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HESS Opinions "Topography driven conceptual modelling (FLEX-Topo)"

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Abstract. Heterogeneity and complexity of hydrological processes offer substantial challenges to the hydrological modeller. Some hydrologists try to tackle this problem by introducing more and more detail in their models, or by setting-up more and more complicated models starting from basic principles at the smallest possible level. As we know, this reductionist approach leads to ever higher levels of equifinality and predictive uncertainty. On the other hand, simple, lumped and parsimonious models may be too simple to be realistic or representative of the dominant hydrological processes. In this commentary, a new approach is proposed that tries to find the middle way between complex distributed and simple lumped modelling approaches. Here we try to find the right level of simplification while avoiding over-simplification. Paraphrasing Einstein, the maxim is: make a model as simple as possible, but not simpler than that. The approach presented is process based, but not physically based in the traditional sense. Instead, it is based on a conceptual representation of the dominant physical processes in certain key elements of the landscape. The essence of the approach is that the model structure is made dependent on a limited number of landscape classes in which the topography is the main driver, but which can include geological, geomorphological or land-use classification. These classes are then represented by lumped conceptual models that act in parallel. The advantage of this approach over a fully distributed conceptualisation is that it retains maximum simplicity while taking into account observable landscape characteristics.

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1 What is the issue?

The hydrological world is complex and heterogeneous. Yet we know that the reductionist approach: combining so-called physically based small scale basic principles (such as the Darcy, Richards, and Navier-Stokes equations) with detailed distributed modelling, leads to equifinality and high predictive uncertainty, mostly because these methods ill account for heterogeneity, preferential pathways and structural patterns on and under the surface. This reductionist approach is not appropriate at the catchment scale, as has been observed by many (e.g. McDonnell et al., 2007). At the same time, we know that – in spite of the high apparent complexity – hydrological behaviour is often unexpectedly simple, whereby parsimonious conceptual models often outperform much more complex ones, and with much less predictive uncertainty. Apparently, catchments are intermediate systems: highly heterogeneous systems with some degree of organisation (Dooge, 1986), where relatively simple models can do the trick. Catchments belong to the realm of organised complexity (Dooge, 2005). Simple catchment-scale models apparently make use of emerging patterns of self-organisation implicit in naturally formed catchments and river basins.

But obviously we cannot be satisfied by this. On the one hand we need simplicity, but on the other hand there is a limit to how simple a model can be (e.g. Dooge, 1997). Simple relationships that behave well in a certain catchment under certain conditions may be useless elsewhere or under different hydrological conditions. Prediction in ungauged basins requires that the relationships found can be transferred, and hence that they are based on objective and physically observable characteristics.

Obviously topography is such a characteristic. Distributed models make use of topography, but in a rather unsophisticated way: as brute force. It would be much more fitting to extract from the topography the signatures of the landscape and to translate these into a conceptual architecture. This is

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not dissimilar to what Beven (2001) suggested when he said that landscape characteristics need to be mapped into conceptual structures and relationships.

The reason why we model is because we want to predict hydrological behaviour under unknown circumstances: either to predict an uncertain future in a gauged catchment (with a calibrated model), or to predict behaviour in an ungauged catchment with an uncalibrated model. In both cases, the question is: How to map topographical, geological, soil, land cover and rainfall heterogeneity on a conceptual representation of dominant physical processes?

2 The role of topography

In solving this question, we need to zoom-out and apply a giant's view, where we model the dominant processes at the relevant scale. The reductionist view of the ant, who observes physical processes at a microscopic scale, does not lead to predictive equations at the relevant scale of the catchment, mainly due to heterogeneity and the disregard of large-scale patterns (Savenije, 2009). Conversely, we need to model our catchments at the macro-scale based on macro-scale observables, one of which is the organisation of the landscape into topographically controlled "functional units", as discussed by Zehe and Sivapalan (2009).

Indeed, there is a lot of heterogeneity: in the landscape, in the soil, in the terrain, and in the rainfall. But at larger scales there are patterns with strikingly simple emergent behaviour. Winter (2001) used topgraphical features to distinguish hydrological landscapes. He suggested that the dominant feature of a hydrological landscape is an upland separated from a lowland by an intervening steeper slope. When driving through the European landscape, a well-developed landscape intensively used for agriculture, forestry and settlements, it occurred to me that hill slopes are mostly forested while the undulating plateaus with their modest slopes are used for agriculture. Where hill slopes are cultivated, they are generally used for fruit trees or vineyards, but the dominant land use of hill slopes is forest. The wetlands close to the rivers are not forested (since trees require unsaturated soils during most of the time). They are generally used for agriculture (seasonal crops), pasture or as wetland areas. Settlements occur both in the riparian zones and on the plateaus, while roads cut through the hill slopes. But the overall picture is: agriculture on the plateaus, forests on the hill slopes and meadows and wetlands on the riparian zones.

At the same time, I have always had the feeling that forests are key to the hydrological dynamics of the European rivers, even though the area occupied by forests is seldom large. While driving through the French landscape and seeing the dense forests on the hill slopes, it suddenly all came together. Floods are for a large part generated on hill slopes. The undulating plateaus do not generate much runoff, only under extreme rainfall conditions where Hortonian overland flow occurs (but this is rare, otherwise the landscape would be dominated by erosion and badlands), and much of the Hortonian overland flow is re-infiltrated downslope. The processes on the plateaus are mainly vertical, where rainfall is to a large extent balanced by evaporation, with the remainder recharging the groundwater. This groundwater partly ends up in the river as base flow but can also be intercepted by trees at the toe of the hill slope, reducing the drainage from the plateau even more. As a result the amount of groundwater from the plateau reaching the stream is probably small, particularly if the distance to the stream is large.

