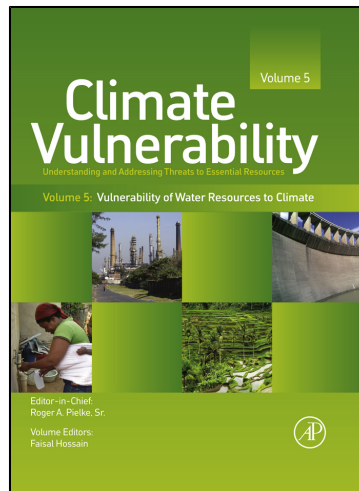


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5.01 Emerging Approaches to Hydrological Risk Management in a Changing World

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5.01.1	Unexpected Events and Risk Management	3
5.01.2	Elements of Integrated Hydrological Risk Management	3
5.01.3	Top-Down (Economic) Approach to Risk Assessment Based on Probabilities	5
5.01.4	Bottom-Up (Social) Approach to Risk Assessment Based on Possibilities	6
5.01.5	Accounting for Black Swan Events	7
5.01.6	Conclusions	9
	Acknowledgments	9
	References	9

5.01.1 Unexpected Events and Risk Management

7 August 1994. The township of Tirlyan in the Republic of Bashkortostan, Russia. The dam operators are at the verge of panicking. There had been major rainfalls on the previous days and the water level of the Tirlyan reservoir had been increasing steadily during the day. While the dam was relatively small with 10 m height, the volume was 8.6 million cubic meters and posed considerable danger for the downstream villages of Tirlyan, Avzalovo, Kazylarovo, and Alakagovo. One of the segment gates had been blocked years before because of concerns about sabotage, and the operators were hectically attempting to release the gate. No way that the remaining gates would be able to cope with the floodwaters. 16:20. The gate is still blocked and the water levels have reached the top of the dam – an earth fill dam constructed in 1917. Villagers have flocked to the banks of the Belaja river downstream of the dam to watch the spectacle. Minutes later, the water of the reservoir starts to overtop the dam. A breach forms and a wide section of the dam gives way. The flood wave spills over the downstream plain and gets hold of dozens of bystanders. The spectacle had turned into a disaster. Many people can be saved, but the flood takes its death toll among the villagers (Moscow News, 19 August 1994).

Avoiding events like this is one of the main purposes of hydrological risk management. In hindsight, the cause of the failure was almost trivial. With a little more lead time, it would have been easy to open the gate and avoid the disaster. Also, it was not a design problem. It was a contingency none of the dam operators had foreseen.

Society is becoming increasingly aware of the risks associated with hydrologic extremes, in particular floods and droughts. With climate being high on the political agenda, it is clear that the links between climate and hydrological risks have become a major concern for politicians, flood managers, and citizens alike. There is a debate on whether there have been climate-related increases in the severity and frequency of floods and droughts in the past decades. While numerous devastating floods and droughts have occurred recently, it has been argued that confirmation bias could play a role in the attribution to

causes, that is, the tendency to favor information that confirms existing preconceptions (Taleb 2007; Merz et al. 2012). Increases in damage may be more related to socioeconomic change than to hydrologic change (Di Baldassarre et al. 2010; Bouwer 2011). In a particular catchment, extremes may or may not have increased but the fact remains that there is an urgent need for managing hydrological risks in the best possible way. Many countries have passed new legislation such as the EU Flood directive (EU 2007) that explicitly requires the establishment of flood risk management plans. There are similar drought risk management plans in a number of countries and states (e.g., Jacobs et al. 2005). The concept of integrated hydrological risk management (IHRM) (for both floods and droughts) is currently implemented widely.

Fundamental to the concept of risk are the notions of hazard and vulnerability, which both contribute to the risk. Hazard relates to a dangerous phenomenon (flood or drought), human activity (river damming), or condition (water scarcity) that may cause societal disruption or environmental damage (see the Hyogo Framework for Action, UN-ISDR 2005), whereas vulnerability relates to the characteristics of the people, the property, or the environment that are at risk. If one is to manage risks one can try to manipulate the hazard, the vulnerability, or both. Figure 1 shows the 2005 flood in Tirol, Austria. Clearly, the risk is high because of the presence of the houses. This is a vulnerability problem.

