND based landscape classifications in a central European meso-scale catchment, Hydrol. Earth Syst. Sci., 15, 3275–3291, doi:10.5194/hess-15-3275-2011

Gharari, S., Hrachowitz, M., Fenicia, F., Gao, H., and Savenije, H. H. G., 2014. Using expert knowledge to increase realism in environmental system models can dramatically reduce the need for calibration, Hydrol. Earth Syst. Sci., 18, 4839-4859, doi:10.5194/hess-18-4839-2014.

Good, S. P., Noone, D., & Bowen, G. (2015). Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. Science, 349(6244), 175-177.

Hrachowitz, M., Savenije, H., Bogaard, T. A., Tetzlaff, D., & Soulsby, C. (2013). What can flux tracking teach us about water age distribution patterns and their temporal dynamics?. *Hydrology and Earth System Sciences, 17 (2), 2013*.

Hrachowitz, M., Fovet, O., Ruiz, L., & Savenije, H. H. (2015). Transit time distributions, legacy contamination and variability in biogeochemical $1/f^{\alpha}$ scaling: how are hydrological response dynamics linked to water quality at the catchment scale?. Hydrological Processes, 29(25), 5241-5256.

Kleidon, A. (2016). Thermodynamic foundations of the Earth system. Cambridge University Press.

Kleidon, A., Zehe, E., Ehret, U., and Scherer, U. (2013) Thermodynamics, maximum power, and the dynamics of preferential river flow structures at the continental scale, Hydrol. Earth Syst. Sci., 17, 225-251, doi:10.5194/hess-17-225-2013.

Kollet, S.J., and Maxwell, R.M. (2006). Integrated surface– groundwater flow modeling: a free-surface overland flow boundary condition in a parallel groundwater flow model. Adv. Water Resour., 29:945–958.

Krakauer, N. Y., & Temimi, M. (2011). Stream recession curves and storage variability in small watersheds. Hydrology and Earth System Sciences, 15(7), 2377-2389.

Lamb, R. and Beven, K. (1997). Using interactive recession curve analysis to specify a general catchment storage model, Hydrol. Earth Syst. Sci., 1, 101-113, doi:10.5194/hess-1-101-1997

Li, H., Zhang, Y., Chiew, F. H., & Xu, S. (2009). Predicting runoff in ungauged catchments by using Xinanjiang model with MODIS leaf area index. Journal of Hydrology, 370(1), 155-162.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res., 99(D7), 14415–14428, doi:10.1029/94JD00483.

McDonnell, J. J., et al. (2007), Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, Water Resour. Res., 43, W07301, doi:10.1029/2006WR005467.

McDonnell, J. J., (2009). Where does water go when it rains? Conceptualizing runoff processes in headwater catchments (John Dalton Medal Lecture), EGU General Assembly Conference Abstracts, 2009.

McDonnell, J. J. (2014). The two water worlds hypothesis: Ecohydrological separation of water between streams and trees?. *Wiley Interdisciplinary Reviews: Water*, *1*(4), 323-329.

Michaelian, K. (2012). Biological catalysis of the hydrological cycle: life's thermodynamic function. Hydrology and Earth System Sciences 16, 2629-2645.

Milly, P. C. D. (1994). Climate, soil water storae and the average annual water balance. Water Resour. Res. 30, 2143-2156.

Milzow, C., Krogh, P. E., & Bauer-Gottwein, P. (2011). Combining satellite radar altimetry, SAR surface soil moisture and GRACE total storage changes for hydrological model calibration in a large poorly gauged catchment. Hydrology and Earth System Sciences, 15(6), 1729-1743.

Nester, T., Kirnbauer, R., Parajka, J., & Blöschl, G. (2012). Evaluating the snow component of a flood forecasting model. Hydrology Research, 43(6), 762-779.

Nijzink, R., Hutton, C., Pechlivanidis, I., Capell, R., Arheimer, B., Freer, J., Han, D., Wagener, T., McGuire, K., Savenije, H., and Hrachowitz, M. (2016). The evolution of root-zone moisture capacities after deforestation: a step towards hydrological predictions under change?, Hydrol. Earth Syst. Sci., 20, 4775-4799, doi:10.5194/hess-20-4775-2016, 2016.