Besides the saturation overland flow generated in the wetlands and riparian zones, the floods and most of the runoff dynamics are generated on the hill slopes, and these are mostly forested. This implies that forests could very well be a dominant land cover when studying flood generation or when performing flood forecasting. In this regard it is worrying that not many rainfall stations are located in forests, on hill slopes, or in mountainous areas. The riparian zones, although they may be responsible for the early flood response through saturation overland flow, due to their limited extent and modest slope, are often not the largest contributor to flood volumes.

For a forest ecosystem to survive on a hill slope there are two important life-support functions which seem to be contradicting. One is drainage, the other is moisture retention. Excess water needs to be drained off so as to maintain an aerated soil. However drainage needs to take place in a way that it does not erode the foundation of the ecosystem (i.e. the soil) and in a way that enough moisture is retained to bridge dry spells. Sub-surface drainage through preferential pathways is an efficient mechanism in this regard. It does not cause excessive erosion and it allows the wetting of stagnant pockets in the soil from which the roots can tap their water (e.g. Brooks et al., 2010). Zehe et al. (2010) demonstrated that this combination of wetting and preferential sub-surface drainage is the most efficient mechanism to achieve maximum entropy, which has evolved over time.

An additional characteristic of hill slopes is that they have a sub-surface connection to the groundwater storage of the plateaus. As a result of the rapid drop in the topography the phreatic level of the ground water comes close to the surface near the toe of the hill slopes. As a result, trees at the hollow of a hill slope can tap into the groundwater reservoir of the plateau during dry periods. Hence, the runoff coefficient of hill slopes is high, higher than the vertical water balance of the hill slope (rainfall minus evaporation) would suggest.

On top of this, hill slopes tend to behave similarly all over the world - that is, they all show threshold-like response to storm rainfall totals. For events below a local rainfall threshold, subsurface stormflow does not occur. For events greater than this threshold, subsurface stormflow is initiated. Despite differences in the matrix-macropore partitioning and different individual flow pathways within the hill slope, the overall scale response is the same (Uchida et al., 2005). The ecosystems on hill slopes have created an environment where sub-surface drainage is the dominant feature. This is a logical arrangement for ecosystem survival. Surface runoff would erode the mere basis for the ecosystem, while water logging would make it impossible for most plant species to survive. Only a system of sub-surface drainage that exceeds a certain storage threshold, which the ecosystem would need to retain, is the hydrological mechanism that can support an ecosystem. Such a system, termed by Jeff McDonnell during his Dalton lecture (2009) as "storage excess subsurface flow" (SSF), is a mechanism that occurs throughout the world in different ecosystems, different geologies and different climates. This is the dominant rainfall-runoff mechanism on humid hill slopes. This sub-surface drainage mechanism through preferential pathways also supports the moisture retention function of the hill slope, so that the hill slope facilitates the two essential functions: drainage and moisture retention.

In the riparian zone, obviously, the dominant mechanism is "saturation excess overland flow" (SOF). In these areas where slopes are modest, open water is near and, hence, the groundwater level is close to the surface, the amount of soil moisture storage available is small. After continued rainfall, an ever-increasing part of the riparian zone will become saturated, partly because of hill slope and plateau groundwater contributing, and saturation overland flow will feed the streams.

The plateaus, on the other hand, do not take an active part in the rainfall-runoff behaviour. They rather have a moisture retention and evaporation function. The phreatic water table is deep and hence the unsaturated storage capacity is large. Trees can develop deep root systems and, year-round, can tap water from the unsaturated, or even saturated layers. Because the distance to the streams is large and the groundwater is deep, water table slopes are modest. In addition, underlying rock may have low lateral permeability and the groundwater reservoir may supply water to the forest in the hollow of the hill slopes. As a result, the groundwater contribution from the plateaus to runoff is small. The runoff process associated with the plateau therefore is termed "deep percolation" (DP). In general, this process is predominantly vertical while the lateral flow component is small with long residence times. During extreme rainfall events, the plateaus can trigger "infiltration excess overland flow", also termed "Hortonian overland flow" (HOF). But this is generally exceptional and linked to land use, otherwise the plateaus would demonstrate constant traces of erosion.

Mutatis mutandis, the same applies to other intensively inhabited regions of the world. Steep hill slopes are not much use for agriculture and are often forested, either by natural forests, production forests or plantations. Riparian zones are used for pasture or seasonal agriculture. Even in Africa, where I have worked for many years, the situation is not much different, albeit that the plateaus are also often forested, but that does not change the image that plateaus hardly generate lateral runoff and that forested hill slopes determine both the flood behaviour and the water resources availability. Hence also in natural environments, forested hill slopes host the dominant drainage processes. In modelling the runoff behaviour of the Zambezi basin, we realised that less than 10% of the groundwater reservoir is active in the rainfall-runoff process (Winsemius et al., 2006). This is the groundwater situated in the near-stream hill-slopes.

3 The role of geology, soil and climate

Until now, we have discussed topography as the main driver of hydrological behaviour. But what is the role of geology and soils? And how important is the spatial distribution of the rainfall and other climatic factors? In an evolutionary sense, geology is less important than it appears at first sight. As stated before, hill slopes behave very similarly all over the world in different geological settings. All "stable" hill slopes (as far as there is stability in geological terms) irrespective of their geology, have developed a sub-drainage system that conceptually functions as a "storage excess subsurface flow" system (SSF). If they had not developed subsurface drainage, they would have disappeared due to the erosion that results from Hortonian overland flow (HOF). So the mature hill slopes that we see have survived as a result of the sub-surface drainage structure, in symbiosis with the ecosystem living on it. Of course there are also hill slopes that are barren, such as in deserts. The dominant mechanism there is most probably Hortonian overland flow, as there is no ecosystem that facilitated the formation of sub-surface drainage. Although the conditions under which they were originally shaped may have been quite different under different climatic conditions. So, in arid climates where ecosystems have not had the opportunity to maintain themselves, the dominant mechanism on hill slopes is probably Hortonian overland flow.

