hess-2013-264 – 'Advancing Catchment Hydrology to deal with Predictions under Change'

Reply to Referees and revised manuscript

Dear Editor, dear Referees,

First of all we want to thank both reviewers for their detailed and constructive comments. We will address their comments in the following point by point and, where applicable, we will also indicate the page in the manuscript where changes were made (page enumeration according to the revised manuscript). For better visibility, our replies are marked green, all changes in the manuscript are marked yellow.

Major points by Keith Beven

Major point 1 and the last of the specific comments (they both deal with the same topic)

P36 While the approaches we presented to deal with catchments under change are not new, and are in fact based on existing and well- established theories, we suggest that their synergistic combination can serve as a paradigm to direct the further development of catchment hydrology to address questions of change.

I do not disagree with the authors here – but I am interested in how it might work. What is needed is an example or couple of examples. Let us take the continuing deforestation of the Amazon basin for example – or perhaps you could go back to a post-hoc analysis of the Aral Sea. We know that such large scale changes to a catchment system can have feedback effects to recharge, evapotranspiration and runoff and consequently on precipitation etc over large areas (some of which were not subject to the original change. The drying of the Aral Sea is itself a consequence of irrigation practice that could have been predicted without invoking any of the principles advocated in this paper. Past (theoretical) work on feedbacks in Amazon rainfalls by Rodgriguez-Iturbe and others, however, also suggests that there might be potentially chaotic responses to change – which could have feedbacks to catchments that have not been directly affected by the change (the impacts are seen only as a change in boundary conditions). In concept we are already aware of these potential sensitivities. How would the principles expressed in this paper lead to a better analysis of such problems? This is not really clear but, for example, the effects of drying of the Aral Sea on rainfall might also have been predictable, but the sensitivities might have been more evident by invoking the concepts of this paper. Doers it amount to more than that? The key would appear to be in the constraints of Figure 3 but it is rather difficult to see how they might be applied in such a case study. I think that the addition of such an example of how it might work in practice would be extremely valuable in making the message much more than a fashion statement. Hence my suggestion of a revision.

Reply: This is a good point. However, after considering several possible options to meet this request for a joint illustrative example, we decided to leave the manuscript as it is. We will explain this in the following:

The first option was to include a report of a real case study. However, being that this paper is intended to be 'forward looking', we cannot present a study, where all of these principles have been jointly applied – were we able to do so, this paper would be largely irrelevant. Nevertheless we believe that the joint presentation of the different perspectives and discussing their interrelations in the manuscript are more than a mere fashion statement, but can be helpful to better understand catchments under change (see also the changes in the abstract).

The second option was to construct a virtual but realistic case study to present a strategy for joint application of these perspectives. In fact we did so and included it into a new section 4.5. However, after extended back-and-forth discussions, we removed it again due to several reasons:

- It was impossible to introduce the test case, describe the application of each perspective and their interactions, including a discussion of possible benefits and limitations in satisfactory detail within a reasonable number of pages.
- With the limited detail of the case study, we found the added value compared to the in-depth discussion of the perspectives and the cited examples of their applications in section 4 to be rather small, and it did not justify the substantial lengthening of the manuscript.

To conclude, we fully agree that conducting such a study and reporting on it would be highly interesting and valuable. However this would involve an extensive project and a paper of its own, which is beyond the scope of our manuscript.

Major point 2

I think the thing I object to most is the suggestion that hydrologists have been stuck in an assumption of stationarity for so long. This is a rhetorical device as a way of contrasting a misguided past with a brighter theoretical future but is simply not true (you can go back to Davis's geomorphological theory, Horton's landscape development theory and seasonal patterns of infiltration, impacts of urbanisation etc etc etc see also examples below). Assumption of stationarity for the purposes of identifying the parameters and structures of predictive models has been a response the practical difficulties of underdeterminism (and even then there have been studies looking at how inferred parameters from both measurements and model calibration change over time).

Reply: This comment is largely congruent with Major point 1 by anonymous referee #2, hence we jointly address them in the following.

At first, we would like to stress that our intention is not to criticize past and current hydrological science and practice as a 'misguided past'. As both reviewers obviously arrived at this impression, we have changed the wording at several places in the revised manuscript (see yellow markers in the abstract, in section 1.1 and the conclusions). We also do not question that hydrologists have since long been aware that non-stationarity exists and that this issue has been addressed in the past (see the examples of Keith Beven).

Rather we claim that in the past, stationarity could either successfully be assumed for many aspects of hydrology without introducing a large error, or had to be assumed due to practical considerations (see manuscript section 1.2), as

- The questions posed to hydrology were more limited with respect to their temporal, spatial, or topical extent. Thus neglecting certain long-term non-stationarities or feedback effects among parts of the hydrological cycle was acceptable, even if they were known.
- Some non-stationarities or feedback effects may have been known, but not considered in the past due to practical limitations (computing power, available observations, available models, etc.).

However, the questions that are posed to hydrology nowadays (or rather the questions that we dare to tackle) have a larger purview (time, space, topics). An extreme example could be *'what is the global drinking water availability for the next 3 decades?*' Also, some of the formerly stationary (or close to stationary) system properties/boundary conditions have become dynamic to a degree that can no longer be neglected (see the discussion on climate change and man-made changes in section 1.1).

The fact that these issues taken together have triggered large hydrological initiatives such as PUC, is an indicator of consensus among many hydrologists that questions of change cannot be solved based solely on existing state-of-the-art tools. Many of the models used in hydrological engineering and administration, even for climate change studies, still neglect essential feedbacks (e.g. land surface - atmosphere interaction, climate - land use interaction etc.) although hydrologists are well aware that such assumptions are questionable. One example: In Bavaria, the effect of climate change on flood magnitude is currently acknowledged by multiplying existing (stationary) design flood estimates from gauge observations with a single 'climate change' factor. Everyone knows this is too simplistic, but the tools to give more realistic transient design flood estimates are lacking.

To summarize: Hydrology deals with increasingly complex systems, both because some system components shift from stationary to non-stationary behavior and because the questions posed requires inclusion of more subsystems. To handle such systems, we can add further observations of initial and boundary conditions or knowledge about the system functioning. In this paper, we mainly discuss approaches of the latter kind.

New text: see Sect. 1.1 in general and page 4, paragraph 1 in particular.

Major point 3

The authors do not answer whether any of their methods will help to reduce underdeterminism.

Reply: We will first give a general and then a more specific answer to this question: The general statement is in the summary and conclusions of the paper (page 32): Following the conclusions of Kleinhans et al. (2005), i.e. that the best way to overcome underdetermination is a combination of 'historical actual-sequence explanations, robust process explanations and causal explanations', we suggest in the paper that our proposed perspectives are such a combination. A more specific answer to this question is for example that exploiting an optimality principle reduces underdetermination, as it reduces the degrees of freedom of a dynamical system and hence reduces the number of observations to achieve 'full observation'. See for example Porada et al. (2011), Kleidon and Renner (2013), Zehe et al. (2013), Schymanski et al. (2009): In each case, the number of required observations was reduced, or, reversely, knowledge about/predictability of the system at issue was increased without adding observations.

Major point 4

New observations might have a much bigger impact on the representation of current catchment responses than any of the proposed principles. This is in the article only mentioned in passing.

Reply: We agree with the referee that new observations have a large potential to improve our understanding of hydrological processes and to provide either additional or higher resolved initial and boundary conditions for hydrological modeling, but they need to go hand in hand with improved understanding. More new observations without improved methods of analysis at worst just reinforce the prior beliefs and at best just tell us something is wrong. The real key to improved science is better and new theories that impose greater requirements for testing (and hence ultimately better observations).

Clearly, an in-depth discussion of the topic of new observations is beyond the scope of our article, but we think a short discussion of the topic will help the reader to put the topics of our article in a broader perspective. We have added this to the last paragraph in section 5 (summary and conclusions).

Specific comments by Keith Beven

Comment 1

P14 Advances in measurement techniques, in particular about spatial patterns (e.g. Grayson et al., 2002), helped address the dispute as they provided new information to identify at least some of the model parameters. Is this statement actually true (in the sense it is being used here rather than the simplistic sense that more information might constrain some parameterization)? If so how?

Reply: We believe that the advances in measurement techniques have indeed provided a new dimension of information, not simply more of the same. Traditional information on catchment dynamics has mainly been time varying data at one (or a few) locations, while the patterns data provide spatial information at a few points in time. Advances have been made in measuring soil moisture, snow cover and stream temperatures by remote sensing methods, Terrain Data Acquisition

Systems (TDAS), distributed sensor networks, distributed temperature sensing, and other instrumentation setups. The new data have been beneficial in

- obtaining SPATIAL estimates of model parameters,
- validating hydrological models in terms of their SPATIAL predictions, and
- assessing the effect of the SPATIAL structure (or organisation) of hydrological characteristics within the catchment on model output and model uncertainty.

Examples for soil moisture, snow and stream water temperatures include Western et al. (2001), Blöschl et al. (1991) and Westhoff et al. (2011).

New text: See on page 12.

Westhoff, M.C., Bogaard, T.A., and Savenije, H.H.G.(2011) Quantifying spatial and temporal discharge dynamics of an event in a first order stream, using Distributed Temperature Sensing, Hydrol. Earth Syst. Sci. 15, 1945-1957, doi:10.5194/hess-15-1945-2011.

Western, A.W., G. Blöschl and R. B. Grayson (2001) Towards capturing hydrologically significant connectivity in spatial patterns. Water Resources Research, 37 (1), pp. 83-97.

Blöschl, G., D. Gutknecht and R. Kirnbauer (1991) Distributed snowmelt simulations in an Alpine catchment. 2. Parameter study and model predictions. Water Resources Research, 27 (12), pp. 3181-3188

Comment 2

P16 Hydrological systems, as systems of “organized complexity”, exhibit a mixture of both dimensions, being roughly predictable under some conditions and at certain scales but unpredictable at others. Waldrop (1992) termed such systems as being at the “edge of chaos”.

Just how is this more useful than a recognition of avulsions, stream capture, meander cut-offs, changes in braided river patterns, landslides and debris flows etc

Reply: We are not fully clear what the referee is pointing at here. We have included the discussion of catchments as systems of organized complexity in the text as it helps to explain the experience of many hydrologists that hydrological systems are at times well predictable, at others not (depending on state and forcing) or that certain aspects of the system are well predictable, others not. This provides a link between these observations/experiences (avulsions, etc.) and a more formal categorization of predictability from a systems classification point of view. In the text, we propose that this way of looking at catchments (under change or not) helps to better decide which components, processes and feedbacks an adequate hydrological model must include and what the limits of predictability for such a systems are.

Comment 3

P21. Despite advances in geomorphology, pedology and ecology in unraveling the pathways and mechanisms that have determined those facets of the landscape, in conventional reductionist approaches the hydrology of a catchment is still largely understood as a system without a history, as brute fact.

See earlier comments. This is simply not true of any hydrologist that I know.

Reply: The statement here was poorly worded. It was not intended to imply that hydrologists themselves have no understanding of the history of the watersheds they study, but rather that the models themselves do not encode this knowledge. The understanding might be brought in implicitly through the choices the modeler makes in setting this model (e.g. by transferring parameters from nearby catchments, which most often share the same historical evolution), but there isn’t much in the way of frameworks or theory to do this in a systematic or rigorous way. We have edited the first paragraph of the section (where this sentence originally appeared) to introduce the co-evolution idea in a less tendentious way, and added an additional paragraph (the fourth) to more clearly express this idea.

New text: On page 19-20

Comment 4

P22 a catchment classification system based on a shared developmental pathway "genotypes") may be more fruitful than one based on similar current hydrologic behavior alone "phenotypes") (see Sect. 4.2.3).

But surely one of the implications of complex dynamic systems is just that we cannot properly know the history of development (e.g. Culling, Phillips in geomorphology), so how would you then classify genotypes in some non-trivial way? And genotype are not mentioned in Section 4.2.3.

Reply: With regards to the first point, we agree with the referee that the potential added value of a classification system based on developmental pathways is dependent on the degree to which signatures of structure-shaping processes are preserved in current structure. Or, in other words, it depends on the degree of determinism of its evolution which, in Fig. 1, can be associated with the number of points of instability a system crosses during its evolution. An example for strong determinism is structured soil created by repeated volcano eruptions during the last millennia; a turbulent flow structure marks the other extreme (weak determinism), as here knowledge of current structure will not allow reconstruction of its exact developmental pathway.

With regards to the second point: the reference to Sect 4.2.3 is for the second part of the sentence only. For clarification, the reference in the text is now '(for the latter, see Sect. 4.2.3).'

New text: see page 20

Comment 5

P22 Darwinian hydrology could similarly search for ways to unify the variability of catchments' hydrologic behavior, but will have to search for its own mechanisms, since clearly "natural selection" does not apply.

But natural selection surely does apply in your framework. The impact of extended droughts on vegetation patterns for example. The modification of ecosystems by anthropogenic impacts in both short and long terms could also be viewed as a form of natural selection.

Reply: What we wanted to say is that natural selection is not a principle that applies to catchment evolution in general and to all of its components.

New text: See on page 21.

Comment 6

P23 It should be noted, however, that even if such optimal states exist, the Darwinian approach admits that the contingencies of history of a system can strongly constrain its degrees of freedom to evolve, creating lasting sub-optimal forms that dominate current structure

But does this not apply EVERYWHERE? What we see now is only partly self-organized – it is often much more shaped by external boundary conditions (the last glaciation, anthropogenic deforestation over millennia, impacts of large scale irrigation etc.). If nearly everywhere is sub-optimal and optimality can only be a tendency to be disrupted every time there is an external forcing, how does it help?