Nobre, A. D., Cuartas, L. A., Hodnett, M., Rennó, C. D., Rodrigues, G., Silveira, A., ... & Saleska, S. (2011). Height above the nearest drainage–a hydrologically relevant new terrain model. Journal of Hydrology, 404(1), 13-29.

Penna, D., Tromp-van Meerveld, H. J., Gobbi, A., Borga, M., & Dalla Fontana, G. (2011). The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. Hydrology and Earth System Sciences, 15(3), 689-702.

Reager, J. T., Thomas, B. F., & Famiglietti, J. S. (2014). River basin flood potential inferred using GRACE gravity observations at several months lead time. Nature Geoscience, 7(8), 588-592.

Rennó, C. D., Nobre, A. D., Cuartas, L. A., Soares, J. V., Hodnett, M. G., Tomasella, J., and Waterloo, M. J.: HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia, Remote Sens. Environ., 112, 3469–3481, doi:10.1016/j.rse.2008.03.018, 2008.

Rodell, M., & Houser, P. R. (2004). Updating a land surface model with MODIS-derived snow cover. Journal of Hydrometeorology, 5(6), 1064-1075.

Rodríguez-Iturbe, I., and A. Rinaldo, 2001. Fractal River Basins: Chance and Self-Organization, Cambridge University Press, 2001.

Rodríguez-Iturbe, I., & Porporato, A. (2007). *Ecohydrology of water-controlled ecosystems: soil moisture and plant dynamics*. Cambridge University Press.

Samaniego, L., Kumar, R., & Attinger, S. (2010). Multiscale parameter regionalization of a grid - based hydrologic model at the mesoscale. Water Resources Research, 46(5).

Savenije, H.H.G., 2001. Equifinality, a blessing in disguise?, HP Today Invited commentary, Hydrological Processes, 15, pp. 2835-2838.

Savenije, H.H.G., 2009. The Art of Hydrology. *Hydrology and Earth System Sciences*, 13, 157–161, 2009.

Savenije, H.H.G., 2010. HESS Opinions "Topography driven conceptual modelling (FLEX-Topo)", *Hydrol. Earth Syst. Sci.*, 14, 2681–2692, 2010. doi:10.5194/hess-14-2681-2010

Schaik, L., Palm, J., Klaus, J., Zehe, E., & Schröder, B. (2014). Linking spatial earthworm distribution to macropore numbers and hydrological effectiveness. Ecohydrology, 7(2), 401-408.

Sivapalan, M., 2003a. Process complexity at hillslope scale, process simplicity at the watershed scale: is there a connection? Hydrological Processes, 17, 1037–1041.

Sivapalan, M., 2003b. Prediction in ungauged basins: a grand challenge for theoretical hydrology. Hydrological Processes, 17, 3163–3170.

Sivapalan, M., S. E. Thompson, C. J. Harman, N. B. Basu, and P. Kumar, 2011. Water cycle dynamics in a changing environment: improving predictability through synthesis, Water Resources Research, 47, W00J01, doi:10.1029/2011WR011377.

Sudicky, E.A., Jones, J.P., Park, Y.J., Brookfield, A.E., Colautti, D. (2008). Simulating complex flow and transport dynamics in an integrated surface-subsurface modelling framework. Geosci. J., 12:107–122.

Sun, W., Ishidaira, H., & Bastola, S. (2012). Calibration of hydrological models in ungauged basins based on satellite radar altimetry observations of river water level. Hydrological processes, 26(23), 3524-3537.

Sun, W., Ishidaira, H., Bastola, S., & Yu, J. (2015). Estimating daily time series of streamflow using hydrological model calibrated based on satellite observations of river water surface width: Toward real world applications. Environmental research, 139, 36-45.

Van der Velde, Y, Heidbüchel, I, Lyon, SW, Nyberg, L, Rodhe, A, Bishop, K, and Troch, PA (2015), Consequences of mixing assumptions for time-variable travel time distributions. Hydrol. Process., 29, 3460–3474. doi: 10.1002/hyp.10372.

Wahr, J., Swenson, S., Zlotnicki, V., & Velicogna, I. (2004). Time ‐ variable gravity from GRACE: First results. Geophysical Research Letters, 31(11).

