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Climate change impacts—throwing the dice?

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> **“I, at any rate, am convinced that He does not throw dice”**
> **Albert Einstein in a letter to Max Born (December 4, 1926)**

Introduction

Although Einstein was referring to quantum mechanics in this statement rather than to hydrology, one sometimes does wonder whether we are throwing the dice in hydrological analyses. When two experts estimate the 100-year flood in a small ungauged catchment, chances are that their estimates are very different. When two groups predict the effects of future hydrological changes on stream flow and recharge for the same catchment, the results will hardly be consistent. Yet, climate change impact analyses have become a standard method in our tool box for addressing issues that seem to be of overwhelming concern to the society today. In this paper, we argue that impact studies often tend to be overly optimistic about the reliability of their predictions, and overly pessimistic about the effects on society. Just as a medical doctor who, when in doubt, would say that his patient is going to die—to be on the safe side. We will contrast this assessment with our views on the current state of change prediction, and outline the opportunities in this exciting field of hydrologic research.

Climate is Changing—Evidences of Changes in the Past

Air temperature-related variables

Air temperature and precipitation are the two climatic variables that are most relevant to hydrologic predictions. When examining climate records it is clear that there have been tremendous changes in temperatures. These changes have occurred over a multitude of scales and have affected diverse hydrological characteristics such as glacier extension, sea levels, the seasonality of snow melting and river flow regime. Glacier changes are probably the most visible consequence of changes in the air temperature. With the current retreat of glaciers it is important to remember that only a part of it can be attributed to human effects, as there have been numerous glacier retreats in the past. For example, there are witnesses that people were crossing the Theodul pass, Northern Italy, in summer without touching snow in the 15th century while one has to walk over a glacier now.

The presence of cycles over a multitude of scales is indeed remarkable. Known as the *Hurst effect*, after the British hydrologist H.E. Hurst who discovered it when analysing series of the Nile River flows, the presence of very long cycles can be very well represented by statistical methods (Hurst *et al.*, 1951; Koutsoyiannis, 2002; Montanari, 2003). From the perspective of impact analysis, there are two important implications from the Hurst effect. First, it puts limits to interpreting trends in the data, as a long cycle may just look like a trend, and provides a theoretical basis why these trends should not be extrapolated into the future (Cohn and Lins, 2005). Second, given that the observed data exhibit short- and long-term cycles one would also like to see them in model results.

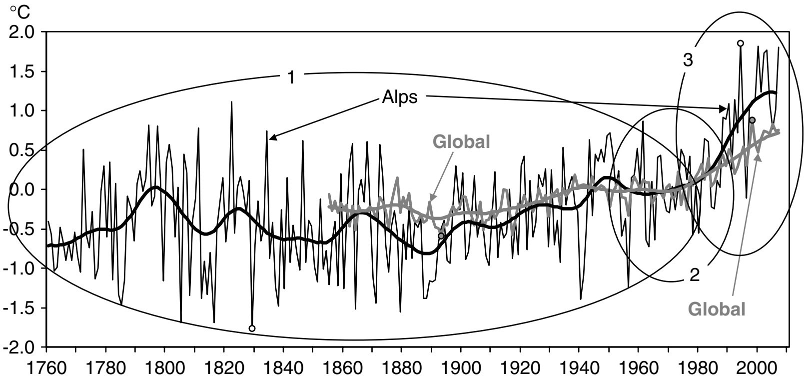

Figure 1. Measured average annual air temperatures in the European Alps 1760–2007 (black line) and global mean 1858–2007 (grey). Shown are the anomalies relative to the mean of the 20th century as well as smoothed values (thick lines). 1: natural period—solar and volcanic influences dominant; 2: first apparent human effects—aerosols; 3: green house gas effects. From Böhm (2008)