Reply:

We do not disagree with the referee that the definition of an optimal state of a system has to include the constraints posed by initial and boundary conditions. Formulating a hypothetical 'global optimum' state for a system ignoring these conditions would be of little practical help, as they are determining factors for the characteristics of the system. And what initial and boundary conditions would be used instead? But whatever the constraints given by initial and boundary conditions are, optimality principles (which direct a system's development towards steady states) and thermodynamic limits (which make a statement about the at 'best' achievable steady state of a system) can help to narrow the range of possible future developmental trajectories, the speed of development and final states.

This does neither require nor imply that these final states will be reached. Also, the 'optimal (steady) state' of a system is not a single-faceted quantity, rather each of its components (river system, vegetation, etc.) has its own optimal state under given boundary conditions and each has a typical temporal scale required to reach the this state from given initial conditions or from a given disturbance. So a system can at a given point in time still be in a sub-optimal (non-steady) state for one aspect (e.g. a non-developed river system) but at the same time be in an optimal state for another (e.g. vegetation distribution). Here not only the initial, but also the boundary conditions play a role, as it can form a disturbance regime continuously pushing certain aspects of the system from optimal back to suboptimal states.

Of course system components interact, and the evolution of one aspect of the system can mean changing boundary conditions for the other. In Günter Blöschl's terms a separation of scales is often possible (e.g. we can assume a fixed river system when we want to determine the optimal state for vegetation). As an example for a frequently disturbed, but short-term optimizing process, Kleidon and Renner (2013) showed that evapotranspiration is essentially limited by atmospheric convective transport and that maximizing convective power (the optimality criterion) provides reasonable estimates of evapotranspiration.

To conclude, even if we do not have a perfect knowledge of the optimum state of a system component, knowing the general tendency of development of a system towards this state and possibly setting upper limits is valuable. Also, initial and boundary conditions can strongly determine a systems evolution, but this does not mean that evolution towards optimal states will not take place.

New text: As we found that this matter requires a more in-depth discussion which is beyond the scope of the paper, we omitted the passage from the manuscript.

Comment 7

P24 For example, catchments satisfying the Budyko curve (Budyko, 1974) manifest the similarity of long-term hydrologic functions (partitioning of precipitation into rainfall, runoff and evapotranspiration) under stationary climatic controls; while the deviation from the Budyko curve likely manifests the remaining degrees of freedom such as vegetation and landscape variations (Troch et al., 2013).

But Budyko was derived from data – with errors – and for long term averages that reflected a particular period of climate variability. Such a statement does more to undermine your case than support it.

Reply: There have been many studies showing that, in a modeled environment, differences between catchments in vegetation cover or soil types can reproduce the deviations from the Budyko curve that have been observed in many empirical studies (e.g. Troch et al., 2013). However, given that any empirical study is based on observations with unavoidable errors, it is not yet clear when deviations from the Budyko curve, which assumes climatic control only, are due to actual differences in landscape characteristics and where it might be the result of data error. More research is needed to separate the two.

New text: See on page 22.

Comment 8

P25 Searching for hydrologic similarities and their organizing principles can help to estimate the future of existing catchments under changed boundary conditions by trading space for time (Singh et al., 2011). So far, little thorough investigation has been done on this topic and its use in hydrology, which means that the validity of its basic assumptions and its broad value still have to be assessed. For example, under what conditions is spatial variability a proxy for temporal variability?

Actually never - except perhaps in some vague sense of helping to constrain some prior distribution of parameters or expectations. But do we not do this already when trying to estimate the impact of changes in a catchment on the basis of regionalized information from catchments with different catchments elsewhere. How does the Darwinian approach help here when the changes are primarily anthropogenic?

Reply: The question of whether spatial and temporal variability can be traded in hydrology has so far been insufficiently addressed. There have been some initial studies that indeed suggest, as the reviewer states, that the approach might be useful to derive priors on model parameters or catchment behavior for catchments that underwent change. This idea is of course similar to the transfer of information from a sufficiently similar catchment before and after a distinct change has occurred (e.g. deforestation). Open questions about what degree of similarity is needed remain. The more recent trading-space-for-time papers are more concerned with the very long-term impacts of climate change (and how climate for example might impact parameter values).

The question can be more complex in cases where the changes are primarily anthropogenic and are not similar to changes that could naturally occur (e.g. urbanization vs deforestation). Here it matters more what the type of change is that is investigated. Changes such as deforestation can use information from other catchments (under assumed similarity), while impacts such as urbanization might have too unique a signature for information to be transferrable. It is in many cases not even possible to understand in how far the signature of the changed catchment has been influenced unless the change is very large, e.g. in the case of urbanization (see Martin et al., 2012).

New text: See on page 23

Martin, E. H., Kelleher, C., and Wagener, T.: Has urbanization changed ecological streamflow characteristics in Maine (USA)?, Hydrological Sciences Journal, 57, 1337-1354, 10.1080/02626667.2012.707318, 2012.

Comment 9

P27. Close to TE (here expressed by a small hydraulic gradient), diffusive water flow is linearly dependent on the hydraulic gradient. Beyond a critical hydraulic gradient, subsurface backward erosion can lead to the formation of (dissipative) preferential flow structures which accelerate the flow and add an entirely new quality to it.

But this is a very special case. What about all the much more common preferential flow structures that are induced by dessication cracking, or root channels, or worm channels or relic glacial/periglacial features that are NOT a product of the flow process?

Reply: We chose this example as here the feedback acts on the domain of the primary process without detour, which we hope makes the example straightforward. Another example, which is not as 'special' as our example, would be the self-induced and self-organized formation of flow structures in catchments (see Kleidon et al. 2013). However, and we will make this point more clear in the text, while all processes create a negative feedback on their driving gradient, by far not all of them will create positive feedbacks (local gradient enhancement or decrease of resistance). But the point is that in principle they can (and some do), and this is the only reason a system can by itself evolve farther from TE, opposite to the direction dictated by the second law. And of course there may be structures (your examples of cracks, worm channels etc.) present in a system which facilitates a flow of interest (in our case water flow) which are either not or only indirectly linked to the process of interest (see also Zehe et al. 2013). But this does not contradict what we are saying.

New text: See on page 26.

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, 4297-4322, 10.5194/hess-17-4297-2013, 2013.

Comment 10

P28. For prediction of catchments under change, an explicit representation of such feedbacks is vital, as for systems far from TE, it is the balance of positive and negative feedbacks that keeps them in or pushes them out of stable quasi-steady states. Further, expressing dynamics via a concept of cascading energy conversions along hierarchical thermodynamic gradients (see Fig. 2) leads to a natural hierarchy of processes which is useful, not only to establish hierarchical modeling concepts, but also to allow formulation of upper thermodynamic limits to the magnitude of each conversion process (see e.g. Kleidon and Renner, 2013). It is, however, important to understand that in this hierarchical view of earth system processes, the boundary conditions of each conversion process are not fixed and there may be strong interactions between dynamics and boundary conditions. For hydrologic fluxes in catchments this is e.g. reflected through evaporative fluxes, which (jointly with the sensible heat flux) deplete the vertical heating gradient between the heated surface and the cooled atmosphere (Kleidon and Renner, 2013).

Please read this again - it is not very meaningful. Just where is the value added here compared to current understanding of these systems and their closures? and what is the practical import of such an insight?

Reply: We agree that part 2 of this section is somewhat out of context and hard to understand. We omitted it from the revised manuscript. However, what is important is the explicit consideration of feedbacks and the view on cascading energy conversions: It allows to formulate upper limits to these conversion processes, irrespective of whether the system has already evolved to such a maximum power state or not. That means that we can estimate upper limits for energy conversions by a process, the fluxes that are associated with this upper limit, and how this limit is altered due to change. To evaluate such limits, we need to not only consider, e.g., the effect of net radiation on evaporation, but also the effect of turbulent heat fluxes (in which evaporation contributes a substantial part) on net radiation. Kleidon and Renner (2013a) recently evaluated this limit analytically for the global hydrologic cycle and showed that they could estimate its magnitude and its sensitivity to global climate change (in Kleidon and Renner, 2013b) very well, reproducing the results of vastly more complex climate models. A practical insight of their work is that the hydrologic cycle reacts differently to changes in solar vs. terrestrial radiation, a non-trivial insight considering that the different radiative terms are typically lumped together into one net radiative forcing term. This difference can, however, only be understood if these processes are looked at in terms of the energy conversions that is involved in these processes and the feedbacks that these cause.

New text: See on page 26.

Kleidon, A., and Renner, M.: Thermodynamic limits of hydrologic cycling within the Earth system: concepts, estimates and implications, Hydrol. Earth Syst. Sci., 17, 2873-2892, 10.5194/hess-17-2873-2013, 2013a.

Kleidon, A. and Renner, M.: A simple explanation for the sensitivity of the hydrologic cycle to surface temperature and solar radiation and its implications for global climate change, Earth Syst. Dyn., 4, in press, 2013b.

Comment 11

P32. In this more general case, it is important to recognize that information can also be wrong (i.e., bad) in the sense that it can result in an increase in uncertainty about the true outcome.

You should properly distinguish between two types of disinformation here. There is data that appear to be self-consistent but leads to an increase in uncertainty (perhaps because of past overconditioning to errors) and there are data that may be inconsistent (e.g. runoff coefficients > 1 in the catchment case) and that should not be used in the inference at all.

Reply: Actually there was a somewhat more serious error in this statement. Accordingly the statement has been changed to read "In general, it is important to recognize that information can be wrong (i.e., bad) in the sense that it can result in an incorrect inference about the true outcome, or the correct inference for the wrong reasons (Kirchner 2006, Gupta et al 2008; Nearing and Gupta 2013a,b). Further, information can also be misapplied (e.g., through misapplications or imperfections in the applications of Bayes Law). Hence it is not just information we care about, but the usefulness and usage of the information.

New text: see page 30

Comment 12

P32. that facilitates a robust evaluation and improvement of model performance (Gong et al., 2013)

Not really – Gong et al. compare a one step ahead information theory prediction with a simulation model. It is no wonder that there is an improvement in performance that has absolutely nothing to do with the application of informational principles.

Reply: Actually the referees comment is a misrepresentation of the more complete context of Gong et al. (2013), who demonstrate that it is possible to arrive at some kind of estimate of "best possible performance" against which model performance can be assessed. Their point was not that the one-step ahead IT prediction was better than the simulation model, but that it provided an idea of what best achievable performance might be given a particular data set (with all of its incompleteness and errors), and therefore what a physically-based simulation model might aspire to.

Comment 13

P32. L25 Clarke should be Clark (but what about the later critical discussion of this paper?)

Reply: We changed that in the revised manuscript on page 30.

Comment 14

P33 Alternatively, the joint entropy can be approximated by the conditional entropy of Qt, given t−L. . .Qt−1. This last quantity involves a model for predicting Q from its previous L time steps, with the model structure assumed to be known (e.g. Gong et al., 2013).

See comment above. And entropy deals only with distributions. It is throwing away information about the structured dynamic response (except in so far as it can be crudely represented by the (stationary??) conditional entropy approach mentioned).

Reply: See reply to comment above. Further, the comment that "entropy deals only with distributions" is curious. Of course it deals with distributions – but distributions are not limited to static system behaviors. There is nothing in principle (other than data availability and imagination) that prevents information about the structured dynamical response being characterized by joint distributions and hence by IT. Just because existing papers have not presented IT applications that acknowledge such dynamics, does not mean it cannot be done. And lack of data is equally a limitation of any approach that requires data. We are not sure what the comments about "stationarity" have to do with it. If there is a "general law" applicable, that implies stationarity of such law. If the identified joint pdf or conditional pdf is found to be non-stationary, that only implies that we have to dig deeper for the fundamental principles.

Comment 15

P33 Finally, in the hypothetical case that meteorological conditions and all hydrological processes are already perfectly known, the information content of the discharge series becomes zero, because the perfectly predictable values no longer contain any surprise.

But this has no relevance at all to the real world (and the Gong et al approach referred to earlier only works because it makes use of Qt-1 etc.!!!)

Reply: The issue is not whether it has absolute relevance to the real world, but whether it helps to illustrate an important point. While the referee is correct in stating that this is an 'academic' example, as we will never be fully and error-free informed about meteorological conditions and never have perfect and perfectly parameterized hydrological models (so there will always be additional information in discharge observations) This sentence illustrates to the reader how information about a target quantity of interest (here discharge) can be provided by different sources, how information can flow and add up by combining these sources (here meteorological observations and the process model) and that redundant information (here the discharge observations) does not improve predictions. In other words, the goal of prediction is to make information from ex-post observations of the predicted variable as redundant as possible.

<u>Major points by anonymous referee #2</u>

Major point 1

Stationarity is the launching point motivating this paper, but the authors don't make the case that this concept really lays at the center of modern catchment hydrology. I don't think that it does. To me, stationarity has never been a concept in Earth Science, but is rather a fairly narrow statistical-methodological assumption needed by Engineers to judge risk in their design work in the absence of accurate numerical horsepower, physical parameterization, and especially input data for a watershed model. I have no reason to believe the authors are talking about anything more than the need for models that are updated with the most recent and accurate parameters and inputs. Can't we have a more detailed and precise discussion about whether those Engineering roots are still holding back Hydrologic theory, or at least about what exactly needs to be improved about our modeling to make it useful in an environment where the underlying physical parameterizations and input data might not be reliable due to change?

Later in the paper I read parenthetically that stationarity has something to do with assumptions that separate timescales of processes. Maybe that thinking could be placed up front to clarify what you mean by stationarity and what non-stationarity means, specifically, for catchments and modeling. Be more specific please and tie this idea to all of the "perspectives" and how they address stationarity- or, alternatively, find another way to motivate catchment hydrology under change!

<u>Reply</u>: This comment is largely congruent with Major point 2 by Keith Beven, hence we have jointly addressed them (see in the reply to Keith Beven).