If sub-surface drainage through preferential pathways is present in all vegetated hill slopes, then the role of geology is probably limited to the interaction with deeper groundwater layers and to the feasible parameter ranges. For instance, Fenicia et al. (2010) showed that for different catchments in Luxembourg, having very distinct geological properties (e.g. one in schist, one in sand stone and one in marl), similar model approaches for rapid subsurface flow could be used, but that the main differences between the catchments were in the parameter ranges and in the interaction with the groundwater (in schist and marl this interaction is almost non-existent, whereas in sandstone it is the dominant mechanism). So it seems that topography is more important to distinguish between hydrological processes than geology.

Soils influence hydrological behaviour significantly. What is important is the texture of the soil: the porosity, the permeability, the layering, the existence of preferential flow channels, the water repellence, etc. An interesting phenomenon is that soil properties are related to the topography. The riparian zones have relatively heavy soils, which may crack in the dry season, but swiftly become poorly permeable when they get wet. The hill slopes are very heterogeneous with a dual porosity consisting of immobile pockets intersected by preferential infiltration channels. Soils are generally not very deep with a decreasing permeability over the depth leading to sub-surface drainage on the interfaces or through a network of preferential drainage structures (e.g. Brooks et al., 2010; Uchida et al., 2005). On the plateau the soils are generally deeper, with a larger storage capacity, particularly if there is deep rooting vegetation. So we see, that also the soil characteristics are correlated with the topography.

The role of climate is that it facilitates the ecosystem to survive and to develop its substratum in an evolutionary process that shapes both the drainage and the retention function. So in certain climates we find different dominant processes. But there is more. The spatial variability of climatic factors can have an important influence on hydrological behaviour. For instance the different radiation levels related to the aspect of hill slopes, may result in different ecosystems to develop. The spatial variability of rainfall has a large influence on how drainage systems function. The spatial variability of temperature is crucial to distinguish between rain, snow and snowmelt. However, these climatic variables are again linked to topography (aspect, elevation). Topography is key to the spatial variability of climatic factors. What appears to be essential in hydrological modelling is to account for the spatial variability of precipitation and moisture levels in a distributed way. Fenicia (2008a) demonstrated that much better model performance is achieved when moisture is accounted for in a distributed sense, while the model structure and related parameters remain lumped at sub-basin scale.

So topography is a main indicator for hydrological behaviour which is also correlated with soil characteristics and climate. This makes topography a key input to hydrological modelling. There are three elements that need to be explored further. First of all we need to derive maximum information from the topography, whereby: (1) we use topography to distinguish the dominant mechanisms (e.g. by distinguishing between wetlands, hill slopes and plateaus); (2) we use topography as a proxy for climatic variability (precipitation, temperature, radiation) and soil classification; and (3) we use topography for the derivation of pathways and travel times. Next, we need to derive information from the geology to confirm model structures (e.g. the importance of groundwater to the drainage function) and to constrain viable parameter ranges (e.g. soil hydraulic properties). Finally, we need to account for the spatial variability of precipitation by distributed accounting of moisture levels.

4 Classification based on topography with respect to nearest open water

The question is whether this simple "wetland–hill slope–plateau" concept is a concept that is useful in the "mapping" between the heterogeneous reality and the much simpler conceptual world of the hydrological model.

It is logical to base a classification system on the topography. With modern technology topographical signatures can be determined accurately. Until now, most approaches that make use of topography use characteristics such as elevation, slope, aspect and drainage structure, but not many methods make use of the height above the nearest open water. Elevation and slope are not sufficient to distinguish between wetland, hill slope and plateau (a wetland can occur at many elevations), but, together with slope, the height above the nearest open water is. The index that comes closest to the heigth above the nearest drain is the topographic index of Beven and Kirkby (1997). However this index assumes that the groundwater saturation that triggers Saturation excess Overland Flow (SOF) is fed by the sub-surface flow from the hill slope. This is not everywhere a correct assumption. I shall come back to this furtheron. Recently, Rennó et al. (2008) developed an algorithm, named HAND (Height Above Nearest Drainage), based on topographical information from the Shuttle Radar Topographical Mission (SRTM) to derive maps with detailed terrain levels above the nearest open water (first order channels). They combined these observations into distribution functions relating topography to distance from the nearest stream. From this information, wetland areas, hill slopes and plateaus could be identified. They showed that the height above the nearest drain is a much more powerful tool to distinguish hydrological landscapes than mere elevation. Hence, this looks like a powerful tool to be used for hydrological classification.

Maybe at this stage we need to better define what is meant by the terms wetland, hill slope and plateau. Here we define them in hydrological terms. A wetland stands for a hydrological landscape element where saturation excess overland flow (SOF) is the dominant runoff mechanism. Likewise the term hill slope stands for a hydrological landscape element where storage excess subsurface flow (SSF) is the dominant runoff mechanism. Plateau stands for hydrological landscape elements with modest slope where the groundwater table is deep and where the dominant mechanism is evaporation excess deep percolation (DP). The word 'excess' indicates a threshold process.