Given the recent and expected future changes in the water-related environment, developing strategies of hydrological risk management and implementing them pose a number of challenges. In this chapter, we will discuss the methods that can be used in IHRM and review emerging approaches of how to prioritize the implementation of these methods.

5.01.2 Elements of Integrated Hydrological Risk Management

The hallmark of IHRM is that a variety of actions are considered and implemented in an integrated way. This sets IHRM



Figure 1 August 2005 flood in Tirol Austria. Only a few decades ago, when there was not a single building at this location of the valley, a similar flood would not have been considered a disaster.

apart from traditional flood protection (and drought abatement) where individual measures were considered in isolation and sometimes the focus was on structural measures (such as dams) alone. Conceptually, the possible measures (or actions) are usually arranged along a hypothetical time axis of the disaster risk cycle that consists of four phases: mitigation, preparedness, response, and recovery (e.g., Thielen et al. 2007). In the case of flood risk management, mitigation involves a range of structural measures to reduce hazard and/or vulnerability, such as dams, levees for flood protection, polders of flood mitigations, and nonstructural measures such as land use zoning and insurances. Preparedness involves the establishment of emergency plans, the training of flood management staff, awareness building of the general public, and issuing flood warnings. Response involves immediate actions for protecting life and property such as evacuations and the provision of food and shelter. Recovery involves longer-term responses such as cleanup and rebuilding of structures. Preparedness, response, and recovery aim to reduce vulnerability. Nonstructural measures can be highly efficient. For example, the 2002 flood in the Czech Republic led to a much smaller number of flood-related fatalities than the 1997 flood, although it was larger. This was a result of the increased flood awareness and preparedness (Di Baldassarre et al. 2010). A similar cycle with a diversified mix of measures applies to drought risk management (UNDP 2011) but the time scales tend to be longer because of the more long-term nature of droughts.

The relative efficiency and effectiveness of individual measures depend on the local conditions (Samuels et al. 2010; Borga et al. 2011). Because of this, prioritizing the

measures is difficult, particularly given the recent changes in demography, economy, assets, land use, and climate as they all contribute to the risk (Hooijer et al. 2004; Thomalla et al. 2006; Birkmann and von Teichman 2010; Etkin et al. 2011; Solecki et al. 2011). There are two approaches of addressing the prioritization of risk management measures (Figure 2).

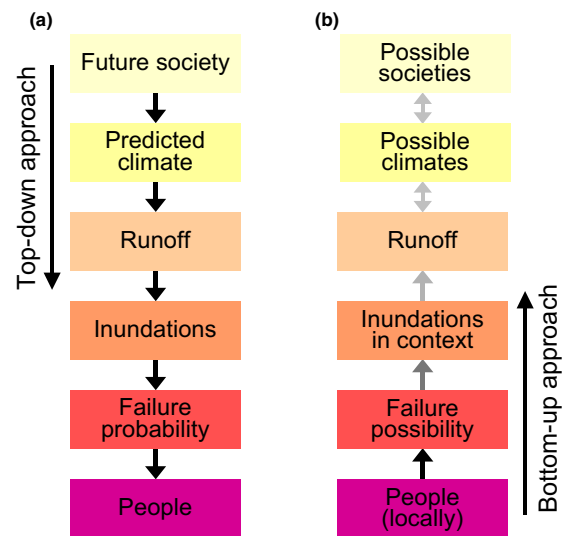


Figure 2 (a) Traditional top-down approach to hydrological risk assessment based on climate projections. (b) Bottom-up approach to hydrological risk assessment that is vulnerability or resilience centered. Approaches are illustrated by a fluvial flood risk example. Gray arrows indicate less dependence than black arrows.

The first, termed the top-down approach, starts from the climate forcing, cascading down information to the people affected by the floods or droughts. The second, termed bottom-up approach, starts from the people affected and explores possibilities of risk management (Dessai et al. 2009a,b; Wilby and Dessai 2010). These two approaches are discussed in the two next sections.