Major point 2

The large section at the end on Algorithmic Information Content, by contrast, is nonsequiter because it is too narrow and specific, both in the sense that it goes into far more detail and is far narrower than the other "perspective" sections, and in the sense that it is myopic regarding the decades-long literature of Bayesian, Jayesian, and Shannon-Entropic/Information-Theory concepts and applications in modeling, geoscience, and hydrology. The reference list and conceptual description reduces this rich history to the last three years of work (mainly by Gupta et al.) interpreting models and hydrology as algorithms using AIC. I know that there are papers being published on this topic right now, and I sincerely hope those papers reflect a much broader understanding of how AIC fits into the big picture. AIC is one narrow interpretation of information theory and probability, which are in turn concepts that are part of a large family of statistical methods old and new that can be used to analyze systems. In order to be helpful and specific, let me ask for a revision that contains a more general but still brief discussion of information, statistics, and probability as frameworks for understanding complex systems and for helping with modeling, and in particular for recent applications that use geoscience and climate data, or catchment data. Here are some google searches on what I mean, below. The authors are certainly aware of this background, but it would be much better, in my opinion, to place AIC in this broader context so that an uninformed reader can learn. I am not convinced that AIC is unique among statistics and probability for its value to catchment hydrology. Statistics and probability, including information theory, and AIC as an example, can be used skillfully to help us test hypotheses and distinguish between models. Be more general please. This section needs attention before publication.

"generalized information theory for engineering modeling and simulation"

"climate model information theory fidelity"

"information theory ecohydrology"

"information theory geoscience"

<u>Reply</u>: We thank the reviewer for these useful comments. We agree that our citation of the literature regarding applications of Information Theory (IT) to hydrology was somewhat limited and so may have inadvertently given the impression that application of information theory to hydrology is a recent development. In the revised document, we have made attempts to rectify this by providing a

brief historical perspective to IT and AIT, and by including reference to some review papers that will introduce the interested reader to the broader scope. Further, it is certainly true that the literature on Bayesian, Jaynesian, and Shannon-Entropic/Information-Theory concepts is both vast and spans several decades, but such a comment could be made about Thermodynamics, Self-Organization, Co-evolution, Complex Dynamical Systems and etc., and it would not be productive or possible in a few pages to review.

However, regarding the reviewers comment that the discussion of “Algorithmic Information Content” (we assume the reviewer means Algorithmic Information Theory) is too narrow and specific, and that the paper would benefit from providing a “revision that contains a more general discussion of information, statistics, and probability as frameworks for understanding complex systems”, we really must disagree as doing so would change the objectives and scope of this paper in a very major way. As prepared, the major goal of this paper is to “present and discuss potentially helpful paradigms and theories that should be considered as we seek to better understand hydrological systems under change” (see clarification in the revised abstract). We do this by providing a somewhat brief overview of several different perspectives that we think could be helpful to bring together. Further, please note that this is rather a forward looking opinion paper, not a review paper, and therefore we are not seeking to detail the path followed to arrive at current understanding but instead to provide some suggestions on how we see the role of information theory for the future.

Finally, regarding the suggestion that AIT is a narrow interpretation of information theory and probability, “which are in turn concepts that are part of a large family of statistical methods old and new that can be used to analyze systems”, it is our view that both IT and AIT go much deeper and offer insights that cannot be arrived at using statistical methods alone. To support this, one need only peruse the interesting indirect links articles offered by the reviewer himself, for example to recent applications in ecohydrology that help to reveal patterns and complexity in such systems. Specifically, IT helps us to understand why and when certain methods in statistics are useful in a given context. In other words, IT helps to answer questions at a more fundamental level, on par with probability theory, and offers an intuitive and insightful perspective on the way probability theory relates to information of various kinds. In turn, Algorithmic Information Theory (AIT) operates at a deeper level, and has not been previously discussed in hydrology, with the exception of a few very recent papers (Weijs et al., 2013a, b ; Cerra and Datcu, 2013). In particular AIT goes beyond Bayesian, Jaynesian or Frequentist perspectives, because it connects the rules of processing information (probability theory), with fundamental results about the limits of mathematics and computation (Turing, 1937; Gödel, 1931). By doing so it provides:

- Perspectives on randomness, complexity and information content operating on a single object, without making reference to (a) observed frequencies or assumptions regarding alternative observations that could have been made, but were not or (b) alternative objects that could exist, but were not observed.
- A connection between probability and description length.
- A formalization of Occam's razor in the form of a universal, complexity based prior

In addition, the limitation that complexity or algorithmic prior probabilities are incomputable can be interpreted to reveal very interesting fundamental limits to inference and mathematics in general.

<u>New text: </u>Sect. 4.4 (pages 28-31),

Cerra, D. and Datcu, M.: Expanding the Algorithmic Information Theory Frame for Applications to Earth Observation, Entropy, 5, 407-415, 2013

Gödel, K.: Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme I Monatshefte für Mathematik, Springer, 38, 173-198, 1931

Turing, A. M.: On computable numbers, with an application to the Entscheidungsproblem, Proceedings of the London Mathematical Society, Oxford University Press, 2, 230-265, 1937

Weijs, S. V., van de Giesen, N., and Parlange, M. B.: Data compression to define information content of hydrological time series, Hydrol. Earth Syst. Sci. Discuss., 10, 2029–2065, doi:10.5194/hessd-10-2029-2013, 2013a.

Weijs, S. V., van de Giesen, N., and Parlange, M. B.: HydroZIP: how hydrological knowledge can be used to improve compression of hydrological data, Entropy, 15, 1289–1310, doi:10.3390/e15041289, 2013b.

Interactive comment by Manfred Ostrowski

The paper deals with dynamic coupled human/environmental systems under change. In this context, some credit could be given to the work by J.W. Forrester (Electronic Engineer) and H. Bossel (Mechanical Engineer) who very early dared to cross disciplinary borders

Reply: The two authors mentioned are indeed among the first to apply systems thinking on various problems, including management and ecology. We included references in section 4.1

New text: on page 13

Yours sincerely,

Uwe Ehret on behalf of all co-authors

Advancing Catchment Hydrology to deal with Predictions under Change

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Abstract

Throughout its historical development, hydrology as an earth science, but especially as an engineering discipline has largely relied (quite successfully) on the assumption of long-term stationary boundary conditions and system configurations, which allowed for simplified and sectoral descriptions of the dynamics of hydrological systems. However, in the face of rapid and extensive global changes (of climate, land use etc.) which affect all parts of the hydrological cycle, the general validity of this assumption appears doubtful. Likewise, so does the application of hydrological concepts based on stationarity to questions of hydrological change. The reason is that transient system behaviours often develop through feedbacks between the system constituents, and with the environment, generating effects that could often be neglected under stationary conditions. The aim of this paper is to present and discuss potentially helpful paradigms and theories that should be considered as we seek to better understand hydrological systems under change. For the sake of brevity we focus on catchment hydrology. We begin with a discussion of the general nature of explanation in hydrology and briefly review the history of catchment hydrology. We then propose and discuss several perspectives on catchments: as complex dynamical systems, self-organizing systems, co-evolving systems and open dissipative thermodynamic systems. We discuss the

benefits of comparative hydrology and of taking an information-theoretic view of catchments, including the flow of information from data to models to predictions.

In summary, we suggest that these perspectives deserve closer attention and that their synergistic combination can advance catchment hydrology to address questions of change.

1 Introduction

Introductory remark: Please note that several terms used frequently throughout the paper are defined in Table 2; their first occurrence in the text is indicated by an asterisk '*'.

1.1 Hydrology and change

Man and water co-exist in a tightly knit relationship: Water is an indispensable resource and the basis for human life, but it also poses threats, either by excess, shortage or poor quality. As a consequence, humans have long struggled to conform natural water availability to their needs, with such prominent historical examples as the Egyptian, Greek and Roman aqueducts, the levees along the Rhine and Danube built for flood protection in the late middle ages, or the centuries-old runoff harvesting techniques used in India (Gunnell and Krishnamurthy, 2003). From practical questions of how to ensure water availability and protection, hydrology developed into an engineering discipline, providing tools for design flood estimation, flood forecasting, and estimation of water availability, etc.

Meanwhile, being one of the most prominent closed loop processes on our planet, the water cycle has also sparked considerable scientific interest, as it plays a major role in global energy and mass cycling (Kleidon, 2010) and connects, like no other, the abiotic environment with the bio- and anthropospheres, thereby governing the distribution of life on the planet. This interest led to hydrology developing into a scientific discipline in its own right, with aims to analyse and describe the phenomena, structures, and processes of the global water cycle.

The dual engineering-science foci of hydrology, along with the multitude of questions, domains and spatiotemporal scales of interest, has led to a diversity of paradigms*, scientific theories*, scientific laws*, and approaches. What unites many ~~most~~ of these, however, is an underlying assumption of 'stationarity'* in regards to many ~~most (if not all)~~ of the boundary conditions and system properties; e.g. stationarity of climate, flow regimes, ecosystem function, catchment and river morphology, etc. While this assumption has, to-date, been helpful in simplifying the search for solutions to many hydrological problems, its general applicability ~~validity~~ is increasingly doubtful due to two main reasons: The tendency for components of hydrological systems to shift from stationary to non-stationary behaviour (particularly due to the ever-increasing influence of man; Wagener et al., 2010), and because the questions posed to hydrology become increasingly complex, which requires to consider the interactions of more and more subsystems and to extend the temporal extent of predictions.

There is, now, very little doubt that man plays an important role in global warming and the related changes to global climate (Oreskes, 2004; IPCC, 2007), thereby triggering a chain of changes that propagate throughout the water cycle. To name just a few: i) Shifts in atmospheric circulation patterns affect the annual and seasonal characteristics of rainfall (Bárdossy and Caspary, 1990), ii) Glacial retreat due to global warming affects river flow regimes (Huss, 2011), iii) Increasing water temperature in lakes alters the regimes of thermal layering and aeration (and hence water quality) and favours the invasion of new species (Werner and Mörtl, 2004), and d) Rainfall regimes at the regional scale are influenced by human strategies for rainfall enhancement (Griffith et al., 2009).

Comparable in impact to the changes in global climate, man-made changes in land use affect all aspects of the water cycle around the world, which in turn alter weather and climate from local to regional scales. Altogether, croplands and pastures have supplanted natural vegetation to become one of the largest terrestrial biomes on the planet, now occupying 40% of the land surface (Foley et al., 2005), and an estimated 60% of present soil erosion yields are induced by human activity (Yang et al., 2003). Arguably the most dramatic example of human influence on regional hydrology is the Aral Sea, where withdrawals of water (for irrigation) from the 1.5 million km^2 basin have led to a massive shrinkage and desiccation of the lake, extinction of the aquatic ecosystem, and reduction of regional rainfall to one third of its initial value and lake inflow to one sixth (Gaybullaev et al., 2012). Another interesting example is the fact that 55% of Dutch land would be under water if it were not for the dykes built by man (IPCC, 2007; Corrigendum to IPCC). Last, but not least, urbanization has had a major effect on local and regional regimes of water and sediment flows and on fluvial morphology (Hawley and Bledsoe, 2011), with the consequence that aquatic life cycles, habitats and food webs have been altered (Poff et al., 2006).

To summarize, the hydrological cycle is increasingly affected by changes, many of them triggered by humans, which extend from the local to global scales, act on short to decadal time scales, affect all characteristics of water-related dynamics (mean, variability, extremes), and extend over the atmosphere, critical zone (boundary layer), groundwater, lakes, rivers and oceans.

1.2 Hydrological complexity and co-evolution

Taking the perspective of systems theory, hydrology deals with an overwhelmingly complex, non-linear coupled system, with feedbacks that operate at multiple spatiotemporal scales (Kumar, 2007; Sivakumar, 2009). The fact that aspects of the hydrological system have been successfully dealt with in greatly simplified ways (through isolated treatment of sub-systems and linearized approximation of dynamics), while neglecting many of the feedbacks, is made possible mainly by the fact that long term co-evolution* of the various system components (morphology, vegetation, river networks, etc.; see Corenblit et al., 2011) has resulted in stable system configurations, wherein stabilizing negative feedback effects govern the system dynamics, so that the system degrees of freedom are greatly reduced.

For such systems, the net effect of the past interplay of feedbacks has become engraved in the system configuration, so that many of the system-shaping feedback processes need not be explicitly included in a representation of system dynamics. However, when such systems are forced sufficiently far from these stable quasi-steady states*, either by changing the boundary conditions or system properties, system reconfigurations towards new, unexpected and potentially unpredictable transient* and stable states may be triggered (Phillips, 1993; Phillips, 2006). As the nature of the new system configurations will be largely governed by the interplay of positive and negative feedbacks, limits to the applicability of hydrologic solutions based in the stationarity assumption quickly become obvious.

1.3 Goals and scope of this paper

The need to move beyond a dependence on the 'stationarity assumption' ~~This so-called 'end of stationarity'~~ therefore poses a grand challenge to hydrology, which has recently been acknowledged (among other initiatives) by the IAHS, devoting the decade 2013-2022 'Panta Rhei' (Montanari et al., 2013) to *'predictions under change'*, PUC (Sivapalan, 2011;

Thompson et al., 2013). Therefore, in the context of this IAHS initiative, the main aim of this paper is to present and discuss paradigms and scientific theories which we believe will be helpful in advancing hydrology towards understanding and predicting the behaviour of hydrological systems under change.

To be clear, this paper is intended to serve primarily as an overview, while many of the topics we identify are dealt with in greater detail within this special issue; we will point to them where appropriate. PUC questions pose both a challenge and an opportunity for the science and practice of hydrology. Because of the increasing need to jointly consider hydrological system components with processes from the abiotic environment, and the bio- and the anthroposphere across many scales, we are afforded the opportunity to begin a unification of the still fragmented landscape of hydrological theories and approaches into a more comprehensive framework. The second aim of this paper, therefore, is to discuss the structure and components of such a framework and to examine what role each of the paradigms presented may play within it.