Interpreting temperature changes in the past is more difficult than to describe them statistically. Clearly, the main drivers are sun activity, volcanic activity, and more recently aerosols and greenhouse gases. For the European Alps, Figure 1 illustrates that, up to the 1950s, natural forcings (solar and volcanic influences) were dominant. In the 1960s and 1970s cooling due to anthropogenic aerosols is considered an important control while in the following decades the effect of green house gases seems to have taken over (Böhm, 2008). Depending on the region, the magnitudes of the temperature changes differ. As indicated in Figure 1, the anomalies in the European Alps have been about twice those of the global mean over the world, so direct hydrological effects, in particular, on snow and ice, will be much larger than in other regions. Why, exactly, the Alps should have larger temperature fluctuations has, however, not been explained satisfactorily (Böhm, 2008). Also, the stagnation of mean global air temperatures over the past decade (Kerr, 2009) is a subject of much speculation. Notwithstanding these doubts, recent air temperature changes are very real. For hydrologic impact analyses this means that those variables that are mainly controlled by air temperature such as snow melt, stream temperature, ground water temperature and low flows (through evaporation) may also have changed. And this is a real change.

Rainfall-related variables—floods

Similar to air temperature, consistent trends in mean annual precipitation have been observed, e.g. an upward trend in the North and a downward trend in the South of Europe. However, for shorter time scales, the evidence is quite conflicting. Alexander *et al.* (2006) found a slightly increasing trend of extreme precipitation contributions to annual precipitation (of 0·41% per decade during 1979–2003) using a global data set but other studies found increasing and decreasing trends depending on the region (Trenberth *et al.*, 2007, p. 302). The main problem with trend analyses of extreme precipitation is that it is very difficult to ensure high data quality. Floods are much easier to observe but, again, trend analyses are not usually conclusive (Kundzewicz *et al.*, 2005, 2007). It seems that extreme rainfall and floods do not follow a spatially consistent tendency. Why is this so?

Part of the problem is related to the fact that rainfall and river flows, typically, are highly non-linear with an asymmetric probability distribution, while temperatures are more linear and Gaussian. This feature makes rainfall and river flows less predictable (Blöschl and Zehe, 2005). Moreover, changing climatic conditions have different effects on the weather and the hydrology, depending on local features like the orography, the geomorphology and the soils of the catchment. Dependence on local conditions is a distinguishing feature of hydrology that can make the effect of climate change less predictable and diversified, in particular, if the Hurst effect comes into play. There have always been periods with above average flood activity. For example, during the 16th and 17th century, 10 floods per century occurred in the Tiber River, including the disaster of the year 1598 with more than 100 casualties in Rome. In the 18th and 19th centuries, however, there were only three floods (Calenda *et al.*, 2005). The Hurst effect exacerbates the dependence of the interpretation of a flood record on the available time window. This is illustrated in Figure 2. The top panel shows the maximum annual floods of the Danube at Vienna for a period of 73 years. If one only examines this panel, the data suggest that there is an increasing trend of floods as five of the six largest floods that have occurred at the end of the series. However, the series shown in the top panel relates to the years 1828–1900, so this will hardy be a human-induced climate effect. The lower panel shows the full series, indicating that the trend at the end of the late 19th century cannot be extrapolated as the first half of the 20th century did not have any large floods.

There may also be a sociological element to the interpretation of flood trends which we term as the *hydrologist's paradox*: A recent large flood in