5.01.3 Top-Down (Economic) Approach to Risk Assessment Based on Probabilities

The 'top-down' approach is designed to represent the main processes causing the hazard and its consequences. In the case of climate impacts on floods (Figure 2), the 'top-down' approach starts at the global scale and cascades information from emission scenarios of future societies to simulated climates using global and regional climate models, to runoff using hydrological models, to inundations using hydrodynamic models, and to damage costs using economic models. The top-down approach is motivated by an economic paradigm. Hence, risk is defined from an economic perspective, specifying hazard as the occurrence probability of a flood (or drought) event, vulnerability as the damage cost in monetary terms, and (economic) risk as the product of the two. This leads to an optimization problem that aims at identifying the most economic management strategy among those discussed in the previous section.

The 'top-down' approach is the most widely used approach for impact and adaptation assessments (Blöschl et al. 2007). The 'top-down' approach is sometimes termed the 'predict-then-act' method as projected scenarios are the starting point and the main emphasis (Dessai and Hulme 2004). Scenarios differ in terms of the global development (affecting greenhouse gas emissions and simulated climate) and in terms of local development such as agricultural development, urbanization, construction of infrastructure, and other human activities (Kundzewicz et al. 2002; Wilby et al. 2009). The entire cascade is rigorously model based. Often, the scenario analysis is complemented by narrative descriptions of multiple facets of possible futures to ensure internal consistency (Merz et al. 2010). Applications of the top-down approach to hydrological risk assessment abound (e.g., Johnson and Weaver 2009; Luger et al. 2010; Veijalainen et al. 2010), many of which have an explicit focus on economics (e.g., Aerts and Botzen 2011; Zhou et al. 2012).

The appeal of the top-down approach is that it is conceptually straightforward and elegant as it mimics what is considered the main process cascade. Two questions arise: (1) should minimizing costs be the main societal goal and (2) is it possible to quantify future hazards and vulnerabilities to the accuracy needed?

1. Societal goals must, of course, be set in a political discourse. Surprisingly, there is relatively little open debate on this in hydrological risk management. Although the economic paradigm seems to be the most frequently adopted today, in practice, risk management measures often depart from it, even if the IHRM in a particular catchment is set in an

(economic) risk framework. This is illustrated by examples from fluvial flood management: Emergency actions such as evacuations are rarely based on cost/benefit considerations but on (social) humanitarian goals. Also, when prioritizing flood defense structures, often, worst-case scenarios that are at variance with the economic optimality goal are considered. Since extreme floods are usually economically less important than smaller floods if a long period is considered (Merz et al. 2009), risk aversion functions can be used to give greater weight to extreme events (Merz et al. 2010), which again deviates from the economic optimality goal toward a more social perspective. Similarly, in issuing flood warnings, maintaining credibility is often of higher priority to the flood warning staff than economic optimality (Blöschl 2008). A more explicit debate on the goals of IHRM in a changing world would be desirable.

2. The accuracy of quantifying future hazards and vulnerabilities has received more attention. Each modeling step of the top-down approach (Figure 2) introduces uncertainties that may lead to different prioritizations of risk management measures, depending on the assumptions made, and in fact to ineffective risk management (van Pelt and Swart 2011). The concept of economic risk hinges on the interpretation of the hazard as a probability. However, it may not be possible to specify such probabilities because of the nature of the socioeconomic processes (Grübler and Nakicenovic 2001). There are therefore two schools of thought in the top-down approach (Dessai and Hulme 2004). The first rigorously defines probabilities of, say, future droughts for estimating the risk. The second interprets scenarios as possible future developments, so the probabilities are more vaguely defined. Another dilemma is that, per definition, one is interested in conditions that are different from the past (in some ways), so testing the models of the cascade to past data does not fully confirm their credibility. Many Earth scientists hold a positivistic world view that assumes that, if enough data are analyzed in the right way, one can understand and resolve even the most complex problems, so the line of thought is that more detailed models will solve the dilemma. Hydrology has a long history of scientific discourse about the primacy of the reductionist (process-based or Newtonian) world view or the alternative holistic (data-based or Darwinian) world view (e.g., Sivapalan 2003; Savenije 2009; Merz et al. 2011). Figure 3 illustrates the point. Assume that we were in the year 1900 and had today's complex process models and computing power. Even with these it would be essentially impossible to predict the evolution of floods in the twentieth century for the Danube. The broader discussion in hydrology suggests that in many instances reductionist approaches are needed for identifying causal links, but there are many cases of societal relevance where feedbacks and emerging patterns make the reductionist approach questionable, so more holistic approaches should be preferred (Peel and Blöschl 2011; Blöschl and Montanari 2010). Similar arguments have been forwarded in Earth System modeling, in particular at the interface between socioeconomic and biophysical processes (Pielke 2004; Koutsoyiannis et al. 2009; Wilby and Dessai 2010; Sivapalan et al. 2012).