For the sake of focus we will limit the paper to the topic of 'catchments', these being the most important and intuitive conceptual hydrological construct, although many of the paradigms presented here will also be applicable to other hydrological sub-systems (e.g. groundwater) and to the global hydrologic cycle.

The remainder of the paper is structured as follows: We begin with some general definitions and an overview of the nature of explanation in hydrology (Sect. 2). Then we present a historical perspective on the development of hydrology, discuss where it stands today and consider whether the methods it offers are suited for questions dealing with PUC (Sect. 3). In Sect. 4, we briefly discuss a number of paradigms and theories that we believe will be helpful for understanding the nature of catchments under change; these include the theory of complex dynamical systems (Sect. 4.1), catchment self-organisation, co-evolution and similarity (Sect. 4.2), thermodynamics (Sect. 4.3) and information theory (Sect. 4.4). In Sect. 5, we summarize and conclude with a discussion of how the various paradigms presented here may contribute to the development of a general framework for the science of hydrology.

2 The nature of explanation in hydrology

Which scientific approaches and methods do hydrologists use to describe, explain and predict hydrological phenomena and why?

In this section, we will discuss the general ways of explanation used in hydrology. This provides the ground upon which to discuss how problems associated with hydrological change can be approached, and to identify which currently available methods may be potentially useful for addressing them.

It is important, first, to recognize that '*explanation*' in hydrology is characterized by a considerable degree of pluralism, as it does also within the earth sciences in general (this paragraph largely draws from Kleinhans, 2005). This pluralism stems from different types of explanation, and the interdisciplinary and underdetermined nature of hydrology, as we will discuss below. In general, we can distinguish three co-existing types of explanation:

a) *Descriptive actual-sequence explanations* of the course of (unobservable) sequences of past events such as soil genesis (Buol et al., 2011), paleoflood reconstruction (Baker, 1987), long-term reconstruction of fluvial morphology (Garcia-Garcia et al., 2013) or land-use and climate (Ropke et al., 2011).

b) *Robust-process explanations* that provide cause-and-effect relations without going into detail (typically, they are referred to as general mechanisms or process patterns). A typical example from hydrology is the description of the general mechanisms of surface runoff production. Such explanation can be formulated without full knowledge of initial and boundary conditions.

c) *Causal explanations in the form of scientific laws* that provide a detailed description of (typically isolated) mechanisms and the exact ranges of applicability, in which they must qualify as exceptionless and irreducible (e.g. Darcy's law for saturated flow in porous media).

In addition to this, further pluralism arises from the diversity of questions that hydrologic investigations deal with, and from the occurrence of emergent phenomena (see Sect. 4.2.1). These multiple perspectives have, historically, favoured the formulation of laws that apply to specific phenomena and at particular spatio-temporal scales. Going further still, and due to its interdisciplinary nature, explanation in hydrology has also embraced concepts from a variety of disciplines including physics, chemistry, biology, geology, ecology and systems theory, and increasingly relies on quantitative computer models (Oreskes, 2003) for analysis, explanation, forecast*, prediction* and projection*, despite their many limitations (Oreskes et al., 1994).

This high degree of explanatory pluralism in hydrology is, we believe, an obstacle to the further development of the science, as it hampers communication and cooperation among its sub-disciplines. However, the main reason for its existence, that being '*underdetermination*', is likely to be difficult to overcome. Here, the term underdetermination is used for 'the lack of sufficient data to formulate (and test) complete causal explanations, caused by the impossibility of complete observation (e.g. in the subsurface or due to long process time scales) and of undisturbed observation'. This situation is, of course, complicated by the fact that many hydrological systems exhibit strongly nonlinear behaviour and have unknown boundary and initial conditions. Together, this imposes principal limits on our ability to make (deterministic) predictions (Koutsoyiannis, 2010). So the important question that arises is:

How can we cope with underdetermination and reduce explanatory pluralism in hydrology?

This has been a longstanding issue, but it has now become even more relevant when faced with the need to address questions of hydrological change. When systems are changing, we can be quickly confronted with a diminished ability to predict the future based purely on past observations, due to the potential invalidation of steady-state* laws.

From a methodological point of view, one useful approach to diminishing the problem of underdetermination is to attempt to combine knowledge contained in actual-sequence and robust-process explanations with laws in a hierarchical way, i.e., locally valid laws can be tested to establish robust-process predictions on a larger scale, and robust-process explanations can be tested against long-term developments of the system. In this paper, such an approach is reflected in our suggestion to view catchments both as i) systems of many component sub-systems that self-organize on the basis of locally valid laws (Sect. 4.2.1) and ii) as co-evolving entities (Sect. 4.2.2). We suggest that a key to explaining self-organization and emergence is to treat catchments as open dissipative thermodynamic systems (Sect. 4.3), which can thereby provide a hierarchical framework in which sectoral laws based on emergent phenomena can be placed. It is also a framework in which limits to the intensity of processes can be formulated.

While considering the above suggestions, it is perhaps helpful to recognize that algorithmic information theory (AIT), offers a complementary (albeit more idealized and philosophical) view of the nature of explanation, data, models and laws. AIT is based on the perspective that all data, models and laws can, in principle, be represented as algorithms on some universal elementary computer (Solomonoff, 1964; Chaitin, 1966; Kolmogorov, 1968). When approached from this point of view, an '*explanation*' is simply a useful form of *'data compression*' which enables a description of some aspect of the system in a much shorter form (requiring less storage), and a '*theory'* or '*law*' is a useful *'computer program'* that is capable of generating the observed data as output (Weijs et al. 2013a, Weijs et al., 2013b). If a theory is able to represent the nature of the structure* in some observed data, then the computer program representing it (the new description) should require less storage than the original data (original description). This quantifies the principle of parsimony by means of information measures. The main implication of this framework is that the 'why' questions of science are, at a fundamental level, really secondary to the 'how' questions, since any explanation of an observed phenomenon ('why') consists of a description ('how') at a deeper level; Feynman, 1965). A more detailed treatment of (A)IT is presented in Section 4.4.

In this context, it is also useful to realize that AIT, as an extension of information theory (IT), is closely linked to Bayesian probability and the classical information theory of Shannon (1948). What makes these attractive as a basis for scientific investigation is that they offer a general framework for the evaluation of information content (expressed in terms of change in uncertainty about a target quantity of interest), across data, laws, and models. Importantly, this reminds us that the information content of any data, law or model depends critically on the question being asked and on the nature of the prior knowledge available. Accordingly, the best current explanation necessarily depends on the information currently available. These insights are particularly important to the investigation of hydrological phenomena, where underdetermination leads to a strong reliance on computer-based models as strong priors in hypothesis testing, analysis and prediction across scales.

3 Catchments and catchment hydrology

The existence of catchments is the blessing and curse of hydrology and it has had a major impact on its historical development. To illustrate this, we will discuss what a catchment is, sketch the historical development of the science of catchment hydrology and, from this, take a look into its future.

3.1 What is a catchment – characteristics and peculiarities

The predominant feature of a catchment is its convergence into a stream channel. This allows the total outgoing flux of surface runoff to be readily measured, which, in turn, allows straightforward closure of the catchment water mass balance. This water balance equation has so far proven to be the most useful physical principle in hydrologic analysis, and it greatly facilitates the estimation of harder-to-observe fluxes such as evapotranspiration. The second interesting characteristic of a catchment is that the processes associated with landscape and soil formation operate at much longer time scales than do rainfall, evapotranspiration and the shallow water flow that contributes to most of the runoff (e.g. Skøien et al., 2003). Similarly, changes in land use typically occur relatively slowly as do changes in stream morphology. This allows a treatment of catchment dynamics in which slow and fast time scales are separated (Blöschl and Sivapalan, 1995), thereby transforming a complex problem into two simpler ones, and avoiding the explicit representation of feedbacks between system states (e.g. soil moisture) and catchment structure (e.g. topography) (Gaál et al., 2012). For example, in hydrological modelling, it is often conveniently assumed that the variables representing climate vary in time while the general model structure and the model parameters representing catchment characteristics remain time-invariant (Merz et al., 2011; Blöschl and Montanari, 2010).

An interesting consequence of this separation of time scales is that hydrological models have, historically, been 'tuned' to remove bias via calibration (Gupta et al., 1998, 2008; Blöschl et al., 2013). The ability to separate slow and fast time scales can also be found in other disciplines such as meteorology, where short time scales are associated with atmospheric motion and long scales with e.g. ocean and ice dynamics (Hasselmann, 1976). However, a key point is that *if the spatio-temporal scales of interest are close to those of structure formation and decay, then more constraints, such as the mass- energy- and momentum balances are required to allow solution of the dynamical system equations*. A typical example from meteorology is local weather forecasting including the formation of local convective structures. In catchment hydrology, time scales of interest are typically such that a separation of scales, and with it a simplified treatment of dynamics, is possible.

3.2 The historical development of catchment hydrology research

The characteristics of catchments discussed above have been a strong motivation for hydrologists to look at hydrological processes from a catchment perspective. Equally important, many societal problems that hydrologists have had to solve occur at the catchment scale, giving additional impetus for a catchment scale perspective. Indeed, when looking back in history, it is clear that the evolution of hydrology has been mainly driven by the societal problems of water management and risk (Nash et al., 1990; Eagleson, 1991). As hydrology is a broad discipline, we will discuss its historical evolution only from the viewpoint of flood modeling, which is of interest both from a theoretical and practical perspective.

The first approaches to model the dynamics of runoff generation and routing, such as the Rational Method (Mulvany, 1850) and the Unit Hydrograph concept (Sherman, 1932; Dooge, 1973) mainly adopted assumptions of linearity and time invariance, and were developed at the event-scale, lumped over the catchment. Early in the 20th century, questions of agricultural management led to the integration of soil moisture dynamics into models, thus introducing the first major representation of interactions/feedbacks (between evaporation, soil moisture and runoff) and the gradual move towards higher temporal resolution, eventually resulting in catchment-scale lumped models such as the Stanford Watershed Model (Crawford and Linsley, 1966), the Sacramento model (Burnash et al., 1973) and the HBV model (Bergström, 1976). Meanwhile, quite isolated from these developments and motivated mainly by flood frequency analysis, flood hydrology also developed a strong statistical branch (Kritsky and Menkel, 1946; Gumbel, 1941; Merz and Blöschl, 2008).

This was soon followed by models with increasing spatial resolution (see the blueprint of Freeze and Harlan, 1969), based on local-scale equations (e.g. SHE, Abbott et al., 1986), and making use of the growing knowledge on hydrological processes and availability of spatially highly resolved data. Today, the development continues towards increasingly complex water balance models involving vegetation dynamics (e.g. LARSIM, Ludwig and Bremicker, 2006) or SVAT models in the context of climate modelling (e.g. CLM, Dai et al., 2003), with increasing representation of within-catchment feedbacks and land-atmosphere interactions.

Over the decades, discussions have taken place on i) how to obtain estimates for the model parameters of these kinds of models given the complexity of the processes in the landscape (Gupta et al., 1999; Hogue et al., 2006; Rosolem et al., 2012) and ii) whether the assumed model structures are appropriate in the first place (Beven 1989; Grayson, et al. 1992; Abramowitz et al. 2006, 2007). Much of the difficulty is related to scale issues, the fact that laboratory equations cannot be straightforwardly extended to the catchment scale, and the difficulty with measuring model parameters in the field at the appropriate scale (Blöschl and Sivapalan, 1995). ~~Advances in measurement techniques, in particular about spatial patterns (e.g. Grayson et al., 2002), helped address the dispute as they provided new information to identify at least some of the model parameters test the model hypothesis.~~ Advances in measurement techniques, in particular about spatial patterns (e.g. Grayson et al., 2002), helped address the dispute by obtaining spatial estimates of model parameters, validating hydrological models in terms of their spatial predictions, and assessing the effect of the spatial structure (or organisation) of hydrological characteristics within the catchment on model output and model uncertainty. Examples for information on spatial patterns include soil moisture (Western et al., 2001), snow (Blöschl et al., 1991) and stream water temperatures (Westhoff et al., 2011). The discussion on what scale best to formulate hydrological processes, however, has not been resolved.

On the whole, the existence of catchments has been a blessing for hydrology, by enabling the development of relatively simple but successful models based on the assumptions of stationarity, linearity concepts and the availability of very few observations. On the other hand, this has also slowed the development of models that properly represent the true complexity of water-related processes along the hydrological cycle and that simulate the interplay of short- and long-term dynamics.

However, it is the latter kind that is increasingly required to deal with catchments under change, wherein the assumption of stationarity (or more generally the assumption of separation of time scales) must be relaxed. In the next section, we will examine several perspectives on catchments that will potentially be useful to direct the further development of hydrological models to approach such questions of change.

4 Perspectives on catchments under change

4.1 Catchments as complex dynamical systems

The first perspective we take is that of catchments as complex dynamical systems. The theory of dynamical systems has since its beginnings in the 1950s (Forrester, 1968) developed to a well-established branch of science, that has been proven useful across a wide range of problems and systems (Strogatz, 1994), ranging from weather prediction (Lorenz, 1969), ecology (Hastings et al., 1993; Bossel, 1986) and hydrology (Koutsoyiannis, 2006) to geomorphology (Phillips, 1993) and coupled human-ecological systems (Bossel, 1999; Bossel, 2007) among many others. The steps of Dynamical System Analysis (DSA) include identification of the system structure (border, components, and state variables) and of the laws governing its dynamics (i.e. the evolution* of system states over time). A major strength of DSA is that it offers a method for system classification based on its degrees of freedom (state variables) and the nature of its dynamics (linear, non-linear, chaotic, see Table 1), which allows conclusions to be made on system stability and predictability.