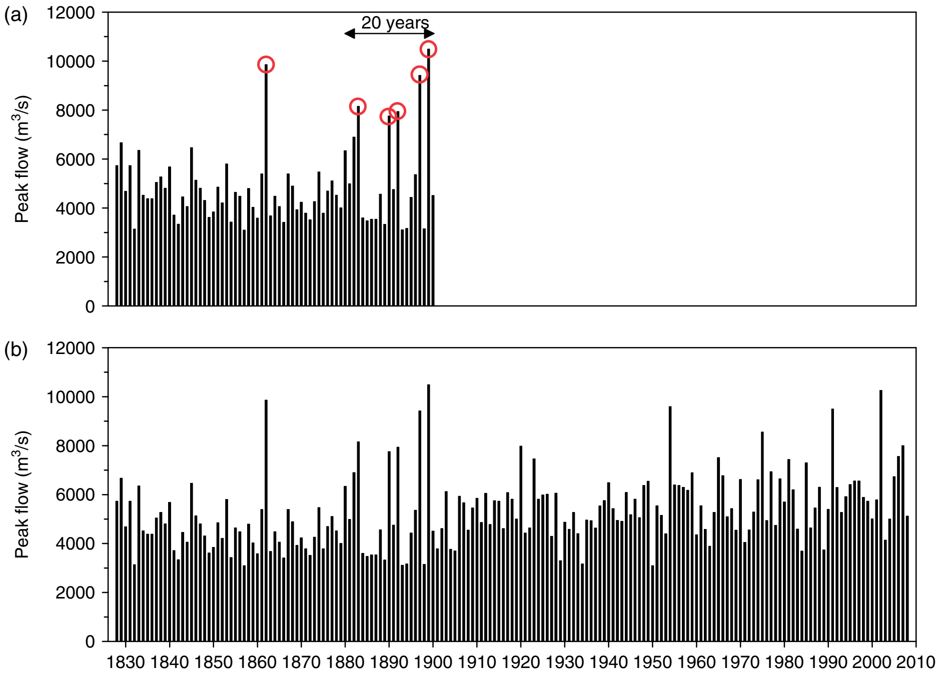

Figure 2. (a) Annual maximum floods of the Danube at Vienna for 73 years (100 000 km^2 catchment area). Five of the six largest floods have occurred in the last two decades. (b) Entire record 1828–2008. Redrawn from Blöschl and Merz (2008)

a catchment will often lead to funding a study on the flood history of that catchment which will find there was a large flood at the end of the record. Simultaneously analysing many catchments in a large region will help reduce the chances of these self-fulfilling prophesies.

Climate is Changing. Future Changes—Soft and Hard Facts

While past changes are usually assessed by analysing time series of hydrological data, possible future changes are typically explored by climate change scenarios. The general concept is straightforward: (i) choose one or more of the climate change scenarios of the International Panel on Climate Change (IPCC) report (see Meehl *et al.* (2007)) depending on the future economy, and depending on the Global Circulation Model (GCM); (ii) downscale the GCM output to the scale of the catchment of interest (Blöschl, 2005); (iii) run a hydrological model using the downscaled GCM output as an input; (iv) compare the model simulations for the current and the scenario climates, leaving everything else unchanged. The appealing thing with the procedure is that it will always give a result, for whatever part of the hydrological cycle. The simulations will give changes in floods, low flows, groundwater recharge, and whatever else is requested. The question here, however, is the confidence we can have in these simulations.

Climate projections for hydrology

Each step in the above simulation procedure will introduce its share of uncertainty. Changes in air temperatures are generally considered a robust result, although the IPCC models have predicted an increase in global air temperatures over the past decade of about 0·2 °C on average (see Figure 10·5 in Meehl *et al.*, 2007) while the most recent data show that the temperatures have not changed or even slightly decreased (Kerr, 2009). Decadal Hurst-like oscillations due to feedback effects seem to be the norm in climate but, apparently, are not well captured by the GCMs. Still, similar to the past, future air temperature changes can be considered a hard fact. We hence can have reasonable confidence in predicting hydrological changes that are mainly driven by air temperature. Precipitation is different. For example, Covey *et al.* (2003) suggested that none of the 18 GCMs they analysed produced precipitation simulations consistent with observations (also see Koutsoyiannis *et al.* (2008)). The uncertainty tends to increase as one goes down in scale and as one moves to more extreme events (Blöschl *et al.*, 2007; Böhm, 2008). We hence consider future changes in the mean precipitation at the continental scale as soft facts while changes in extreme precipitation are really speculative. When one zooms in to a single catchment the uncertainty of rainfall-related future changes increases even further. This means that we cannot have much confidence in any simulations of rainfall-driven floods in a changed climate. There are elements of throwing the dice.