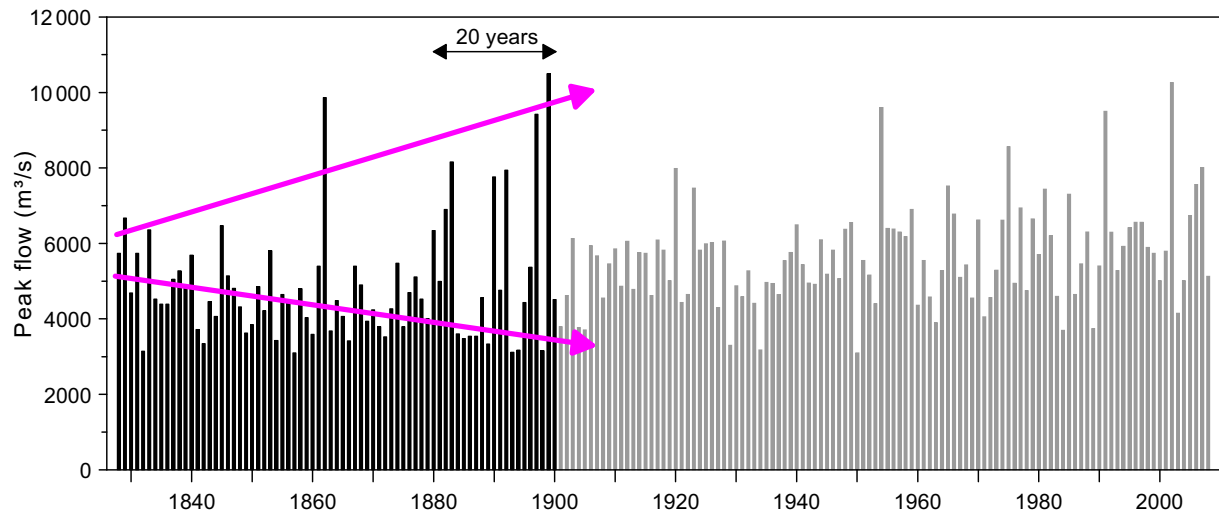


Figure 3 Maximum annual floods of the Danube at Vienna. Based on the data 1828–1900 (highlighted in black) it would be essentially impossible to predict the evolution of floods in the twentieth century for the Danube even if today's complex process models and computing power were available. Pink arrows indicate possible evolutions of large and small floods. Modified from Blöschl and Montanari (2010).

One way of addressing the uncertainty dilemma is to perform probabilistic uncertainty analyses (Dessai and Hulme 2004). Emerging methods represent the uncertainty of the hazards and/or vulnerabilities by Ensemble (Monte Carlo) methods while keeping a process-based approach that allows one to profit from available process knowledge. A number of recent studies have demonstrated the feasibility of this approach for the case of inundations due to fluvial floods (e.g., Apel et al. 2004; Di Baldassarre et al. 2009; Merz et al. 2010). By recognizing randomness and uncertainty, such a framework does not yield deterministic predictions, but the uncertainty estimates can be very useful. Extending these probabilistic uncertainty frameworks to a range of processes relevant to hydrological risk management has, *inter alia*, been proposed by Koutsoyiannis et al. (2009) and Blöschl and Montanari (2010), and Wetterhall et al. (2011) presents a study of probabilistic uncertainty analyses of hydrological risk in Sweden.

