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Comparative assessment: fact or fiction?

Zbigniew W. Kundzewicz

Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Poznan, Poland

Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

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Abstract

The paper will briefly review observations illustrating the ongoing climate change. It will discuss the key uncertainties involved in the application of the current methodologies. The effects of non-stationarity, especially those attributed to climate change, will be examined. It will be analyzed what is fact and what may be fiction when applying the key "standard" trends for the hydrologic design of water-related projects. A question will be posed – Are climate projections for the future ready for prime time? Indeed, even if models adequately reproduce past and present conditions, we cannot be sure that they will adequately simulate future conditions. However, in reality, climate models still do not represent the details of past and present conditions adequately. Challenges to adaptation to climate change in the water sector will be discussed. Local projections for the future, necessary for adaptation, are very uncertain, so that a question "adapt to what?" comes about. It is difficult to disentangle the climatic change component from strong natural variability and direct human impacts on river flow, hence a question „adapt to what?" comes about. Robust adaptation procedures, which do not rely on precise projections of changes, need to be developed. There is a focus on the ''soft path'' and low-regret options to climate adaptation.

1. Introduction

It is a general wisdom that all three categories of water problems (having too little water, too much water, and water in inadequate quality) can be exacerbated by climate change. However, observed and projected changes are not ubiquitous. Indeed, in the global system, everything is connected to everything else. Hence values of hydrologic variables are influenced by climatic and non-climatic factors. The climate and freshwater systems are intimately interwoven, in a complex way, so that any change in one of these systems induces a change in the other.

There has been considerable recent interest in nonstationarity in various areas, including water resources. Since several interpretations of the term ‘‘stationarity’’ exist, the high-impact paper by Milly et al. (2008), declaring that ‘‘stationarity is dead’’ raised controversy. According to some experts, stationarity is alive and well. Others express opinion that strict stationarity in water resources has never been born.

The scientific term ‘‘stationarity’’ does not necessarily mean constancy of variables (Kundzewicz, 2011). What it does mean is constancy of laws and patterns. For example, variables may feature strong but regular natural variability and quasi-periodic oscillations, while the processes ruling the changes can be nearly constant. A stationary stochastic process, per definition, has a property that its probability distribution does not change with time, i.e. the mean and the variance are constant. In contrast, statistical properties of nonstationary processes vary over time, e.g., featuring abrupt or gradual changes.

Nonstationarity opens a Pandora’s box with practical problems in water planning and management. Constancy of statistical properties allowed water planners to coin a convenient conceptual notion of a 100-year flood or a 100-year streamflow drought (i.e., a river discharge, whose probability of exceedance in any given year is 1% or 99%, respectively). In a nonstationary situation, the notion of a 100-year event has to be redefined, as it can be assumed constant only for a restricted time period.

Stationarity can be interpreted as the rule ‘‘the past is a key to the future’’. Literally, a key should open the door. If it does not, this means either that the key is worn out or that the lock has changed. However, even if in nonstationary situation the past is not a key to the future (it does not really open the door), there are useful lessons that can be learnt from the past (Kundzewicz, 2011).

2. What do observations tell us?

Atmospheric warming currently occurs at different spatial scales, including the whole globe. It is unabated and unequivocal. The warming trend is evident, for example, from observations of air temperature, which show clear increase at a range of scales, from local, via regional, to continental, hemispheric, and global. The global warming rate over the last 25 years is over twice faster than it was over the last 100 years (IPCC, 2007).

Figure 1 illustrates the global temperature anomaly, based on NASA GISS data and analyses. It shows that the year 2010 tied (even slightly surpassed) 2005 as the globally warmest year in the instrumental, thermometer-based, record extending since 1880. This was rather surprising due to the cold La Niña phase continuing from early summer of 2010 (until the end of the year 2010 and later into 2011) and low sunspot numbers.