Although there is, to date, no consensus regarding an exact definition of what characteristics define the special class of *complex* dynamical systems, several constituent features are generally accepted (Heylighen, 2008; Sibani and Jensen, 2013). These include strongly nonlinear and possibly chaotic behaviour, resulting from the combinatorial effects of damping/amplifying feedbacks and interactions between sub-systems, the occurrence of emergent behaviour, limited predictability and the potential for self-organisation in Ashby's terms (Ashby, 1962; see also Sect. 4.2.1). Accordingly, catchments qualify as complex dynamical systems: Hydrological processes exhibit nonlinearity over a wide range of spatio-temporal scales, from micro-scale fingering in soil water infiltration (Ritsema et al., 1998) to the Hurst-Kolmogorov behaviour of hydrological processes on the climatic scale (Montanari et al., 1997; Koutsoyiannis et al., 2009), which can lead to high sensitivity to initial and boundary conditions and potentially to chaotic behaviour (Sivakumar, 2000). In addition, catchments exhibit emergent behaviour (see Sect. 4.2.1), changing patterns of stable and unstable states (Dooge, 1986; Brandes et al., 1998; Zehe et al., 2007), complexity of sub-system behaviour at different scales (Zehe and Blöschl, 2004; Rodriguez-Iturbe et al., 1991) and varying sub-system memory (e.g. residence times in rivers typically on the order of days, whereas in groundwater systems it may be decades).

More specifically, according to the definitions of Weinberg (1975), hydrological systems are often systems of *intermediate* complexity and organization (Dooge, 1986). Existing between the realms of organized simplicity (mechanisms) on the one hand and unorganized complexity (aggregates) on the other implies that hydrological systems can neither be fully described and predicted by methods of deterministic mechanics (as for mechanisms) nor by statistical physics (as for aggregates). Hydrological systems, as systems of '*organized complexity'*, exhibit a mixture of both dimensions, being roughly predictable under some conditions and at certain scales but unpredictable at others. Waldrop (1992) termed such systems as being at the *'edge of chaos'*. In this context, DSA may prove useful for hydrology science by providing the tools (Strogatz, 1994) for constructing a required "concept of reality intermediate between determinism and randomness in which changing patterns of stability and instability contribute to the self-organization of systems" (Dooge, 1986).

In the context of PUC questions, an important potential of DSA lies in providing a method for *classifying hydrological systems with respect to their predictability* and, therefore, for distinguishing between predictable and unpredictable systems (one of the "key unresolved issues and research challenges in hydrology"; Blöschl, 2006). A number of studies have been carried out in this context, including i) identification of patterns of hydrologic predictability (Zehe and Blöschl, 2004; Zehe et al., 2007), ii) analysis of predictability limits caused by dynamic changes in spatial catchment complexity (Kumar, 2011) and iii) defining factors affecting global hydrologic predictability (Shukla et al., 2013). Further, DSA can contribute to the *identification of patterns of long-term predictability* in regional water cycle processes, through division of the system into components of different memory length (Demchenko and Kislov, 2010) similar to approaches used in climate prediction (Hasselmann, 1976). DSA can also be useful for analysing *projected scenarios of hydrological change*. Conditions can be analysed, and physical mechanisms detected, which lead to instability of hydrological systems, induction of new stable states, and conversion of former time-invariant structures into time-variable ones, etc. In particular, dynamical invariants (known as the Lyapunov exponents) related to the average rates of divergence or convergence of trajectories in phase space, can be used to quantify the effects of instability, and can thereby serve as measures of stability, resilience, and ultimately predictability of hydrological systems under change.

In the context of addressing PUC questions, some limitations of classical DSA are its traditional focus on systems having time-variable states but time-invariant structure. From a thermodynamic perspective, catchments are open, dissipative, and far from equilibrium, and can experience substantial changes in structure (either build-up or decay, see also Sect. 4.3). Further, DSA does not, by itself, provide answers about whether principles exist that direct the development of catchment structure. Pathways to address these issues will be discussed in sections 4.2 and 4.3. Finally, caution should be exerted when estimating the degrees of freedom of a hydrological system. Deriving this number from its number of dependent variables may result in an overestimation, as it may in reality be much smaller due the synchronizing effect of emergence at various scales, (see also Sect. 4.2.1).

To conclude with the words of Dooge (1986), *"Generally, systems theory attempts to produce laws that provide insight rather than specific answers*". In accordance with this, we believe that it is these insights that form the potential of DSA for hydrologic science in the context of PUC questions.

4.2 Catchments as self-organizing, co-evolving systems

In this section we discuss why, despite the dazzling array of hydrological processes acting at various scales and across many compartments, catchments do not behave as random conglomerates, but instead exhibit a high degree of organisation and structure. In fact it is not *despite*, but rather *because* of the large number of sub-systems and processes that self-organisation and emergence can take place (see Sect. 4.2.1) and that the interaction of catchment components over time (i.e. co-evolution in the sense of a joint, non-random development) eventually leads to harmonized sets of constituents (see Sect. 4.2.2) that are likely to occur repeatedly given similar initial and boundary conditions. By taking the view of catchments as self-organizing, co-evolving systems and by exploiting catchment similarities to transfer information across space or time (Sect. 4.2.3), it becomes possible to constrain the range of future trajectories of the evolution of a catchment, thereby enabling predictability under change.

4.2.1 Catchments as self-organizing systems

The organization of light waves into coherent laser light, a bowed string emitting sound waves of only a single key and its harmonics, establishment of predator-prey cycles in ecology, and the formation of eddies in fluid flow are all examples of a phenomenon that is ubiquitous in nature - the ability of systems to spontaneously develop macro-scale (macro-scale here refers to a scale similar to the extent of the system) properties or structures (spatial, temporal or functional) from the cooperation of its micro-scale (i.e. much smaller than the extent of the system) constituents (i.e. for the system to become more than the simple sum of its parts). This is fundamentally different from macro-scale properties that simply arise from superposition of the properties of a set of micro-scale constituents (e.g. total mass of a system as the sum of sub-system mass or the linear macro-scale function of a system composed of linear sub-systems). The appearance of such macro-scale structure and hence the establishment of a hierarchy within the system is referred to as *emergence*, the underlying process *self-organisation* (Jetschke, 2009). In this context, 'organisation' can be thought of as a process leading to conditionality, i.e. the dependence of the value or state of an entity on the state or value of another (Ashby, 1962). Altogether, the notion of self-organisation is reminiscent of Darwins concept of evolution (Haken, 1980).

Within the scientific field of synergetics, which is closely related to the theory of complex dynamical systems (see Sect. 4.1) and thermodynamics (see Sect. 4.3), several criteria for the occurrence of emergence have been established (e.g. Haken, 1980). In particular, the system is typically composed of many similar, interacting sub-systems that are subject to external influences. Further, the nature of their interactions can usually be described by a few macro-scale *order parameters*, which are in turn dependent on external conditions. Depending mainly on the values of these order parameters, the nature of the interactions change (often in an abrupt, threshold-like manner, and caused by a shift from none or negative towards positive feedback effects among the sub-systems) from non-cooperative (non-conditional) to cooperative (conditional) behaviour. Importantly, for an emergent macroscopic property/structure to arise, the temporal persistence of the order parameters must be much larger than the time scale of the cooperative processes. Also, states that are far from thermodynamic equilibrium* are favoured for self-organisation to occur (see section 4.3).

There are many striking examples of emergence along the hydrological cycle: Flow fingering (Hill and Parlange, 1972) leads to structured flow at the macro-scale (soil columns), its occurrence being governed by the relationship between soil moisture and the hydraulic properties of soil and fluid. This cooperative effect is caused by a positive feedback between soil moisture and hydraulic conductivity. Similarly, the formation of persistent preferential flow structures in a catchment (e.g. river networks visible at the macro-scale) is governed by just a few order parameters (the degree of convergence of initial geopotential gradients, and the relationship between fluid shear stress and resistance to soil erosion), but adds an entirely new function to the system. In this case, the conditional (positive feedback) mechanism is related to the locally steepened gradients (towards the channel) and the reduced flow resistance (in the channel); see also Kleidon et al. (2013). Note that the formation of hillslope subsurface stormflow (see Fig. 1 in Troch et al., 2009 or Lehmann et al., 2007) and other kinds of threshold-like behaviour (Ali et al. 2013; Zehe and Sivapalan 2009) can also be seen as resulting from a hierarchy of emergent phenomena.

From the above discussion, it should be clear that hydrologists (and scientists in general) have long taken advantage of emergent phenomena when formulating laws for macro-scale dynamics in systems composed of many sub-systems (with the definition of the macro-scale being dependent on the specific purpose). However, for hydrological systems that can be viewed as *exceedingly complex*, and where one has to deal with predictions under change, there still lies considerable potential in the synergetic view. Although it is likely that we will never be able to fully describe such systems in terms of their smallest component entities (in a reductionist sense), a strategy based on making use of emergent phenomena can greatly reduce the degrees of freedom to a manageable number of order parameters, thereby making prediction a more straightforward (and less uncertain) task. It should be noted, however, that while self-organisation typically leads to macroscopically stable (and hence predictably steady) states, such systems can also exhibit complex (even chaotic) dynamics under certain conditions of their order parameters.

The general findings of synergetics have been found to be applicable to a wide range of systems, from physical and chemical to biological and social. As hydrological systems can comprise components from all of these, working within a common framework and language of synergetics has the potential to simplify the transfer of knowledge and improve communication. Further, the fact that self-organisation constrains the degrees of freedom for a catchment to develop is also a reason for the apparent similarity of many catchments (see Sect. 4.2.3). However, despite the potential of exploiting self-organisation, there are many challenges and limitations that should not be ignored; for example, the macro-scale order parameters and their corresponding macro-scale laws must be identified, the ability to make meaningful statements about detailed behaviours at the micro-scale is lost, and the effects of self-organisation can only be exploited under the assumption that the system does not change at the micro-scale. The latter may not always be true, especially for catchments under change. If for example the micro-scale soil hydraulic properties in a catchment change due to external influences, previously visible fingering may cease to occur.

4.2.2 Catchments as co-evolving systems

The hydrologic system embedded in a catchment is both a driver and a result of changes in soil, topography, biota and human actions over multiple time scales of history, resulting in striking and remarkable patterns at all spatial scales, as described in the previous section. ~~The interactions between the movement of water, the evolution of topography and soils, and shifts in ecosystems are so complex it is unlikely that any model will be able to predict or even retrodict the co-evolution of all these landscape systems in a deterministic way~~. Recent advances in geomorphology, pedology and ecology have begun to unravel the pathways and mechanisms that have determined these patterns of topography, soils and species in individual landscapes. They do so by asking a different type of question about the landscape to that posed by a hydrologic model – rather than trying to predict the behavior of an individual place in terms of its current properties, they seek explanations for the variations in structure and function between places in terms of the mechanisms that have dominated their co-evolution (Harman and Troch, 2013).

~~Hydrologic models that aim to predict the hydrologic functioning of the landscape based on the traditional reductionist or Newtonian approaches, face enormous challenges in finding ways to represent and parameterize the structure of the landscape (Sivapalan, 2005), but entirely ignore the constraints on parameter combinations or self-organization that may reasonably result from the history and co-evolution of the geology, soil, topography, and biota. Despite advances in geomorphology, pedology and ecology in unraveling the pathways and mechanisms that have determined those facets of the landscape, in conventional~~

reductionist approaches the hydrology of a catchment is still largely treated as though the system has no relevant history, as brute fact (except to the extent that the informed hydrologist uses knowledge of history to constrain the model hypothesis).

This approach has been called 'Darwinian' to contrast it with 'Newtonian' efforts aimed at prediction of individual catchments based on physical laws The 'Darwinian' approach to hydrologic science aims to identify, explain and make use of the patterns of functional diversity in populations of catchments (Sivapalan et al., 2011; Harman and Troch, 2013; Wagener et al., 2013). Charles Darwin's own profound insights can be traced to his focus on the relationship between individuals and populations, rather than either alone, and in his search for theories that explain patterns of variations in populations in terms of mechanisms that operate on individuals over history (Harman and Troch, 2013). A Darwinian approach to catchment hydrology would echo this focus. The primary data for Darwinian hydrology would likewise combine detailed analysis of the *signatures* of holistic hydrologic function in individual catchments, and the *functional patterns* that emerge when many catchments are compared on the basis of functional similarity, giving rise to the notion of *comparative hydrology* (Falkenmark and Chapman, 1989; Jothityangkoon et al., 2001; McDonnell et al., 2007; Blöschl et al., 2013), see also Sect. 4.2.3 on catchment similarity.

The objective is to find *generalizable* mechanisms of landscape change that apply to a range of places that share broad conditions (Ghiselin, 1969; Kleinhans et al., 2010; Gupta et al., 2013a). For example, it appears that there is a consistent trajectory of hydrologic evolution in upland basaltic watersheds from groundwater-dominated in relatively young landscapes to shallow subsurface lateral flow in older ones, as the works of Lohse and Dietrich (2005) and Jefferson et al. (2010) indicate. These findings suggest that one may be able to find predictive relationships between the degree of drainage incision (a topographic signature of the older watersheds) and hydrologic partitioning in landscapes with a similar history.

The kind of understanding the Darwinian approach yields could have direct practical utility in the parameterization of hydrologic models. At the moment, any understanding a hydrologic modeler has about the historical evolution of a watershed's hydrologic system provides very little constraint on model structure and parameters. The understanding might be brought in implicitly through the choices the modeler makes in choosing a particular model structure, setting the model (e.g. by transferring parameters from nearby catchments, which most often share the same historical evolution), but there isn't much in the way of frameworks or theory to do this in a systematic or rigorous way. Understanding the way co-evolution generates interdependency between landscape properties may yield ways of constraining unobserved hydrologic behavior using new types of observable information (such as novel geophysical observations), or existing types in new ways (such as the spatial distribution of vegetation).