Wang-Erlandsson, L., W. G. M. Bastiaanssen, H. Gao, J. Jägermeyr, G. B. Senay, A. I. J. M. van Dijk, J. P. Guerschman, P. W. Keys, L. J. Gordon, and H. H. G. Savenije, 2016. Global root zone storage capacity from satellite-based evaporation. *Hydrol. Earth Syst. Sci.*, 20, 1459–1481, doi:10.5194/hess-20-1459-2016.

West, G. B., Brown, J. H., & Enquist, B. J. (1997). A general model for the origin of allometric scaling laws in biology. Science, 276(5309), 122-126.

Winsemius, H. C., H. H. G. Savenije, N. C. van de Giesen, B. J. J. M. van den Hurk, E. A. Zapreeva, and R. Klees, 2006. Assessment of Gravity Recovery and Climate Experiment (GRACE) temporal signature over the upper Zambezi, Water Resources Research, 42, W12201, p. 1-8.

Winsemius, H.C., B. Schaefli, A. Montanari, H.H.G. Savenije, 2009. On the calibration of hydrological models in ungauged basins: a framework for integrating hard and soft hydrological information. Water Resour. Res., 45, W12422, 1-15.

Wulf, A. (2015) "The Invention of Nature. Alexander von Humboldt's New World", John Murray publ.

Xie, H., Longuevergne, L., Ringler, C., & Scanlon, B. R. (2012). Calibration and evaluation of a semi-distributed watershed model of Sub-Saharan Africa using GRACE data. Hydrology and Earth System Sciences, 16(9), 3083-3099.

Zehe, E., and Flühler, H.: Preferential transport of isoproturon at a plot scale and a field scale tile-drained site, Journal of Hydrology, 247, 100-115, 2001.

Zehe, E., Maurer, T., Ihringer, J., Plate, E. (2001). Modeling water flow and mass transport in a loess catchment. Phys. Chem. Earth Part B Hydrol. Oceans Atmos., 26:487–507.

Zehe, E., Ehret, U., Blume, T., Kleidon, a., Scherer, U. and Westhoff, M.: A thermodynamic approach to link self-organization, preferential flow and rainfall–runoff behaviour, Hydrol. Earth Syst. Sci., 17(11), 4297–4322, doi:10.5194/hess-17-4297-2013, 2013.

Zehe, E., Ehret, U., Pfister, L., Blume, T., Schröder, B., Westhoff, M., Jackisch, C., Schymanski, S., Weiler, M., Schulz, K., Allroggen, N., Tronicke, J., van Schaik, L., Dietrich, P., Scherer, U., Eccard, J., Wulfmeyer, V., and Kleidon, A. (2014). HESS Opinions: From response units to functional units: a thermodynamic reinterpretation of the HRU concept to link spatial organization and functioning of intermediate scale catchments. Hydrol.Earth Syst. Sci., 18:4635–4655.

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.