Figure 1 is based on Rennó et al. (2008). It shows how the elevation above the nearest stream and the distance of the pixel to the nearest stream generates a pattern where the inflection points determine the limits between wetland, hill slope and plateau. Each of these sub-systems should have its own conceptual model structure. If information is available on the geology of the substratum, then the geology can provide indications for the strength of the dominant hydrological

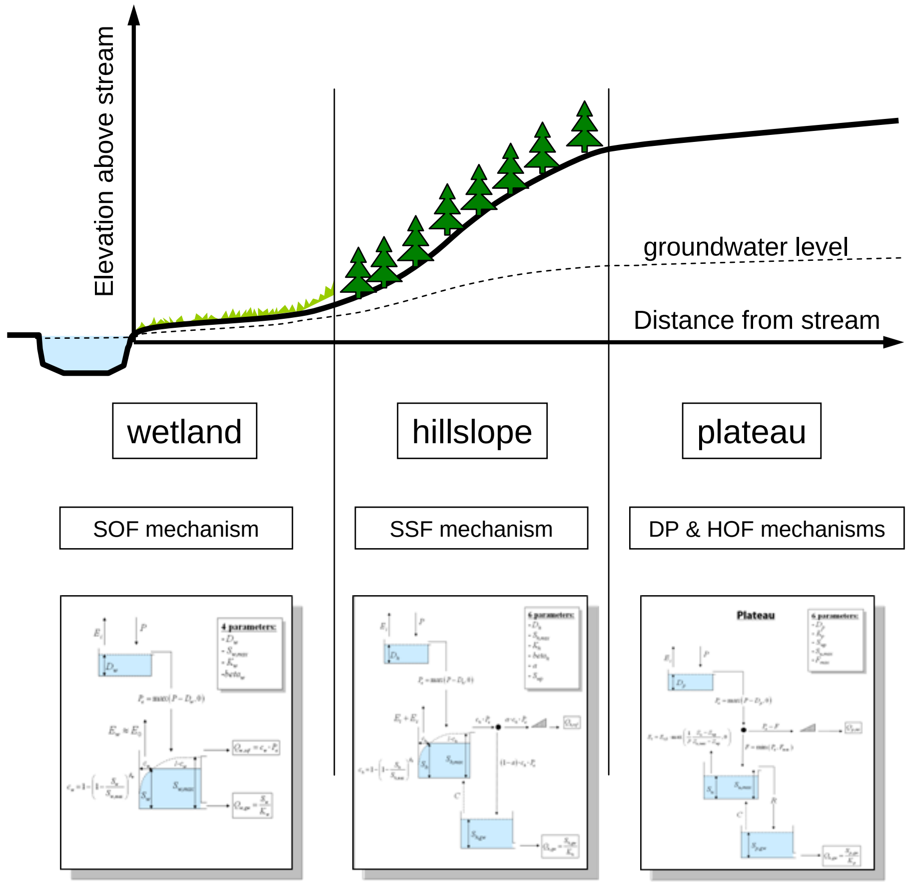

Fig. 1. Model concept.

process through estimates of: permeability, storage capacity, infiltration capacity and residence times, leading to different parameter ranges. Table 1 summarises the characteristics of these three subsystems.

These three classifications are not dissimilar to the classification by Winter (2001), cited above, and Scherrer and Naef (2003), who also linked them to four dominant runoff mechanisms: Saturation Overland Flow (SOF) in flat lands, SubSurface Flow (SSF) on sloping terrains with low permeability, Deep Percolation (DP) on permeable substratum, and Hortonian Overland Flow (HOF) where rainfall intensity exceeded infiltration capacity. A similar approach was suggested by Uhlenbrook and Leibundgut (2002) and by Uhlenbrook et al. (2004), who differentiated seven and eight different landscape units in a Black Forest Mountain catchment. Thereby, they distinguished between four different hill slope components based on their detailed geomorphological mapping. It is observed, however, that even this relatively simple distributed conceptual model suffered from equifinality with poorly identifiable parameters. Here, the proposed methodology is even simpler: it has less landscape classes and considers these as lumped and parallel processes. The four different runoff processes have been attributed to the three classes: Wetland, Hill slope and Plateau (see Fig. 1).

Geomorphologists have made use of similar classifications, separating between landscape elements with different slopes (e.g. Park and Van de Giesen, 2004), however, the link to lumped conceptual modelling is a new approach. In mountainous areas, it may be necessary to add a class for largely impermeable steep rock. Likewise, in permafrost areas different classifications need to be made. But these are basically refinements of the general modelling approach proposed here.

5 Conceptual models related to three classes

So, as an example of the methodology, let's limit the approach to a typical Western European landscape in a temperate climate with the three sub-systems: wetland–hill slope–plateau. As an example (as a prior), I shall formulate a conceptual model set-up based on my perception of the Meuse catchment. Each of the three hydrological sub-systems have their own model structure that should reflect the structure of these sub-systems in the real world. Figures 2–4 give examples of what these conceptual models may look like, each with their equations and parameters. The parameters are summarised in Table 2. Of course other conceptualisations

Table 1. Characteristics of the Wetland–Hill slope–Plateau system.

Classes	Wetland	Hill slope	Plateau
Topography	flat	steep	undulating
Land use	pasture, wetland	forest	agriculture, pasture
Soils	shallow	shallow	deep
Dominant Function	drainage	drainage	storage/evaporation
Supporting Function	storage/evaporation	storage/evaporation	drainage
Dominant runoff mechanism	saturation excess[1] overland flow (SOF)	storage excess[1] sub-surface flow (SSF)	evaporation excess[1] deep percolation (DP)
drainage direction	lateral	lateral	vertical
time scale	very fast	fast	very slow
Supporting runoff mechanism	groundwater flow (DP)	groundwater flow (DP)	infiltration excess[1] overland flow (HOF)
drainage direction	vertical	vertical	lateral
time scale	very slow	slow	very fast

[1] Note that the term excess indicates a threshold process.