5.01.4 Bottom-Up (Social) Approach to Risk Assessment Based on Possibilities

The 'bottom-up' approach (Figure 2) starts at the local scale of individuals, households, and communities and explores the factors and conditions that enable successful coping with hydrological extremes (Wilby and Dessai 2010). The bottom-up approach is motivated by a social paradigm. Hence, risk is not defined in monetary but in more qualitative terms. The main goal is not to find the most economic management strategy but to ensure the well-being of people by reducing vulnerability and enhancing resilience (the ability to recover after an event). It does not take climate projections as a starting point but the vulnerability and resilience of the risk-related system itself (van Pelt and Swart 2011). It is sometimes termed the 'assess-risk-of-policy' method as it explores alternative policies first.

Although the top-down approach is currently more popular, realization of the importance of the bottom-up approach is emerging: "Society will even benefit much more from a greater understanding of the vulnerability of climate-influenced decisions to large irreducible uncertainties than it will from extremely expensive attempts to increase the accuracy and precision of climate predictions. An alternative approach to the conventional one based on climate prediction would therefore focus on exploring how well strategies perform across wide ranges of assumptions and uncertainties (Robust Adaptation Decision-Making)." (European Commission 2009, p. 13).

The bottom-up approach differs from the top-down in that the main aim is to reduce vulnerability and enhance resilience. It has therefore particular value in countries in which the vulnerabilities to floods and droughts tend to be high such as in the developing world (Di Baldassarre et al. 2010; UNDP 2011). Also, it may be more ethically justified as it puts people center stage. Typically, the strategies are not optimal from an economical perspective but they are robust, that is, they are designed to perform well over a wide range of assumptions about the future and potentially extremely negative effects. In other words, they are 'low-regret' strategies. Note that 'no-regret' strategies do not exist in any kind of nontrivial decision making. Since the starting point is local communities, they tend to be more creative and inclusive of a broader range of information, such as governance and lessons learned from the past and other catchments, context-dependent information, contingencies, and narratives (Pielke 2004). Clearly, the Tirylian disaster could not have been anticipated by a top-down risk approach. It may have been possible to speculate in advance about the possibilities of blocking the gate based on local experience, but this is not a type of information that can enter into a formal optimization analysis. The bottom-up approach is therefore based on 'possibilities' rather than on probabilities. Because of this, it tends to be less dependence on probabilities inferred from the predictive scenario approach (Sarewitz et al. 2003). The preference for alternative strategies may become



Figure 4 Drought predictions, however accurate, delivered by the young man are completely useless to the old man because of his high vulnerability. The course of action is clear; the actions just need to be done. [Available online at <http://sriks6711.wordpress.com/2009/08/03/india-is-drought-hit-in-2009>.]

insensitive to the assumptions of climate scenarios since other factors (including local socioeconomic factors) dominate, but this will depend on the local setting. This is a notion that Prudhomme et al. (2010) term 'scenario-neutral'. In Figure 2, the weaker sensitivity (or lack of sensitivity) to the scenario predictions is indicated by the gray arrows. Local information on the social characteristics related to floods and droughts may indeed be more relevant than global predictions. Consider the cartoon in Figure 4. It appears that the drought predictions, however accurate, delivered by the young man are completely useless to the old man sitting by the tree because of his high vulnerability and the lack of options he has. The point of the bottom-up approach is that scenario predictions are not helpful for deciding how to improve the fate of the people in the cartoon. The course of action needed is clear; the actions just need to be done.

However, the pros of the bottom-up approach come at an expense. It is significantly more 'messy' and lacks the conceptual elegance of the top-down approach. The most relevant consequence is a more difficult interaction with stakeholders. As a matter of fact, the effort to explore what the future will be looks more appealing than a seemingly unstructured analysis of the present. Indeed, vulnerability is determined by a host of factors including variations in wealth, social equality, food availability, health and education status, physical and institutional infrastructure, access to natural resources, and technology (Wilby and Dessai 2010) that condition the analysis and prevent to set up a unified framework for the bottom-up approach. Also, the methods tend to be more messy, as is often the case in the social sciences (see, e.g., the evaluation of participative methods in water resources, Carr et al. 2012).