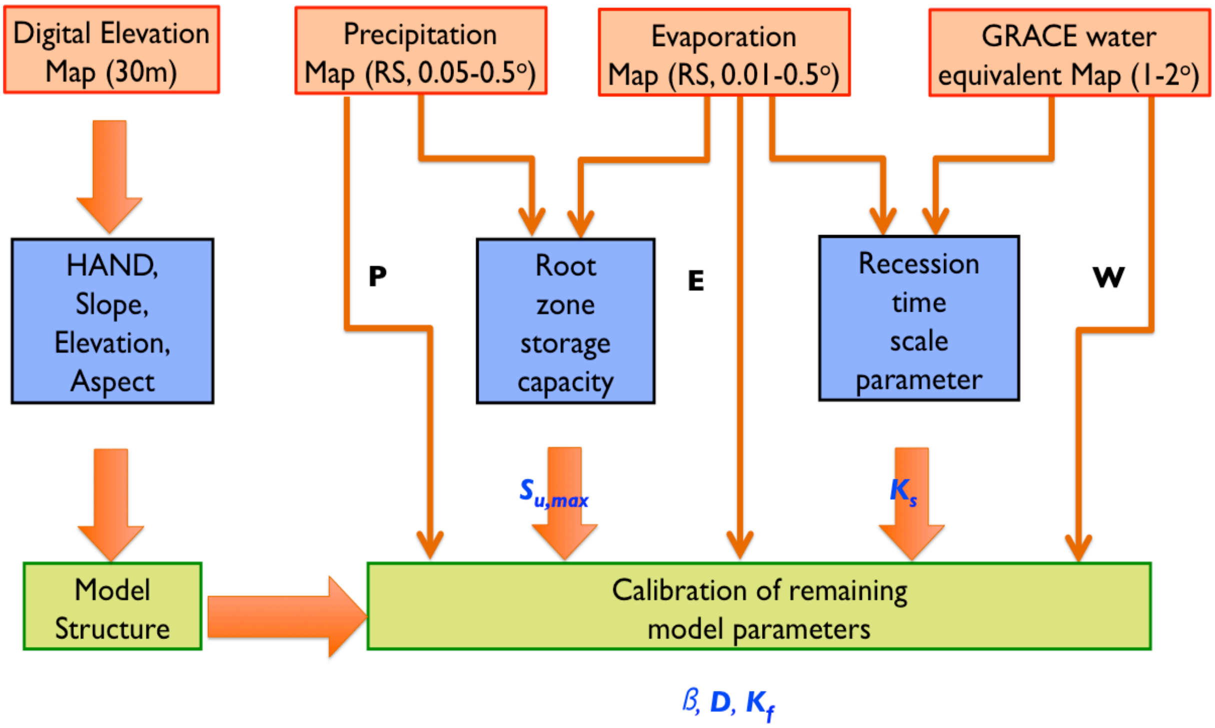

Figure 1. Flow diagram for Prediction in Ungauged Basins

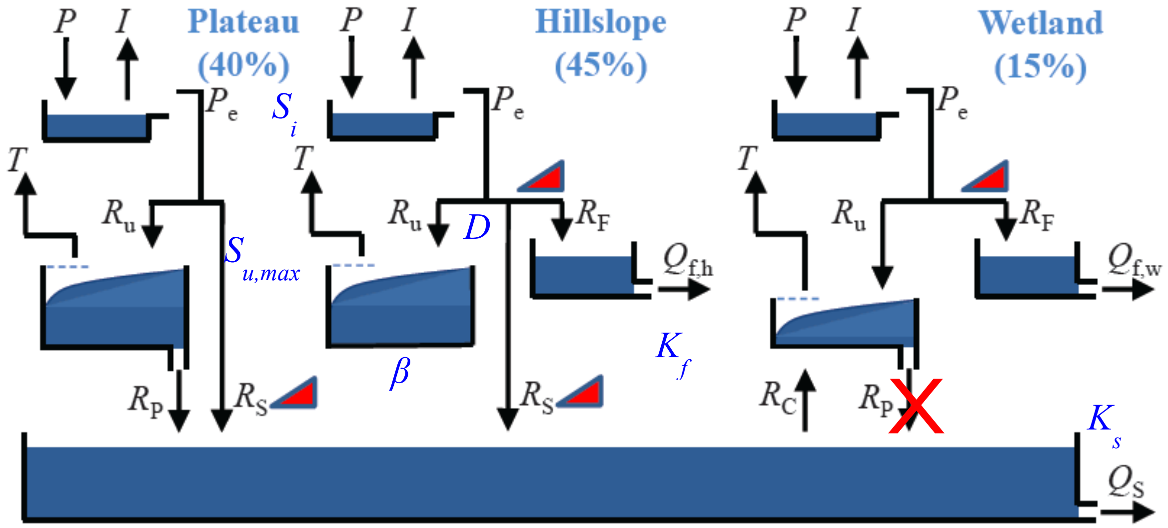

Figure 2. Model structure derived from DEM, showing three landscape classes and the groundwater system connecting them.