Table 2. Parameters involved in the three sub-systems: Wetland, Hill slope and Plateau. cc means constrained calibration, fc means free calibration, mc mean manual calibration and est means estimated.

Model	Wetland	Hill slope	Plateau
Dominant mechanism	saturation overland flow	rapid sub-surface flow	groundwater flow
parameters	D_{w} [L/T], cc $S_{\mathrm{w,max}}$ [L], fc β_{w} [–], fc	D_{h} [L/T], cc $S_{\mathrm{h,max}}$ [L], fc β_{h} [–], fc a [–], fc T_{h} [T], fc	D_{p} [L/T], est $S_{\mathrm{u,max}}$ [L], est S_{wp}[L], est p [–], est K_{p} [T], mc
Supporting mechanism	groundwater flow	groundwater flow	infiltration excess flow (during high intensity rainfall)
parameters	K_{w} [T], mc	K_{h} [T], mc C [L/T], est	F_{max} [L/T], est T_{p} [T], est

may be generated, but as an illustration these three models are further elaborated. In this example, the wetland system requires 4 parameters: an interception threshold D_{w} [L/T], a maximum moisture storage before the wetland is fully saturated $S_{\mathrm{w,max}}$ [L], a power of the beta-function β_{w}, and a slow groundwater seepage residence time K_{w} [T]. The latter is difficult to determine in isolation and may have to be estimated together with the residence time for the hill slope K_{h} [T] and the plateau K_{p} [T] (for definitions see Figs. 2–4). I suggest to lump the groundwater system (as Fig. 1 suggests) and to estimate one lumped residence time for the groundwater reservoir from the recession curve.

The daily interception threshold D_{w} [L/T] is here presented as a flux to be substracted from the precipitation, which is appropriate at the daily time scale (De Groen and Savenije, 2006). At shorter time scales use can be made of a Rutter model with a storage threshold (Gerrits et al., 2010). Both thresholds can be estimated from the literature or can be calibrated between well-defined constraints. There are good estimates available for canopy, forest floor, grass land and cropland interception thresholds (Gerrits et al., 2010; Gerrits, 2010). As De Groen and Savenije (2006) showed, the total amount of intercepted precipitation is not very sensitive to the threshold. The daily variability of the rainfall is far more important in determining the evaporation from interception. The same applies for the interception thresholds on the hill slope and the plateau (D_{h} and D_{p}). This leaves two important calibration parameters for the wetland: the maximum subsurface storage and the power of the beta-function. These can be calibrated on the basis of the sharp peaks shortly after the rainfall has started which are generated by saturation overland flow on the riparian zone.

For the hill slope this leaves 4 parameters to be obtained by calibration: the maximum storage in the unsaturated zone $S_{\mathrm{h,max}}$ [L], the power of the beta-function β_{h} [–],the separator between rapid subsurface flow and groundwater recharge a [–], and the time lag for the rapid subsurface flow T_{h} [T]. There is not much cross-correlation between these parameters, hence, if runoff records are available, these parameters should be identifiable. The amount of capillary rise C [L/T] needs to be estimated on the basis of the water balance of the hill slope. In principle this is not an influential parameter. If it is made a function of the moisture storage in the hill slope (S_{h}) then it merely functions to maintain the evaporative capacity of the forest.

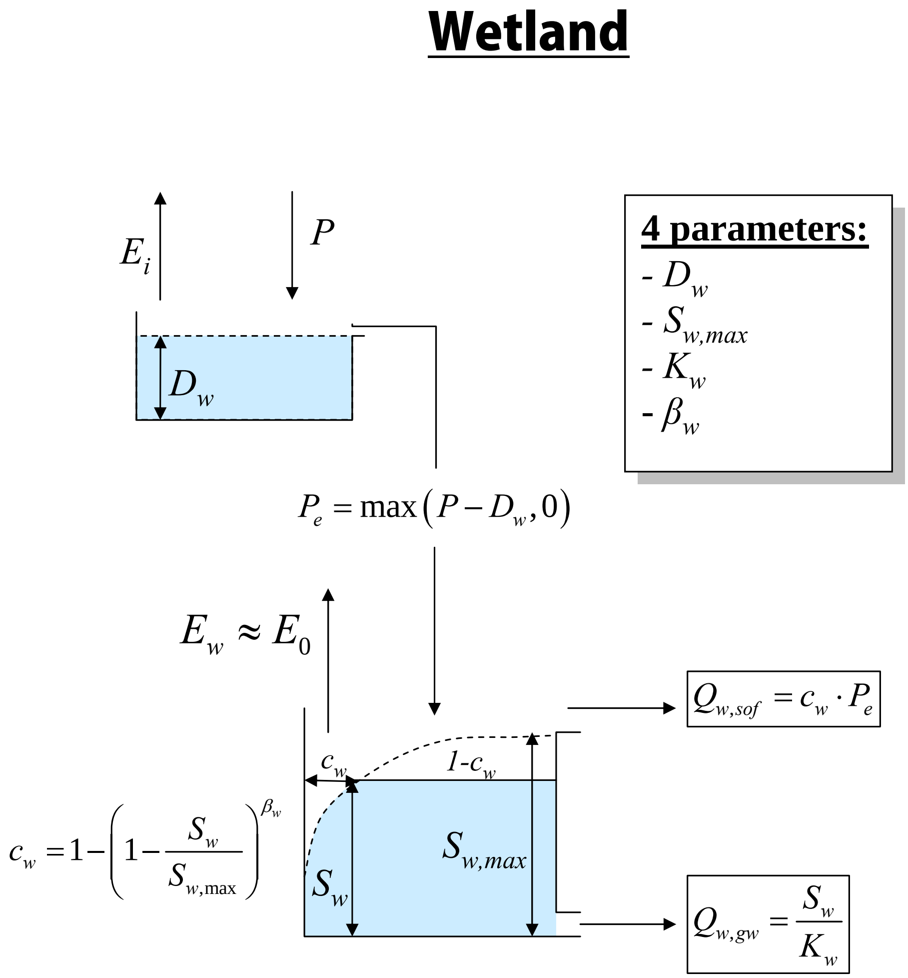

Fig. 2. Wetland conceptual model.