Methods often involve exploratory modeling approaches in which multiple runs of simulation models are used to systematically explore the implications of a wide range of assumptions and contingencies (Dessai et al. 2009a). These assist in making policy arguments. An important role is played by historical data in the case study or similar catchments. Equally important, a range of methods from the social sciences are used, such as surveys, impact diagrams, mind maps, causal loop methods, and visualization methods involving the local risk managers and stakeholders (e.g., UNDP 2011; Waser et al. 2010), to explore the perceived or real causal structure of the system.

Since the problem is messy, case studies play an important role. The vulnerability approach of Simonovic (2010), for example, starts from analyzing existing policies and management practices in a Canadian catchment with respect to critical flood and drought situations, which he then transforms into corresponding critical meteorological conditions. Schelfaut et al. (2011) focus on enhancing the resilience by identifying the opportunities and bottlenecks of flood risk management in a number of European catchments, such as institutional interplay, flood management tools, and risk communication. For a flood risk case study of the river Rhine van Pelt and Swart (2011) conclude "The 'assess-risk-of-policy' approach recognizes local interests and conditions, and offers possibilities to deal with uncertainties that cannot be quantified, by focusing on the resilience of the system. First results of this method show that it can offer policy makers a new, complementary tool for evaluating adaptation strategies that also addresses their non-climate priorities and maybe [provides] a different view on the urgency of adaptation to climate change." In Southern Austria, experience with the 2003 drought was used to assess the vulnerability of the water supply system and to enhance the connectivity of the infrastructure (Blöschl et al. 2011). Harou et al. (2010) explore the economic effects and potential adaptation strategies of water trading of California's water supply system using past droughts from paleorecords rather than climate projections. Similarly, Watts et al. (2012) test the resilience of drought plans in England to droughts that are outside recent experience using nineteenth century drought records. The method combines system modeling with an interactive approach that asks water system managers to work through the actions that they would take at different stages of the drought, without knowledge of subsequent drought development.

In the top-down approach, the hydrological modeling is usually performed in a mechanistic way by running hydrological models with prescribed boundary conditions (e.g., climate or land use scenarios), whereas the bottom-up approach has a more creative role for hydrologists to play. Their role is explorative modeling across a wide range of assumptions, contingencies, and uncertainties taking into account the expertise of local risk managers and stakeholders. The aim is to assist them in understanding the potential consequences of alternative policy options.

5.01.5 Accounting for Black Swan Events

The previous two sections discussed two alternative approaches to prioritizing hydrological risk management. There is another



Figure 5 A black swan among numerous white swans is unexpected but may be the important one. There is a potential for Black Swan events in hydrology that are unexpected but have high impact from a societal point of view. [Available online at [http://www.lonelyplanet.com/japan/hokkaido/images/black-swan-among-white-swans-hokkaido\\$24256-1](http://www.lonelyplanet.com/japan/hokkaido/images/black-swan-among-white-swans-hokkaido$24256-1).]

facet to it. Taleb (2007) observes that the worst disasters in history have been the unexpected ones because of the inability to brace against them. He terms such unexpected large-impact events 'Black Swan events,' based on the anecdote that, before the discovery of Australia, all swans were considered to be white because of the lack of black swan sightings in the Western world (Figure 5). For such Black Swan events, prior risk calculations are, invariably, grossly in error. An example is the 2001 terrorist attack on the World Trade Center (Sarewitz et al. 2003). Black Swan events are unexpected and have large impacts and, interestingly, failed predictions can always be explained *in retrospective*.

Experience with unexpected events with large consequences abounds in hydrological risk management – that is to say after the fact. The Tirylyan disaster is a case in question, and there are many more. They make up the 'lessons learned' from any recent disaster. For example, the lessons learned from the 2002 flood in Austria include the following situations to be considered: blockage of reservoir spillways by an excessive amount of woody debris due to landslides into the reservoir, leaky oil tanks in the cellars of houses due to buoyancy when being flooded, and the resulting oil spills, missing local details in flood management plans such as passageways under railway embankments causing major unexpected flooding beyond the embankment. All these events were unexpected, were created by context and contingencies, and had large (potential) consequences, but they could have been easily avoided if only one had known of them *a priori*.