Generally, the term *projections* is used instead of “forecasts” to soften the statement. The term *projections* implies that there are a number of possible futures, rather than one best guess as in a forecast. However, this terminology is not particularly helpful as, in most hydrological impact analyses, climate projections are used in exactly the same way as forecasts. Climate modellers are currently making a major effort to reduce and assess this uncertainty. This is usually done by ensemble runs that identify a range of possible GCM outputs (Murphy *et al.*, 2007). However, from a statistical perspective these ensemble runs may be less informative than generally thought, as the likelihood of each of the ensemble runs is not generally calculated the way it is defined (Rougier, 2007). The likelihood should be calculated from the difference between simulations and observed data but since observed data are not available for the future climate, differences between many simulations of different models are used, as Murphy *et al.* (2007, p. 2011) noted: 'the specification of [climate model] discrepancy is ..... based on the judgement that relationships between model errors for different climate variables can reasonably be expected to follow relationships between inter-model differences for different variables'. It follows that one would underestimate the error if the models were all producing a comparable, but nevertheless biased, output. It is like throwing a loaded dice: one would get a higher frequency of, say, fours and would make an erroneous estimate for the outcome of an unbiased dice. Perhaps, hydrology has something to offer here to assist in the uncertainty assessment of climate projections, as hydrology has a long track record of estimating uncertainty (Koutsoyiannis *et al.*, 2009).

Hydrological modelling of change

GCM structure may often be the largest source of uncertainty for simulated river flows, followed by emission scenarios and, finally, hydrological modelling as suggested by Kay *et al.* (2006) for two UK catchments. This is hardly surprising as GCM results of future climate cannot be validated against data in the same way as hydrological models (for current conditions) can, for instance, by split sample exercises. But it is still worth worrying about the hydrological part, as calibration to past data may not be very relevant to the future, and biases may be large without calibration. One often tries to minimize calibration to the past and instead use more complex models that better represent the underlying physical processes (Bergström, 1991). But the physically based hydrological model may become a paradox—the model is made more complex to better describe the process dynamics but parameter values may not be representative of the underlying processes and therefore the model goes back to the status of a black box model, but with a larger number of parameters and therefore increased uncertainty (Beven, 1989).

We recently talked to the coordinator of a multimillion Euro impact project for a major European river basin. On the basis of the standard procedure above and a very complex hydrological model, they had found that floods were increasing by 10%. We then asked what they thought was the reason for this—changed weather patterns, larger number of convective storms or a change in antecedent soil moisture. He shrugged the shoulders. 'It just came out of the model.' Honestly, without understanding the *reasons* for the changes, the results of impact studies are of little value to us. Maybe simpler models that capture the most important processes, instead of modelling everything, give more insight—something that has been termed the dominant processes concept by Grayson and Blöschl (2000).

There are indeed limits to the level of process detail that can be modelled accurately at the catchment scale, and these limits are perhaps narrower than what is usually thought. This is illustrated by data from sprinkling experiments in Figure 3. The plots were irrigated with constant rainfall intensity until equilibrium and surface runoff was measured. The ratio of surface runoff (at equilibrium) and rainfall intensity then is the runoff coefficient which does not depend on initial soil moisture. The experiments were performed twice at the same sites, the first time in spring and the second time in late summer or autumn. For most of the sites the summer and autumn runoff coefficients are much larger than the spring ones, in some instances by a factor of 10. The sites are on pastures with cattle grazing during summer which leads to soil compaction and increased runoff. During winter, earth worms and other animal activities increase the soil permeability, and another cycle of soil compaction follows. A detailed process model would have to model the cattle activity (with data on the number of heads per unit area) and earth worm activity. Clearly, we cannot hope to reduce all uncertainty by including more detail into the models.

Therefore the hydrological modeller is forced to seek a balance between model complexity and uncertainty, with the awareness that simplified (empirical) approaches cannot explicitly model processes like the

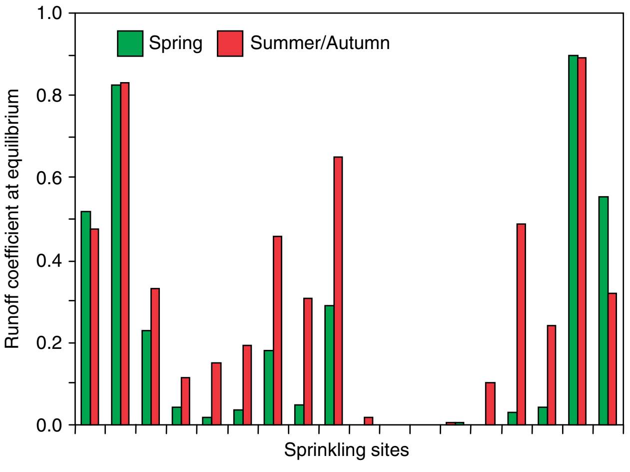

Figure 3. Results of sprinkling experiments in the Austrian Alps. The larger runoff coefficients in summer and autumn are due to soil compaction by cattle. Redrawn from Kohl and Markart (2002), BFW