Since in this concept no substantial runoff from the plateau is expected, the parameters for the plateau should be determined on the basis of soil moisture or groundwater observations. If such data is not available, they need to be estimated. If only groundwater levels are available, then calibration on the dynamics of the groundwater level fluctuations makes it possible to constrain the maximum soil moisture storage $S_{\mathrm{u,max}}$ [L], which is the key parameter depending on rooting depth and soil characteristics. Values for the S_{wp} [L], the "wilting point" and the factor determining moisture constrained transpiration p [–] can be estimated on the basis of soil information and an estimation of the root depth. The residence time of the groundwater K_{p} is selected in conjunction with the residence times of the hill slope and wetland and is derived from the recession curve. The time of concentration T_{p} [T] for overland flow can be estimated from the topography. A key parameter to estimate, depending on the soil characteristics, is the maximum infiltration capacity $F_{\max}$ [L/T], above which Hortonian overland flow occurs. Of course there are uncertainties related to estimated parameters, but these uncertainties can also be estimated on the basis of literature values and experience.

This leaves six parameters to be determined by free calibration (fc) and two observable parameters to be determined by constrained calibration (cc), between well-defined limits based on experiments and literature. The groundwater time scales (K_{w}, K_{h}, K_{p}) can be lumped and determined by manual calibration (mc) on the recession curve. Hence 7 parameters need to be estimated (est), based on literature or experience (D_{p}, p, $S_{\mathrm{u,max}}$, S_{wp}), experiments ($F_{\max}$), topography (T_{p}) and the water balance of the hill slope (C). If necessary plausible ranges for parameter values can be given to constrain a calibration procedure. Possibly groundwater information can help to constrain some of the plateau parameters, particularly: $S_{\mathrm{u,max}}$, and p.

This turns the method into a six-parameter calibration process. By considering different catchments with different proportions of Wetland, Hill slope and Plateau, focus on different parameters can be given, which allows further insight into the appropriate parameter values. Also distinguishing

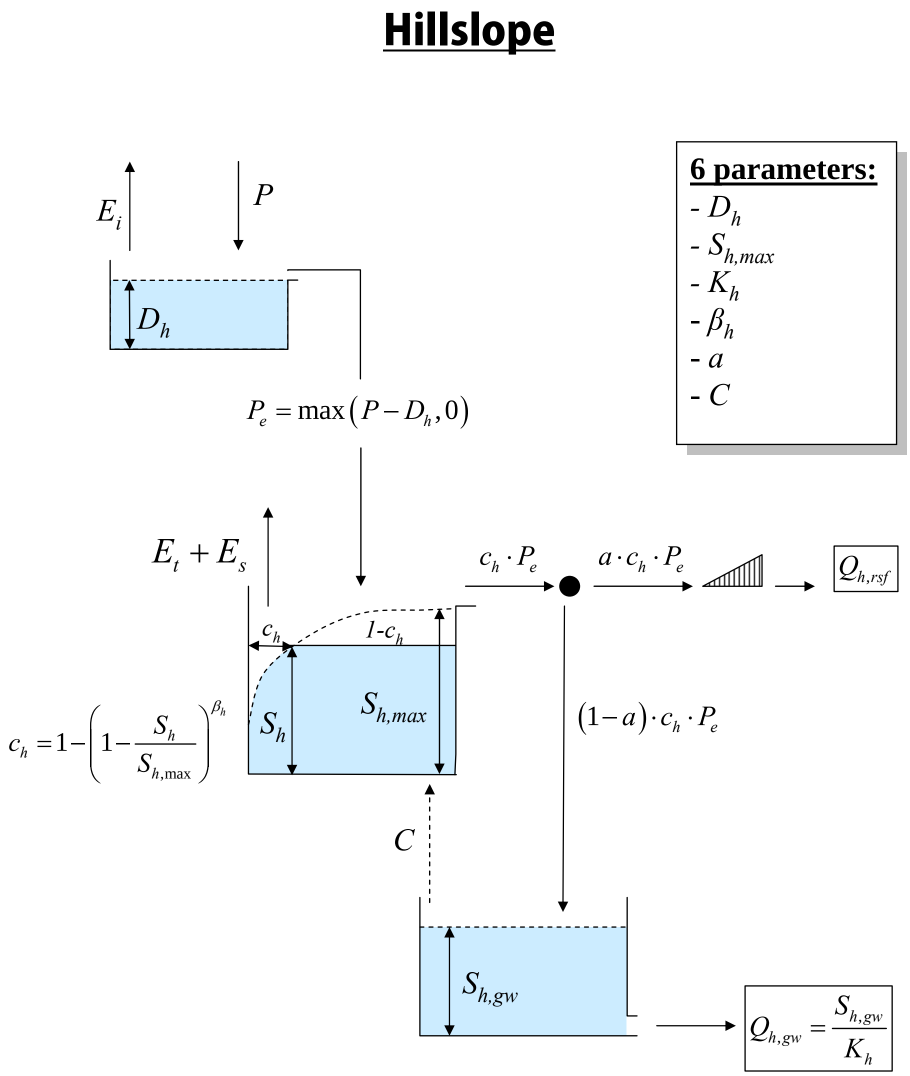

Fig. 3. Hill slope conceptual model.

between very fast, fast, and slower processes can focus the calibration on different processes. In principle the calibration will be step-wise (e.g. Fenicia et al., 2008a), only leaving a limited number of parameters to be determined by (automated) calibration.