The coupling between predictions based on co-evolution and particular mechanisms of watershed change suggests that a catchment classification system based on a shared developmental pathway ('genotypes') may be more fruitful than one based on similar current hydrologic behavior alone ('phenotypes') (for the latter, see Sect. 4.2.3). Approaches for testing such explanatory theories have been widely discussed in the geology and ecology literature (Chamberlin, 1890; Rhoads and Thorn, 1996), Srinivasan et al. (2012) offers a nice recent example of how this type of thinking can be applied to socio-hydrologic questions (Sivapalan et al., 2012). The potential added value of a classification system based on developmental pathways is dependent on the degree to which signatures of structure-shaping processes are preserved in current structure. Or, in other words, it depends on the degree of determinism of its evolution which, in Fig. 1, can be associated with the number of points of instability a system crosses during its evolution. An example for strong determinism is structured soil created by repeated volcano eruptions during the last millennia; a turbulent flow structure marks the other extreme (weak determinism), as here knowledge of current structure will not allow exact reconstruction of its developmental pathway.

~~Some have characterized Darwin's approach 'hypothetico-deductive', in which the central hypothesis is used to generate a series of corollary statements (*if A is true then B must also be true*) that can be compared to subsequent observations, leading to an iterative relationship between theory and observation (Ghiselin, 1969; Mayr, 1991).~~

Note that it should be uncontroversial to suggest that catchments 'evolve' since this simply implies change over time, and says nothing about the mechanism of that change. Similarly 'co-evolution' in this context is simply the hypothesis that changes in hydrology, topography, soils, ecosystems and human activities are interdependent. Darwin's 'theory of evolution' was not a proposal that evolution occurs (that idea had been around for centuries) but rather a mechanism for that change that unifies and explains observed patterns of variations in species (i.e. natural selection). Darwinian hydrology could similarly search for ways to unify the variability of catchments' hydrologic behavior, but will have to search for its own mechanisms, since clearly 'natural selection' applies only to the biotic components of a hydrological system.

Rather than a single 'new theory', the Darwinian approach to hydrology aims to develop a body of knowledge and wisdom about landscapes that provides constraints on the current and future unknown parameters (or perhaps on the hydrologic fluxes themselves, bypassing the need for such parameters). This knowledge should be predicated on a set of theories that explain and predict the co-evolution of the hydrologic functioning of the landscapes as a whole, locally dependent on the smaller set of key historical and contemporary forces (climate and geology) that have conditioned and constrained that evolution. In this sense there is a clear need for a synthesis of the traditional 'Newtonian' approaches that involve the study of individual catchments and 'Darwinian' approaches that are based on the comparative study of populations of catchments, as called for in a series of papers culminating in the most recent outcome of the Predictions in Ungauged Basins initiative (Sivapalan, 2005; McDonnell et al., 2007; Sivapalan et al., 2011; Blöschl et al., 2013; Gupta et al., 2013b). The question is open whether Darwinian theories and constraints can be found and used to constrain and test predictive reductionist models.

4.2.3 Catchment similarity

Catchment similarity, in a hydrologic sense, refers to the question why two catchments exhibit similar hydrologic response characteristics (Wagener et al., 2007). Catchment similarity is the basis for catchment classification, for transferability of information, for generalization of our hydrologic understanding and also for understanding the potential impacts of environmental change (McDonnell and Woods, 2004). The apparent similarity of many catchments around the world is likely rooted in their shared principles that guide catchment evolution over time and on their shared emergent effects (see Sect. 4.2.1). Comparing catchments of presumably common initial and boundary conditions with respect to their dissimilarities therefore gives insight into remaining degrees of freedom, while comparing them with respect to their similarities gives insight into universal constraints of catchment evolution. Typically, this similarity is assessed by estimating the distance between two catchments in a suitably chosen metric space, although careful exploration of the consequences of choices made regarding distance measures and potential clustering approaches is necessary to understand their impact on the similarity analysis results. An overview of techniques and measures to quantify similarity of catchment structure, function and response on various scales is given in Wagener et al. (2007). Blöschl et al. (2013) organize their comparative assessment of runoff predictions in ungauged basins around the notions of catchment, climate and hydrological similarity.

For example, catchments satisfying the Budyko curve (Budyko, 1974) manifest the similarity of long-term hydrologic functions (partitioning of precipitation into rainfall, runoff and evapotranspiration) under stationary climatic controls; while the deviation from the Budyko curve might manifest ~~likely manifests~~ the remaining degrees of freedom such as vegetation and landscape variations (Troch et al., 2013). The current state of this issue has to be treated with caution though. There have been a range of studies showing that, in a modeled environment, differences between catchments in vegetation cover or soil types can reproduce the deviations from the Budyko curve that have been observed in many empirical studies using different assumptions (e.g. Troch et al., 2013). However, given that any empirical study is based on observations with unavoidable errors, it is not yet clear when deviations from the Budyko curve, which assumes climatic control only, are due to actual differences in landscape characteristics and where it might be the result of data error. More research is needed to separate the two.

The similarity of climate control on base flow and perennial stream density shows the common constraints on shallow groundwater discharge and basic stream network formation (Wang and Wu, 2013). Similarity in geology (e.g. karst versus non-karst) is reflected in the strength with which an incoming precipitation signal is filtered (damped) by a catchment, so that strongly different flow regimes can be observed even under similar rainfall regimes (e.g. Tague and Grant, 2004). Land use will also create hydrologic differences between otherwise similar catchments (similar in pedology, geology, and climate). For example, differences between mature forest and pasture landscapes in neighboring catchments in Mexico become clear under more intense storms (once every 2 years) (Munoz-Villers and McDonnell, 2013). Under those conditions, the infiltration capacity of the pasture is exceeded and event water contributions are much higher than for the forested landscapes even though both overlay rather permeable volcanic soils.

The difficulty in assessing the degree of similarity and dissimilarity is unfortunately most often complicated through the interaction of multiple physical characteristics (e.g. a mixture of geologies), which does not allow for a very clear separation in many cases. For example, Martin et al. (2012) concluded that the degree of urbanization in US catchments had to exceed about 15% before hydrological signatures could be differentiated between urbanized and non-urbanized catchments. Given this ambiguity and our limited ability to exactly estimate the physical characteristics of a catchment, it is often necessary to resort to the use of dynamic models in which the physical system is parameterized (Carrillo et al., 2011). As a consequence, we still have to face the widely discussed issues of equifinality and model structural uncertainty.

Searching for hydrologic similarities and their organizing principles can help to estimate the future behavior of existing catchments under changed boundary conditions by trading space for time (Singh et al., 2011). The question of whether spatial and temporal variability can be traded in hydrology has so far been insufficiently addressed. There have been some initial studies that indeed suggest that the approach might be useful to derive priors on model parameters or catchment behavior for catchments that underwent change. This idea is of course similar to the transfer of information from a sufficiently similar catchment before and after a distinct change has occurred (e.g. deforestation). Questions about what degree of similarity is needed in this context still remain open. The more recent trading-space-for-time papers are more concerned with the very long-term impacts of climate change (and how climate for example might impact parameter values).

The question can be more complex in cases where the changes are primarily anthropogenic and are not similar to changes that could naturally occur (e.g. urbanization vs deforestation). Here it matters more what the type of change is that is investigated. Changes such as deforestation can use information from other catchments (under assumed similarity), while impacts such as urbanization might have too unique a signature for information to be transferrable. It is in many cases not even possible to understand in how far the signature of the changed catchment has been influenced unless the change is very large, e.g. in the case of urbanization (e.g. Martin et al., 2012).

4.3 Catchments as open dissipative systems far from equilibrium

Since its beginnings with the work of Carnot and Clausius in the 19th century, thermodynamics has been recognized as a fundamental theory about nature (Klein, 1967) and has so far proven to be applicable to any natural system, be it physical, chemical or biological. While its first law essentially states the conservation and convertibility of energy, the second law states that in isolated systems, the *entropy* of the system can only increase. Entropy is a physical property of the system that describes the extent to which energy is dispersed (unavailable to perform work) within the system. In other words, spontaneous processes always deplete (and never establish) potential gradients, thereby increasing the system's entropy. The second law describes *irreversibility* caused by dissipative processes such as heat transfer, friction, chemical reactions and diffusion and hence introduces an *arrow of time* to natural processes (Eddington, 1928).

Viewing catchments as open, dissipative thermodynamic systems far from equilibrium in the framework of thermodynamics offers several advantages. We will discuss them by first addressing what these terms imply using the example of heat transport in a reservoir heated at the bottom and cooled at the top (the well-known Benard experiment, see Fig. 1): The state of any thermodynamic system can be characterized by a set of macroscopic state variables and a unique stable state termed thermodynamic equilibrium (TE) at which it will arrive in isolation. The reservoir in Fig. 1 is in TE if the temperature gradient between the top (T_o) and the bottom (T_u) is zero. If the system is open, (i.e. it exchanges mass, momentum, energy and entropy with the environment) but sufficiently close to TE, there exists a unique steady state it will attain. Along this continuous set of steady states termed *'thermodynamic branch'*, linear relations between the system components dominate. In the reservoir (Fig. 1), this is associated with conductive heat transport, which is a linear function of the temperature gradient (T_u – T_o).

Along the thermodynamic path (including TE), systems invariably settle to a state of *minimum* Entropy Production (minEP) (Kondepudi and Prigogine, 1998). If an open system in steady state is, however, kept sufficiently far from TE (openness being, in fact, a precondition for this), nonlinear relations and cooperative micro-processes among system components can start to predominate, the thermodynamic branch can become unstable and, triggered by random micro-perturbations, bifurcations can lead to several branches of possible stable steady states. Sufficient distance from TE is hence a precondition for self-organisation to occur (see Sect. 4.2.1).

In the reservoir, self-organisation occurs in the form of convective cells if a critical temperature gradient $dT_{crit,1}$ is exceeded. All stable steady states after the point of instability of the thermodynamic branch are called *'dissipative branch'*, all systems along it 'dissipative systems', as here energy fluxes and energy dissipation are increased compared to systems on the thermodynamic branch. Increasing distance from TE is often associated with higher system structure (in Fig. 1 the existence of macroscopic convective cells) and stable dissipative systems typically settle to steady states of *maximum* Entropy Production (maxEP) as the most probable states (e.g. Dewar, 2005; Virgo, 2010).

Moving still further from TE, systems may reach further points of instability, in the case of the reservoir this is marked by a transition from convective to turbulent flow at $dT_{crit,2}$. The relation between the distance from TE, self-organisation associated with structure formation, accelerated dynamics and entropy production shown in Fig. 1 can also be applied to water flow through cohesive, erodible soils. Close to TE (here expressed by a small hydraulic gradient), diffusive water flow is linearly dependent on the hydraulic gradient. Beyond a critical hydraulic gradient, subsurface backward erosion can lead to the formation of (dissipative) preferential flow structures which accelerate the flow and add an entirely new quality to it. Most hydrological systems of interest can be viewed as dissipative structures, exchanging mass, energy and entropy with the environment, being kept far from TE by solar radiation or mantle convection (directly or indirectly), being composed of many sub-systems connected by highly nonlinear relations, exhibiting dissipative processes such as radiation, soil heat flow, frictional water flow, diffusion, photosynthesis. Thermodynamics therefore lends itself as a framework to deal with catchments as complex dynamical systems (Sect. 4.1), catchment self-organisation (Sect. 4.2.1) and co-evolution (Sect. 4.2.2).

So what does application of a thermodynamic perspective to hydrological systems actually imply? At a minimum, it comprises the definition of the system, i.e. its boundary and relevant sub-systems, keeping track of mass-, energy-, momentum- and entropy budgets while ensuring conservation of mass, energy and momentum and establishment of all relevant thermodynamic state variables. Further, all dynamics should be expressed on the basis of paired (conjugate) variables: The gradient of one of the two variables is depleted by the flux of the other; together they always describe a form of energy. For example, a gradient in geopotential fuels a mass flux, which eventually depletes the gradient. Together, mass [kg] and the gradient in geopotential [m^2/s^2] describe energy in the form of potential energy [J] (see also Kondepudi and Prigogine, 1998 or Kleidon, 2010). The direct benefit is that thus relating dynamics to the *universal 'currency'* of energy provides a link between any kind of process, be it abiotic, biotic, or anthropogenic. Moreover, it puts emphasis on the role of feedbacks: Based on the above general form, fluxes are equal to a driving gradient divided by a resistance term, which is essentially a linear process. Nonlinearity then enters dynamics in the form of feedbacks: Any flux depleting its nourishing gradient is associated with a negative feedback, positive feedbacks can occur through local enhancement of the gradient (e.g. formation of locally steepened hill slopes which increase fluxes of water and sediment, Kleidon et al., 2013) or by local decrease of the resistance (e.g. by formation of low-friction drainage networks, Kleidon et al., 2013, or by the decreasing flow resistance of soil caused by wetting). It should be noted that by far not all processes create such positive feedbacks, but the point is that in principle they can (and some do). This is the only reason a system can by itself evolve locally farther from TE, yet still obeying the direction dictated by the second law at a broader scale.