energy fluxes between the soil and the atmosphere, animal activity, and microbial activity in soil formation. In any case, it is important to recognize that there will always be limits to the predictability of hydrological response (Blöschl and Zehe, 2005). Errors of 100% in the simulation of high flows and 1000% for low flows are not uncommon. Yet, uncertain information is definitely more useful than a wrong certainty. Indeed, we often deal with uncertainty in every day life, and very efficiently too. Even if we do not know the exact outcome of throwing a dice, knowledge of its probability can be very useful. The question then is how to best profit from an uncertain prediction.

Where to Go from Here?

Are hydrological impact studies of climate change just like throwing a dice? Despite the limitations of hydrological impact studies noted earlier, perhaps, the future is not so bleak. We think there are some elements where impact studies do resemble the throwing of a dice, and others where they do not. In any case, uncertainty is an attribute of information and therefore does not mean lack of knowledge. So what would be the way forward to an improved assessment of the future of water resources?

We believe it is first of all necessary to improve our knowledge of the connections among climate, weather and hydrology under the current climate. An interdisciplinary effort is needed here, because joining different backgrounds is a prerequisite for any significant progress in geosciences. For instance, a better understanding of groundwater recharge is a key issue in assessing freshwater resources, yet we are barely able to model it now. There is now an increased awareness that hydrology not only has to deal with physics. While in the 1980s the term *physically based models* seemed to encompass all the processes that needed to be modelled, chemical and biological processes can also be very important, even if one is only concerned with water quantity. For example, chemical processes control soil hydrophobicity, while biological processes not only control evaporation but also flow processes in the soil. There is a new generation of hydrological models based on large scale optimality principles that take these interactions into account in a holistic way by considering the coevolution of soils, vegetation and climate, and by treating the catchment as an open thermodynamic system across a wide range of time scales (Schymanski *et al.*, 2009; Zehe *et al.*, 2009). Similarly, there is a new generation of measurement methods available that allow us to infer patterns of the hydrological dynamics such as new remote sensing methods (Winsemius *et al.*, 2006), new precipitation measurements by microwave links (Berne and Uijlenhoet, 2007), distributed temperature sensing (Westhoff *et al.*, 2007), and distributed soil moisture sensing (Western *et al.*, 2004). These are neither impact studies nor adaptation measures but we believe they can vastly contribute to understanding the current system, from which impact studies will also benefit.

A better understanding of the hydrological processes should not necessarily translate into more complex models used in impact studies. Putting more detail in the models may not always help because a significant part of the uncertainty could stem from the variability of the underlying natural process rather than from incomplete knowledge about the process under study (Montanari *et al.*, 2009). Holistic models based on large scale optimality principles are one way to avoid excesses complexity. An alternative is the Dominant Processes Concept of Grayson and Blöschl (2000) that focuses on a set of the most important processes in a particular context rather than on modelling everything. There is not only the advantage of reduced model uncertainty due to fewer parameters; there is also the advantage that the processes modelled can be more readily understood by the modeller. Unless we understand *why* an impact study predicts changes in a given hydrological variable we cannot trust that the results are valid. How one can focus on flood processes rather than the flood magnitudes has been illustrated by Merz and Blöschl (2003) and Sivapalan *et al.* (2005). Perhaps a code of best practice for climate impact modelling would be useful. The main idea of the code would be to require that, apart from presenting the assumptions and the results, the impact study should explain *why* certain changes are predicted. This would help increase confidence of the scientific community and the general public in these types of studies.