If an overlay with the dominant geology is made, some parameters can be made geology-dependent, particularly the time scale parameters. The infiltration capacity can be made land-use and soil texture dependent.

Finally, it is important to keep track of the interception and soil moisture in a distributed sense, within the lumped conceptual approach (so we account the moisture in a distributed way, as a response to distributed rainfall, but the parameters remain lumped). In fact the approach requires an overlay of topography, geology, land use and climatic drivers over a simple conceptual model structure.

6 Is there connectivity between these hydrological landscapes?

The question whether the three hydrological landscape systems function in parallel or in series is an important issue to raise. For example, the topographic index (Beven and Kirkby, 1979) mentioned above assumes that the hill slope feeds the wetland system, after which the surface area of the wetland expands, so that the area of SOF becomes larger. This connectivity is probably correct in the catchments where this approach was developed, but not for the hill slopes in the Meuse catchment where we are going to test this approach. I know that there is also connectivity between the hill slope and the wetlands in the Zambezi, which consists mostly of Kalahari sands. There the recharge from the plateaus and the hill slopes feeds the groundwater, as a result of which

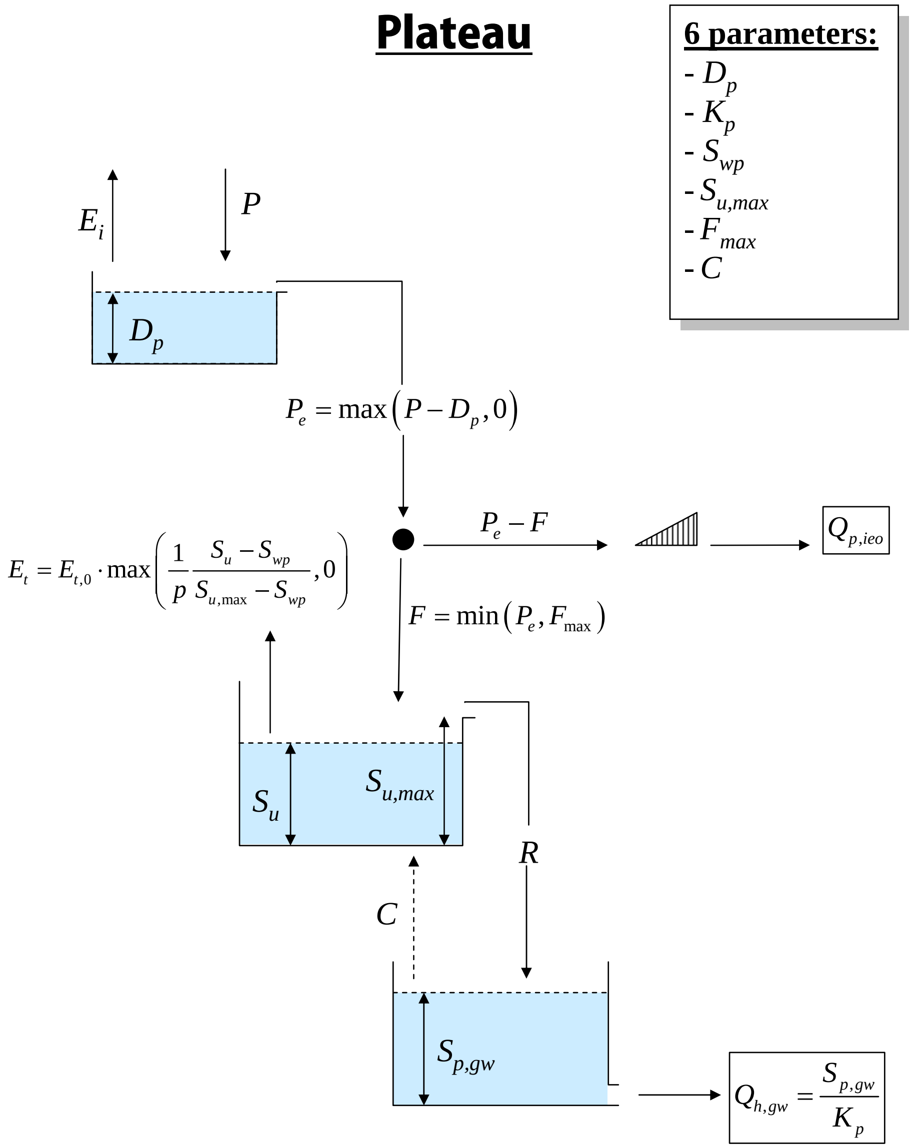

Fig. 4. Plateau conceptual model.

the drainage system expands (Winsemius et al., 2006). So whether there is significant connectivity or not depends on the local conditions, and depending on the local conditions different conceptual model structures need to be tested. In the Meuse catchment, for instance, the hill slopes discharge directly to the stream, without passing through the groundwater system. The plateaus feed the groundwater which discharges directly to the stream. There may be some interception in the intersection with the hill slope, but this is probably minor. One can also safely assume that the recharge on the wetland itself raises the groundwater level to saturation earlier than the groundwater flow from the plateau or the hill slope, where there is probably a longer delay between rainfall and recharge. So in my example the processes are not connected but act in parallel. Only the groundwater reservoir itself, I think, is more likely to be lumped, so that plateau, hill slope and wetland recharge the same groundwater reservoir and jointly are responsible for the recession of the hydrograph. So in summary, the fact that in the proposed model structure the elements are not connected may be one of the key raisons why this model structure is conceptually better. Of course it still needs to be tested to be able to draw this conclusion, but for the time being my hypothesis is that the dominant processes in the Meuse catchment act in parallel.