For prediction of catchments under change, an explicit representation of such feedbacks is vital, as for systems far from TE, it is the balance of positive and negative feedbacks that keeps them in or pushes them out of stable quasi-steady states. Further, expressing dynamics via a concept of cascading energy conversions along hierarchical thermodynamic gradients (see Fig. 2) leads to a natural hierarchy of processes which is useful, not only to establish hierarchical modeling concepts, but also to allow formulation of upper thermodynamic limits to the magnitude of each conversion process (see e.g. Kleidon and Renner, 2013a). Knowledge of such upper limits can be helpful to assess the effects of climate change to catchment dynamics. One example of such an application is given by Kleidon and Renner (2013b), who derived the sensitivity of the hydrologic cycle to surface warming that matches the results of vastly more complex climate models very well.

~~It is, however, important to understand that in this hierarchical view of earth system processes, the boundary conditions of each conversion process are not fixed and there may be strong interactions between dynamics and boundary conditions. For hydrologic fluxes in~~

catchments this is e.g. reflected through evaporative fluxes, which (jointly with the sensible heat flux) deplete the vertical heating gradient between the heated surface and the cooled atmosphere (Kleidon and Renner, 2013).

4.3.1 Optimality principles

Analysis of non-equilibrium systems has led to the proposition of extremum or optimality principles such as minEP (see above) and maxEP (Paltridge, 1978; Ozawa et al., 2003; Kleidon and Lorenz, 2005; Dewar, 2005), which direct their development towards final steady states. For transient dissipative systems with many degrees of freedom, they can therefore be used as *'selection criteria'* distinguishing more and less probable pathways of development. MaxEP, for example was proposed for prediction of the partitioning of water between evapo-transpiration and runoff (Kleidon and Schymanski, 2008) and was used to predict effective global transfer coefficients for root water uptake and base flow (Porada et al., 2011), and for the effects of vegetation banding on aggregated biomass and water fluxes (Schymanski et al., 2010).

Closely related to maxEP, it has recently been suggested that dissipative systems develop such that the time to reach TE is minimized, or in other words that work done over time (power) by the system is maximized (maximum Power Principle maxP, Kleidon, 2010; Kleidon et al., 2013). Recently, Zehe et al. (2013) have shown that the choice of macroporosity as optimal with respect to maxP has allowed calibration-free reproduction of observed hillslope hydrological dynamics. Optimality principles can thus reduce data demands and the need for calibration, which is especially useful for transient or ungauged catchments. Many other optimality principles have been proposed, such as maximisation of gross or net primary productivity to predict biomass dynamics or maximum net carbon profit to predict vegetation water use (Schynamski et al., 2009). It has been suggested, however, that upon choosing system extent and scale of consideration appropriately, many can be translated to maxEP (Dewar, 2010).

Disturbance of steady-state dissipative systems can either leave them unaffected or cause build-up or decay of structure, depending on the system's position on the dissipative branch (proximity to points of instability, see Fig. 1) and the strength and nature of the disturbance. Viewing catchments under change as complex, dynamical (see Sect. 4.1) and dissipative systems can therefore provide a framework to evaluate their stability, resilience and predictability. Last but not least, adding energy considerations to the analysis and prediction of hydrological systems offers additional observables which can help to better determine system dimensionality and to represent and constrain system dynamics.

4.4 Catchments as sources and flow paths of information

The next perspective we take is that of information theory. It focuses on the way information is extracted from data, how it can be compressed, stored, communicated in the form of explanations, and its relation to uncertainty. Although important foundations were laid earlier, the birth of Information theory is mainly attributed to the seminal paper by Shannon (1948), who defined information and uncertainty as quantities that can be represented, for example, as bits (binary digits). Information theory is closely related to probability theory, but was developed relatively independently from statistics, where e.g. the different definition of Fisher information exists, instead evolving mainly from advances in the fields of cryptography, communication engineering and signal processing. The adoption of Shannon's information theory back into statistics is mainly due to the principle of maximum entropy (Jaynes, 1957). Also in the hydrological literature information theory has been widely applied, see for example the review papers by Singh and Rajagopal (1987), Singh (1997) and recent papers by Brunsell (2010), Ruddell and Kumar (2009a, b) and many more. In this paper, we focus on the role information theory can play in analysing and optimizing the way information feeds into predictions.

As '*information*' is a universal quantity, information theory is a potentially useful framework in which the information content, for a given purpose, across data, scientific laws, model structures and model parameters can be evaluated. Its primary value with respect to addressing questions of change is therefore not so much in its direct application to such problems, but rather by providing a basis for the evaluation and improvement of predictive models by learning from data.

'*Information*' can be viewed as a quantity that connects processes and quantities in the real world with conceptual representations of those processes and quantities in our minds, or in computers. To understand this, note that '*observation*' consists of a process by which attention to a quantity under investigation brings about some kind of change of state – in a brain this can be a change in potential level of one or more neurons, and in a computer this can be the change in value of a bit within memory. Arguably, all of the knowledge accumulated about a catchment eventually stems from observations (including perceptions), and this then provides the information upon which our mental and computer models are based.

As mentioned earlier in Sect. 2, all observations about reality are converted into representations of knowledge by a process of '*explanation*', which can be viewed as a form of compression (Weijs et al., 2013a) in which a compact conceptual and/or mathematical description is used to describe/represent the structures that exist in the observations. If enough observations are present, if the noise in the observations is not too large, and if the structure is sufficiently strong and unchanging (i.e. consistent co-variation among the variables actually exists, and is not strongly dependent on non-observed variables, at the space-time scale of interest), then these compact descriptions will represent any relevant structure in the data and therefore most likely describe the general laws that can be deduced from the observations. These descriptions will then allow the transfer of relevant information contained within those observations, to other, *sufficiently similar* situations, thereby allowing the values of unobserved quantities to be predicted and decisions to be made regarding our interactions with the real system.

4.4.1 Representing information and its role in the reduction of uncertainty

~~Although important foundations were laid earlier, the birth of Information theory is mainly attributed to the seminal paper by Shannon (1948), who defined *information* and *uncertainty* as quantities that can be represented in terms of discrete values known, for example, as bits (binary integers).~~ According to Shannon (1948), uncertainty or missing information is viewed as being connected to the process of *'choice'* (decision making) and is represented in terms of the probabilities associated with different possible outcomes of an event. For events that can take on a discrete number 'n' of possible outcomes (i=1,…n), the measure for uncertainty, called information entropy (H), is defined as the expected value of the negative log-probability $-log_b P(i)$ of those outcomes, given as (there is also an analogous definition for continuous variables):

$$H = E\{-log_b P(i)\} = \sum_{i=1}^{n} -log_b P(i) \cdot P(i) \qquad (1)$$

Since anything that contributes to our knowledge/understanding about the value of an event can be thought of contributing to a change in our prior state of uncertainty (expressed in terms of a distribution of probabilities) about the value of that event, a gain in information can be defined as a change in uncertainty (Cover and Thomas, 2006). Alternatively, when observing an event, the gain in information can be equated to the *'surprisal'* caused (i.e., the extent to which the new observation is unexpected, ~~or changes our expectation about the value of the event~~), which was defined by Shannon to be $-\log_b P(i)$, where b can be chosen in some convenient fashion. Therefore, the entropy (H) can be interpreted as the *'expected surprise'* about the true outcome.

In a more general sense, the probabilities referred to above can be thought of as reflecting states of knowledge (instead of just representing frequencies of occurrence), and we can adopt a more general (Bayesian) view in which probability distributions are used to represent (incomplete) information, and in which the axioms of probability function as the rules for logical reasoning (Jaynes, 2003). In general, it is important to recognize that misinformation can ~~be wrong (i.e., bad) in the sense that it can~~ result in an incorrect inference about the true outcome, or the correct inference for the wrong reasons (Kirchner, 2006; Gupta et al., 2008; Nearing et al. 2013a, b) and that information can also be misapplied (e.g. through misapplications or imperfections in the applications of Bayes Law). Further, information content of a data set depends on the question being asked, and hence it is not just information we care about, but the usefulness and usage of the information.

4.4.2 Applying concepts of information theory to catchment hydrology - potential and limitations

Information theory provides a formal framework for linking observations, laws, models, and computerized algorithms. It therefore has the potential to play an important part in a theory of evaluation (Gupta et al. 1998, 2008, 2012) that facilitates a robust investigation and improvement of model performance (Gong et al., 2013), and in the evaluation of models of different degrees of complexity as in the case of multiple working hypotheses (Solomonoff, 1964; Clark et al., 2011). Information theory also can provide a framework to optimize strategies of data collection (Alfonso et al., 2010; Mishra and Coulibaly, 2010; Li et al., 2012, Gupta et al., 2013a) and data assimilation (Nearing, 2013; Nearing et al. 2013a, b) in catchment hydrology. As information and uncertainty are closely linked (see Sect. 4.4.1), this framework is also potentially suited for quantification and minimization of uncertainty associated with decisions, e.g. in water resources management (Weijs et al., 2010) or choices of model structure (Nearing, 2013; Gong et al., 2013).

When applying information theory in practice, however, we should keep in mind that information theoretical quantities depend on probabilities, which in turn depend on states of (prior) knowledge. So results will depend importantly on our prior knowledge and how we choose to formalize it, which adds subjectivity and non-uniqueness to the processes of evaluation and prediction. For example, a time series of perfectly measured discharge contains, N*H(Q) bits of information for specifying what the discharge is at every time step, where N is the length of the time series and H(Q) is the entropy of the suitably (subjectively depending on the question asked) binned discrete distribution (histogram) of Q, but this assumes knowledge of the frequency distribution and no knowledge of or learning from temporal dependencies. When taking these dependencies into account, the information content is equal to the joint entropy of the entire series, and the frequency-based approach breaks down, since the joint entropy depends on an N-dimensional histogram with one observation. Alternatively, the joint entropy can be approximated by the conditional entropy of Q_t, given $Q_{t-L}\ldots Q_{t-1}$. This last quantity involves a model for predicting Q from its previous L time steps, with the model structure assumed to be known (e.g. Gong et al., 2013). Models of different complexity will give different answers. If the models are not known a priori, but inferred from the data, the model description length in bits should be added to the information content (Weijs et al. 2013a). Finally, in the hypothetical case that meteorological conditions and all hydrological processes are already perfectly known, the information content of the discharge series becomes zero, because the perfectly predictable values no longer contain any surprise. In other words, the goal of prediction is to make information from ex-post observations of the predicted variable as redundant as possible.

To summarize, applying concepts of information theory to catchment hydrology does not eliminate subjectivity associated with the way we treat prior knowledge, but it forces us to be more explicit about it and about the way it affects our predictions and decisions.

5 Summary and conclusions

We started from the observation that the hydrological cycle is increasingly affected by changes, which extend from local to global scale, act on short to decadal time scales and affect all characteristics of water-related dynamics. Humans play a double role in this, as they cause many of these changes and are at the same time concerned by them, thus demanding answers regarding the hydrological effects of global change. These changes potentially push hydrological systems out of the quasi-steady states they have reached through long-term co-evolution of their constituents, giving rise to the interplay of feedback effects which determine the systems path towards new stable states. Hydrological concepts developed under in many aspects stationary conditions may not capture all the mechanisms that are relevant under transient conditions.

Therefore, the main focus we have pursued in this article was to present and discuss paradigms and theories which we consider helpful to advance hydrology towards understanding and predicting hydrological systems under change. To this end, we started with a discussion of the general nature of explanation in hydrology, which is characterized by considerable pluralism stemming from different explanation types, the interdisciplinary nature of hydrology and underdetermination.

We continued by discussing the special characteristics of catchments, namely straightforward closure of the water balance due to convergence and existence of distinctly separate process scales for water flow and structure formation. Both have favoured development of simple, but successful sectoral hydrological models based on the assumption of stationarity, linear concepts and limited availability of observations. From this, we proposed several perspectives on catchments to deal with transient conditions (an overview is shown in Fig. 3): treating catchments as complex dynamical systems offers ways to classify them (Table 1) and to assess their stability, resilience and predictability. Looking at catchments from the point of view of the related field of synergetics highlights the occurrence of self-organization and emergence of macro-scale structures (spatial, temporal or functional). The advantage of exploiting such phenomena is that it greatly reduces the systems' degrees of freedom to the number of order parameters, making predictions a more straightforward task. It can also help to explain the apparent similarity of many catchments.

The next viewpoint we adopted is that of catchments as co-evolving systems, focusing on the mutual historical evolution of catchment constituents, and learning from analysis of the similarities and dissimilarities of catchments that started from presumably similar conditions in the past (Fig. 3). This is closely related to the analysis of catchment similarities, and both can help to provide constraints on parameters of predictive models and to transfer information among catchments in 'space-for-time' trading approaches.

The thermodynamic view of catchments focuses on stocks, fluxes, conversions and dissipation of energy. Treating catchments as open dissipative thermodynamic systems far from equilibrium offers a framework which explains both the fundamental tendency towards degradation of structure, but also the preconditions for its build-up, whose interplay plays an important role in the evolution of hydrological systems over time. The benefit of expressing dynamics in the universal 'currency' of energy is that it provides a link between any kind of process, be it abiotic, biotic, or anthropogenic. Also, optimality principles formulated in the fundamental terms of energy and entropy can potentially be applied to direct the development and prediction of new stable states of systems under change.

Then we took the perspective of information theory, which offers an alternative view on the nature of explanation (as data compression) and a general framework for the evaluation of information content (expressed in terms of the change in uncertainty about a target quantity of interest), across data, laws, and models. This makes it potentially a useful part in a theory of evaluation that facilitates critical assessment and improvement of predictive models.

In their article on the nature of explanation in the earth sciences, Kleinhans et al. (2005) conclude that the best way to overcome underdetermination is a combination of historical actual-sequence explanations, robust process explanations and causal explanations in the form of laws. We adopt this view for hydrological systems, and especially hydrological systems under change, which is reflected in the previously proposed perspectives on catchments (see Fig. 3): Analysing catchment co-evolution provides insight into the historical development of actual catchments and potentially robust process explanations of the underlying mechanisms. Applying the methods of complex system analysis to catchments under change can provide general statements on predictability, and allows linkage of existing scale-specific hydrological laws, when seen as manifestations of emergent phenomena on different macroscopic scales. Expressing dynamics on the basis of the universal laws of thermodynamics facilitates linking all the processes involved in the hydrological cycle and allows formulation of constraints to its dynamics. Finally, the information-theoretic view is both helpful as a common framework for the many modeling approaches in hydrology, and has links to the self-organisation of systems (Kumar and Ruddell, 2010).