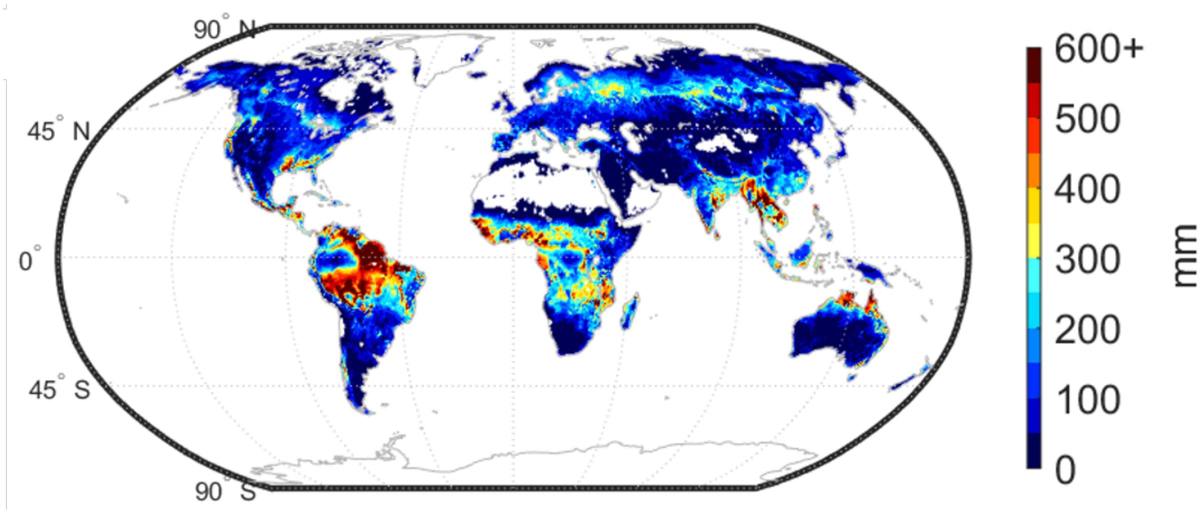

Figure 3. Root zone storage capacity as determined by Wang Erlandsson et al. (2016)

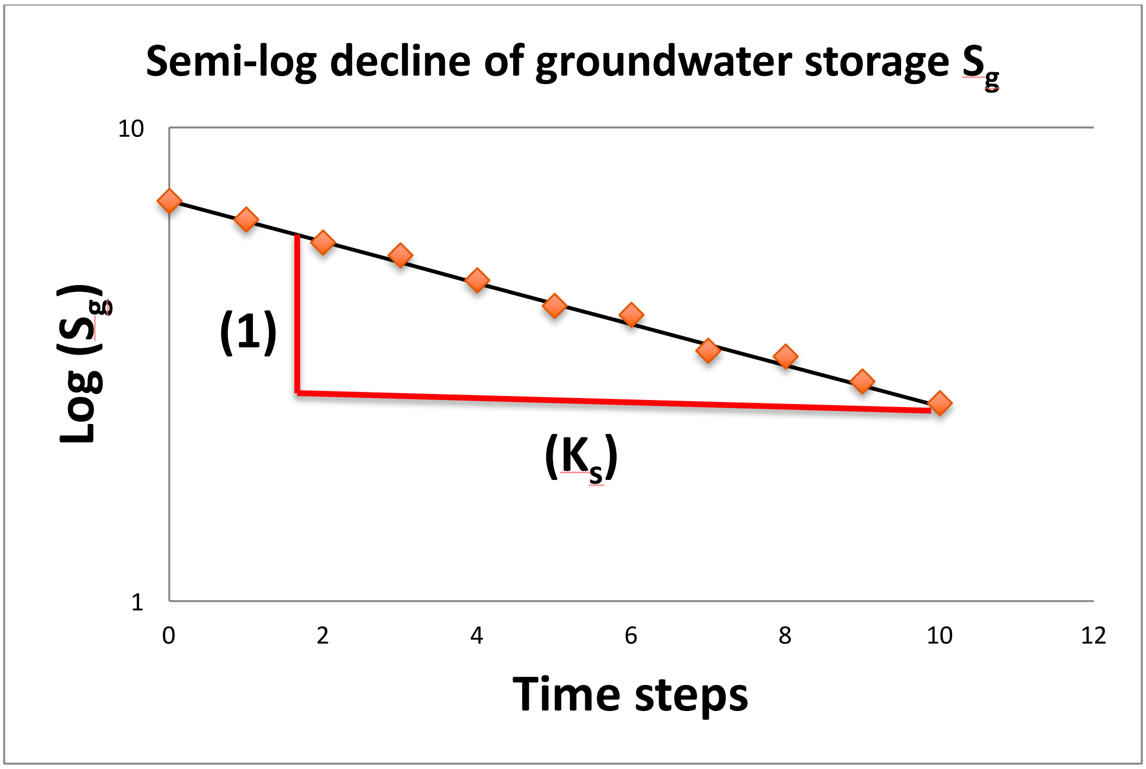

Figure 4. Indication of how groundwater recession can be determined by gravity observations from space.