Along the lines of enhancing the trustworthiness of impact studies, we believe there is also a need for better uncertainty estimation. While reducing the uncertainty in data and models obviously contributes to more reliable predictions (Di Baldassarre and Montanari, 2009), it is equally important to better understand just how uncertain these predictions are. The predictions in ungauged basins (PUB) decade (Sivapalan *et al.*, 2003) has dramatically raised the profile of uncertainty in runoff predictions from something perceived as a deficiency of the modeller to a subject worthy of study. Sivapalan (2009) argues that fossilized models and uncertainty tools are a deadly cocktail. We could not agree more. What are needed are uncertainty tools that account for the hydrological processes rather than simply throwing the dice. There is room for improving uncertainty estimation in hydrology that combines process-based models with statistical or fuzzy set models, thus embedding uncertainty estimation. For instance, Merz and Blöschl (2008a,b) have recently introduced the notion of 'flood frequency hydrology' to go beyond the traditional purely statistical treatment of the extreme value problem. In a similar way, Koutsoyiannis (2009) proposed to use stochastic and deterministic hydrological models to jointly carry out prediction and uncertainty estimation. This would also be a very valuable research subject for climate projections and impact studies. In doing this, both hydrologists and climate modellers need to effectively communicate uncertainty to end users. A formal and clear terminology is needed to make clear what we mean by uncertainty (Apel *et al.*, 2004; Montanari, 2007). In particular, the difference between sensitivity analysis (intercomparison among models) and uncertainty estimation (comparison with observations) should be stated. Equally important, it must be clear how uncertainty estimates, when available, will be used. Even for a comparatively simple subject such as design flood estimation, the use of uncertainty bounds in the hydraulic design can be difficult if there is no full understanding of the meaning of uncertainty. Given that hydrological change does occur, it would perhaps also be useful to always state the reference period on which design floods and other hydrological estimates are based.

Communication should also ensure that a balanced view of hydrological change is provided by the hydrological community with an emphasis on both positive and negative effects. We are sometimes amazed that our first year students seem to know all about climate change and its detrimental effects on floods. Clearly the media play a key role here. It is understandable that it is more interesting to convey a dramatic message rather than to say 'Sorry, there is very little evidence that floods have increased but it is possible'. Showing photos of past floods in a newspaper article on climate change increases the urgency of the message, but we believe that, in the long term, a more careful—and honest—treatment of the subject is wise. As Böhm (2008) puts it, there are hard and soft facts on climate change and, in some instances, there is no evidence at all. Changes in processes that are directly related to air temperature (such as snow melt) tend to be hard facts, while those related to precipitation tend to be soft facts. The further we move away from mean values to extremes the thinner the ice gets. Clearly, the more subtle treatment of climate change impacts will have implications for water management.

Impact studies are such a timely issue in hydrology today because climate adaptation is high on the political agenda in many countries. It is a bit like a child who gets a new toy and forgets about all the other play things. However, it is important to realize that, whatever is the setting, climate adaptation is just one of many water management goals. While water managers are surely aware of this, apparently, not all scientists are. For example Kundzewicz *et al.* (2008, p. 7) note that 'Adaptation to climate change should also include reduction of the multiple non-climate-related pressures on freshwater resources (such as water pollution and high water withdrawals) as well as improvement of water supply and sanitation in developing countries', which is somewhat like the tail wagging the dog or as if one said that coffee should include dinner. Shrinking glaciers may cause serious water supply problems for Lima and sea level rise may increase flood risk in Bangladesh (Kundzewicz *et al.*, 2008). However, there are many areas where other water management issues dominate. Often, water abstractions provide impacts that are orders of magnitude larger than projected climate impacts (Falkenmark and Lannerstad, 2005) and land subsidence in coastal areas of southeast Asia due to groundwater pumping can be orders of magnitude larger than projected sea level rises (Taniguchi *et al.*, 2009). Notwithstanding the importance of climate adaptation measures, these need to be put into the perspective of all the other water management goals.

Improving the understanding of hydrological processes under the current climate, focusing on *why* impact studies predict changes rather than on the magnitudes of the change, improving hydrologically driven uncertainty methods, being more transparent about what we can and cannot predict and being realistic about the role of adaptation measures in the context of water management, we believe, are the cornerstones of more successful climate impact studies. We are truly optimistic that hydrologists will make progress in this important and exciting area of hydrology in order to go beyond the simple throwing of dice.

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