The approaches we presented to deal with catchments under change are based on established theories. Nevertheless we suggest that they deserve closer attention and that their synergistic combination can, in combination with recent advances in observation technologies and in storing and sharing data (e.g. Hrachowitz et al., 2010 and references therein; OGC, 2012; Overeem et al., 2013; Selker et al., 2006; Schmelzbach et al., 2012), advance catchment hydrology to address questions of change.

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Table 1. Classification of dynamical systems (simplified from Strogatz, 1994, p. 10, Fig. 1.3.1).

	Number of variables				
	n = 1	n = 2	n ≥3	n >> 1	Continuum
Linear	*Growth and Decay* Radioactive decay	*Oscillations* 2-body problem		*Collective phenomena* Solid-state physics Equilibrium statistical mechanics	*Waves and patterns* Heat and diffusion Viscous fluids
			Chaos		*Spatio-temporal complexity*
Nonlinear	Fixed points Bifurcations Overdamped system Logistic equations	Pendulum Anharmonic oscillators Predator-prey cycles	Strange attractors 3-body problem Fractals Forced nonlinear oscillation	Lasers Nonequilibrium statistical mechanics Nonlinear solid-state physics Ecosystems	Nonlinear waves Turbulent fluids (Navier-Stokes) Reaction-diffusion, biological and chemical waves

Table 2. List of definitions (alphabetical order)

Co-evolution: Joint evolution (see also 'evolution') of several interacting components (abiotic and/or biotic) of a system. Biological co-evolution is the joint biological evolution of two species connected by conflicts or cooperation.

Evolution: In this article we adopt the general meaning of evolution as gradual development of something. This can include the special case of biological evolution, which is characterized by natural selection leading to adaptation, speciation, divergence or extinction of species on the basis of inheritance, random mutation and recombination of genetic information.

Forecast: Quantitative prediction for a given location at a specified future time.

Non-steady state: No change of structure over time, but state variables and fluxes (within the system and across its borders) do change.

Paradigm: Worldview or code of practice commonly accepted in a scientific field at a given time. It guides both the kind of questions (experiments, observations) that are being asked in a scientific field as well as the way the results are interpreted (e.g. Kuhn, 1970). It can include several scientific theories.

Prediction: Approximating an unknown state of a system with full, partial or no knowledge of initial and boundary conditions. In statistical terms it is the approximation of the actual but unknown realization of a stochastic variable.

Projection: Prediction of a possible future state of a system under certain assumptions (e.g. assumption of an emission scenario in climate projections). A projection hence cannot be associated with an occurrence probability.

Quasi-steady state: Steady state for long (aggregation) time scales (steady state of long-term mean states and fluxes), but non-steady state for shorter time scales. See also 'steady state'.

Scientific law: Statements on causal relations among its constituents, exceptionless and irreducible within its scope (system, scale, boundary conditions). Laws are based on empirical evidence, can often be expressed by mathematical equations and hence be used in computer models.

Scientific theory: Explanation of some aspect of the natural world, established by following the scientific method and confirmed by observation and experiment (empirical evidence). A theory has explanatory and predictive power; its strength is related to the parsimony of its principles, the diversity of phenomena it can explain and the quality of its falsifiable predictions (e.g. Popper, 2002). It can contain several scientific laws.

Stationary state: In this text used interchangeably with steady state. In statistical terms: The underlying distribution of a random variable does not change with time.

Steady state: No change of structure, states and net fluxes (within the system and across its borders) over time, at least one flux is non-zero. See also 'quasi-steady state' and 'stationary state'.

Structure:

General: Any non-random deviation from a mean (spatial and/or temporal).

Hydrological modeling: Any time-invariant system characteristic.

Algorithmic Information Theory: Structure in data allows compression without loss of

information. Thermodynamics: A thermodynamic potential gradient.
Thermodynamic equilibrium (TE): No change of structure, states and fluxes (within the system and across its borders) over time, all fluxes are zero.
Transient state: State of a system that undergoes structural changes over time.

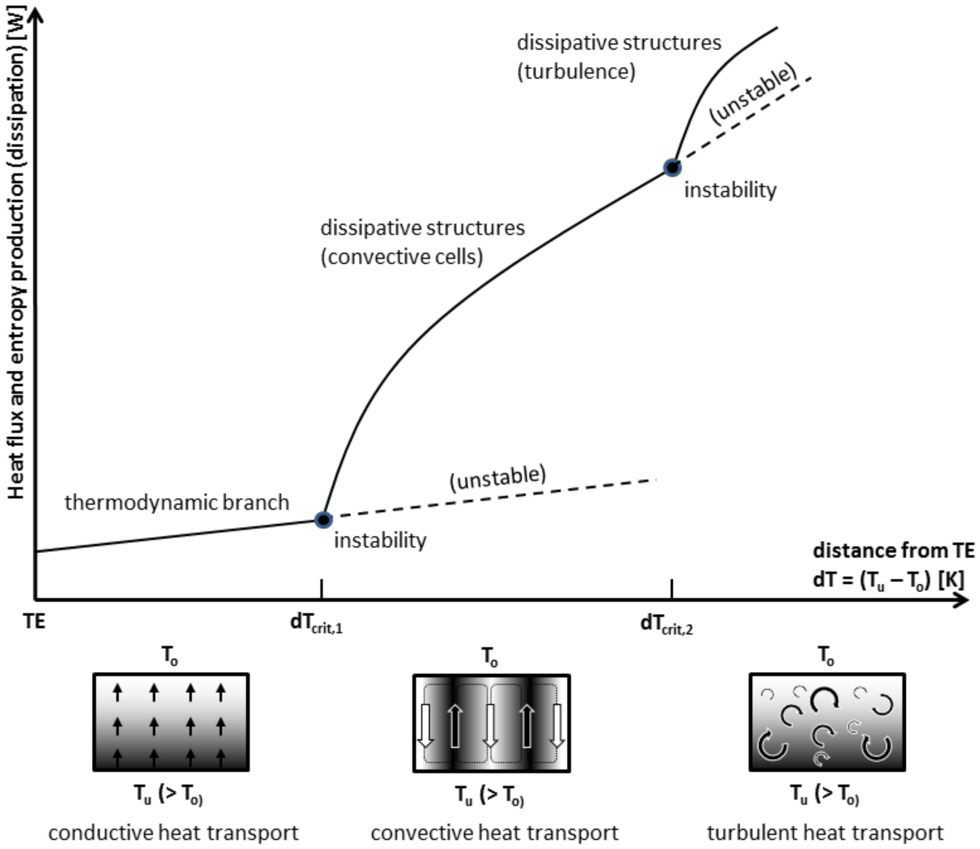

Fig. 1. Highly simplified sketch of steady state heat transport and entropy production (dissipation) in a reservoir heated at the bottom, as a function of distance from thermodynamic equilibrium (TE). The distance from TE is expressed by the temperature difference between bottom and top. Beyond a critical distance from TE, self-organisation creates macroscopic structure (convective cells, turbulence), accelerating the heat flux from bottom to top.

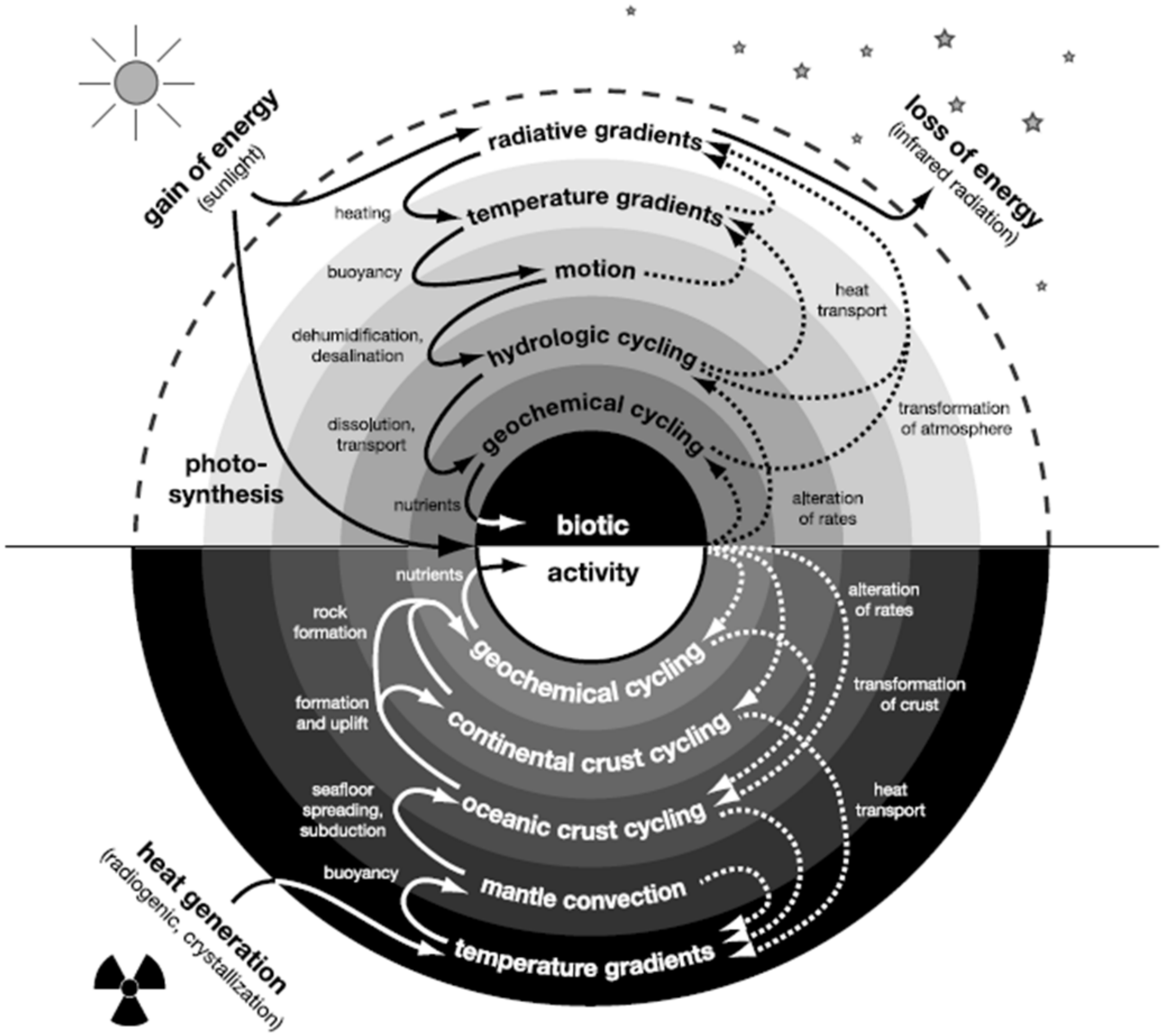

Fig. 2. Simplified summary of a hierarchy of power transfer among Earth system processes. Solid arrows describe flows of energy, while dotted arrows describe effects. From Kleidon (2010).

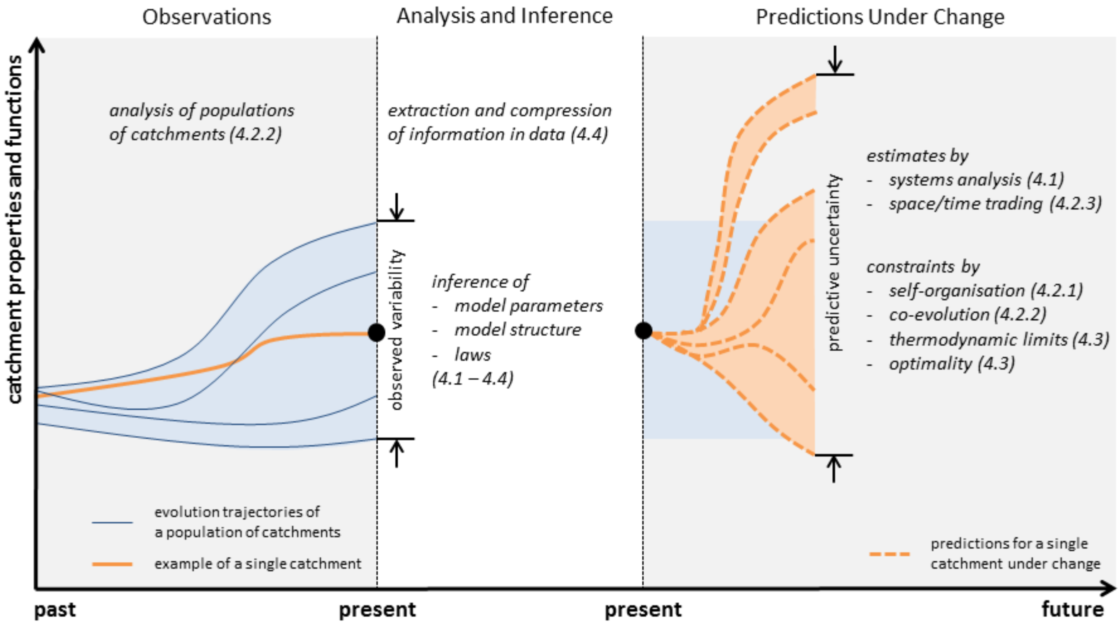

Fig. 3. Overview and connection of the paradigms discussed in the paper to improve hydrological predictions under change.