Unexpected large events are produced by the nonlinearities of the system (Blöschl and Zehe 2005; Koutsoyiannis et al. 2009), in particular in the interplay of the biophysical and the social system (Sarewitz et al. 2003; Sivapalan et al. 2012). Climate variability has therefore the potential to produce Black Swan events for hydrology that are unexpected but have high impact from a societal point of view.

The implications for hydrological risk management are important. The bottom-up approach has more potential to prepare for unexpected events than the top-down approach as

the focus is on reducing the vulnerability of the system by robust methods. As Taleb (2007) noted "it is much easier to deal with the Black Swan problem if we focus on robustness to errors rather than improving predictions" (Taleb 2007, p. xxiv). For a flood management system, for example, the vulnerability of the system can be reduced by using free overflow spillways rather than funnel-like morning glory spillways since the former are more robust against hydraulic overload, by designing spillways for dikes (which is not usually done), and by planning for redundancy in emergency plans. For a drought management system, the vulnerability of the system can be reduced by increasing the connectivity of water supply infrastructure and converting permanent abstraction licenses to time-limited status, among other low-regret strategies (Wilby and Dessai 2010). They may not be optimum in an economic sense but may be more robust than alternative approaches to extreme events with large consequences. The bottom-up approach starting with the policy options at the local scale may also be more creative by exploring a wide range of possibilities causing flood- and drought-related disasters. The actual measures taken may be quite different from those resulting from the top-down approach, as in the bottom-up approach one may rank the measures by the harm they may cause rather than by their contributions to total economic risk.

The flood risk management study of Wardekker et al. (2010) is interesting in that it explores imaginable surprises, something they term 'wildcards.' The study proposes an uncertainty-robust adaptation strategy of strengthening the resilience of the city of Rotterdam, using literature study, interviews, and a workshop. The 'wildcards' or imaginable surprises for the area include thermohaline circulation collapse, port freezing events, port malaria incidents, modified German water safety policy, enduring heat and drought, extreme storm, and failure of the storm surge barrier during an extreme storm. Their resilience approach is designed to make the system less prone to disturbances, enable quick and flexible responses, and make it better capable of dealing with surprises than traditional predictive approaches.

5.01.6 Conclusions

The two main approaches to hydrological risk management are the top-down approach that starts from the projected scenarios and the bottom-up approach that starts from the vulnerability of the communities in question. While the top-down approach is conceptually appealing as it mimics the main process cascade and strives for economic optimality, the probabilities used in this approach may be difficult to estimate, in particular in a changing world. The bottom-up approach is 'messier' involving methods that can be less clearly structured, but it has a social motivation and is more amenable to accounting for surprises as it strives for reduced vulnerability and increased resilience by robust methods. In the bottom-up approach, risk involves possibilities rather than probabilities. The bottom-up approach has an important and creative role for hydrologists to engage in explorative modeling to assist local risk managers and stakeholders in defining policy options.

Van Pelt and Swart (2011) noted that too much focus on climate scenarios alone may lead to ineffective risk management. Montanari et al. (2010) conclude "Offering insightful explanations for predicted changes may be more helpful than perfecting the estimates of what are inherently uncertain changes. Such a nuanced assessment will gain wider acceptance in society and will bring more credibility to the research community." We argue in this paper that the possibilistic thinking of the bottom-up approach (including worst cases) should not complement the scenario-based top-down approach. It is like the tail wagging the dog. It should be the converse: the bottom-up approach should be the starting point in hydrological risk management, which may be complemented by climate scenarios and economic optimality analyses. In highly vulnerable settings as they occur in developing countries, it is particularly important to perform bottom-up risk analyses, that is, to start from policy options and their risks, rather than to perform top-down modeling. Climate variability has the potential to produce Black Swan events for hydrology that are unexpected but have high impact from a societal point of view. Reducing the vulnerability and increasing the resilience of the system by a bottom-up approach leading to robust and flexible strategies will therefore be the hallmark of hydrological risk management in a changing world.

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