7 How to test the new approach?

As soon as we launch a new approach, it is fair to ask how we can test whether the approach is better than another – more conventional - one. The proof of the pudding is in the eating and we have to set-up an objective way of proofing “the pudding”. Here we touch upon a fundamental problem in hydrology where an objective proof is hard to get. In catchment hydrology we always suffer from the problem that we do not know – with sufficient accuracy – what the exact forcing of the system was. Rainfall is highly heterogeneous in space, and point measurements can result in substantial biases. Maybe in the near future, making better use of radar and remote sensing instruments, we shall be able to reduce these biases, but with an uncertain forcing of a model it is extremely hard to reject or accept a hypothesis.

Clearly there is no such thing as the correct or “best” model. In absolute terms, such a model most likely is not available under the given circumstances (cf. Andréassian et al., 2009). We should instead strive to develop “better” models than those available to date (Savenije, 2009). A model (hypothesis) that performs consistently better than another model (hypothesis) is most likely a better hypothesis. Although such a conclusion may be very site and case specific. As a result we have to ask ourselves how broad a sample should be (consisting of various catchments in different climatic, geological and topographical conditions and/or various climatically different calibration and test periods) in order to be able to draw the conclusion that one model is better than the other.

Assuming that we have a broad enough sample, how do we test different model structures and parameterizations? And how do we conclude that a model is “better” or more adequate than another? A powerful tool to identify model improvement is multi-objective calibration. Objective functions emphasizing, for example, peak as well as low flow can be used to generate pareto fronts of model parameterizations (Fenicia et al., 2008a). Shifts of these pareto fronts towards the origin illustrate improvements in model structures, while structures and parameterizations whose objective functions plot far from the pareto optimal solution can be rejected.

Clearly, there remains a level of subjectivity in such an approach. However, in conjunction with a rigorous model crash test as suggested by Klemes (1986) and reiterated by Andreassian et al. (2009), there can be some confidence that a chosen model can adequately represent the processes in a given catchment. The mentioned model crash test involves several levels of model testing, including common split-sample tests, followed by differential split sample tests, proxy-basin tests and proxy-basin differential split sample tests (Klemes, 1986). In order to extract even more information about the adequacy of the respective models one could extend the concept of differential split sample tests. That is, instead of merely identifying a few periods of different climatic conditions for sequential model calibrating and testing, the concept of re-sampling (in a way similar to “boot-strapping”) could be adopted to increase the sample sizes and therefore the information content of the tests. For example, from the available data record with length n, the model could be sequentially calibrated for one hydrological year (or any other chosen period) and thereafter the parameterization could be tested individually for all preceding and subsequent $n-1$ years (or any other chosen periods). This is then repeated by calibrating the model to another hydrological year and testing it on the remaining $n-1$ years, until the model has been calibrated for all individual n years.

It is always better to evaluate model performance under validation circumstances and not under calibration circumstances. The ratio of the calibration performance to validation performance could be an interesting indicator for the predictive uncertainty of a model. Model structures that do not perform significantly better than a bench mark model or another model structure should be rejected. For benchmark models one could consider well established parsimonious conceptual models such as HBV (Bergström, 1992) or GR4J (Perrin et al., 2003).

The ensemble of tests would not only identify adequate model structures but also provide insight into temporal and spatial model transposability. Most importantly, it would be possible to identify under which climatic and topographic circumstances which model structures fail, allowing us to identify weaknesses in model structures and potentially giving the modeler the possibility to adjust model structures according to the observed weaknesses (Fenicia et al., 2008a).

8 Conclusion

Clearly this topography-driven conceptual modelling approach is not yet an established and tested methodology, even though related concepts have been tested. It is widely accepted that different parts of the landscape fulfill different tasks in runoff generation and the incorporation of additional information to delineate these different response units was done before (e.g. Scherrer and Naef, 2003; Uhlenbrook et al., 2004). These attempts, while valuable for gaining insights into underlying catchment processes, were of limited use for operational application as they were either incorporated in distributed, process based model structures, resulting in considerable parameter equifinality (e.g. Uhlenbrook et al., 2004) or because they simply required detailed data (e.g. soil properties) which are frequently not available (e.g. Scherrer et al., 2007; Hellebrand and van den Bos, 2008; Rosin, 2010). What is presented here instead, is an even simpler conceptual approach to hydrological modelling, where topography is used as a key for classification. The opportunity lies in the fact that topography is closely linked to geology, geomorphology, soil, land use, ecosystems, climate and, as a result, the dominant hydrological processes. This is a possible interesting venue to find the middle way between model complexity and simplicity, making use of the patterns inherent in the landscape. I have purposely not yet tested the approach on specific catchments or situations. That would only divert the attention from the opinion forming character of this paper and lead to a discussion on which model best fits the hydrographs (Sivapalan, 2009). In my view, testing it and refining it is an interesting venue for further research. More importantly, this modelling approach should be seen as an instrument for learning and for testing hypotheses (Fenicia et al., 2008b), within a framework of observable topographical characteristics.

Finally, it needs to be stressed that this approach is not another conceptual model but a framework to develop appropriate model structures for the problem at hand, making use of topographic information to distinguish between dominant hydrological processes. It is not a straightjacket that is confined by a predefined model structure. Model structures are flexible in the way as proposed by Fenicia et al. (2008a,b, 2010). Through this flexible approach conceptual models can be developed for different climatic, geologic and land-use conditions, making use of the information available in the topography.

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