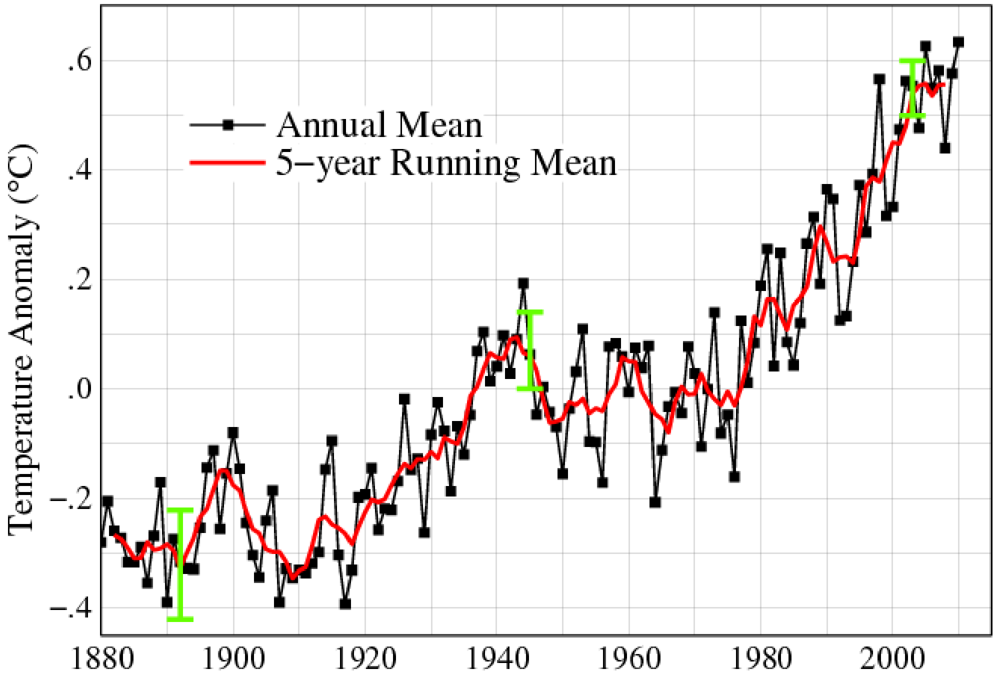

Fig. 1. Global land-ocean temperature index 1880-2010.
http://data.giss.nasa.gov/gistemp/graphs/Fig.A2.gif

The clustering of globally warm years observed in the 21st century would be very unlikely to occur by chance in a stationary climate. However, climate change should not be equated to a monotonic warming (Schultz, 2011). Figure 1 illustrates that expecting a monotonously smooth growing temperatures would be futile, in view of strong natural variability, driven by a complex dynamics of the climate system. Interpreting this complexity could have important consequences for the future. Natural variability of climate may enhance or mask anthropogenic warming. The particularly warm year 1998 (when El Niño phase was very strong) was a positive outlier (much warmer than the value corresponding to the long-term trend).

Observed precipitation changes have been less regular than changes in temperature, but increases over land north of 30°N over the period 1901-2005 were observed (Trenberth et al., 2007). Several studies lead to the conclusion that over the last 50 years, there has been an increasing probability of heavy precipitation events for most extra-tropical regions; at the continental and global scales (cf. Groisman et al., 2005; Trenberth et al., 2007). It is likely that there have been widespread increases in the number of heavy precipitation events (e.g., 95th percentile determined for the control period) and in the contribution to total annual precipitation from very wet days, i.e., days in which precipitation amounts exceed the 95th percentile value (determined for the control period), in many land regions. However, the rainfall statistics are strongly influenced by interannual and interdecadal variability. There are also problems with data homogeneity, e.g., related to changes in snowfall. Observed changes of the timing, intensity, duration, and phase of precipitation in a site of interest, or in a region, are often weak and statistically insignificant. But even if significant changes are detected, they are inconsistent throughout regions and seasons.

Observed changes in river flow – the variable integrating precipitation over the catchment – have been even more complex then changes in precipitation, due to various compounding effects.

Clear violation of stationarity in water resources results from direct human activities. Many river basins experience massive human manipulations of land and water resources, driven by population changes and by economic development. Development at the river basin scale usually means a roster of anthropogenic changes, such as changes in land use (urbanization, intensification or extensification of agriculture, deforestation or afforestation, mining), resulting in land-cover change; water engineering measures in rivers, e.g., levee and dam construction, straightening and shortening of rivers, in-channel modifications (dredging, channelization); or in-catchment water management, like water abstractions, irrigation, water transfer schemes, wetland drainage. The time interval between action and impact can be significant and some land-use change impacts may become obvious only after a considerable time lag (Kundzewicz, 2011). For example, the effects of afforestation on low flow or nitrate pollution of groundwater may be revealed only decades later.

The rise in exposure to floods has been caused by human encroachment into floodplains. It may grow as people become wealthier and more exposed. Technology and economic imperative help populate more ‘‘difficult’’ areas. Many wrong locational decisions have been taken, and the assets at risk from flooding are very high, and growing.

The sea level has been rising over many last decades, with considerable impact on freshwater (e.g., via saltwater intrusion into groundwater and estuaries). The principal mechanisms of the sea level rise have been: thermal expansion resulting from temperature rise and melting of the cryosphere (including mountain glaciers, which are a source of water supply to more than a billion people, worldwide). The global average rate of recent sea level rise, from 1993 to 2003 is 3.1 ± 0.7 mm⁄ year (IPCC, 2007), therein thermal expansion is found responsible for 1.6 ± 0.5 mm⁄year and cryospheric changes for 1.2 ± 0.4 mm⁄year.

3. Facets of uncertainty

Climate change attribution statements play a crucial role in the assessments made by the Intergovernmental Panel on Climate Change (IPCC). The essential attribution statements in each of the four assessment reports of IPCC have evolved with time, towards decreasing uncertainty. In the First Assessment Report (FAR – IPCC, 1990), „little evidence of detectable anthropogenic influence on climate" was reported. The Second Assessment Report (SAR – IPCC, 1995) noted a „discernible human influence on climate". In the light of accumulated evidence, the attribution statements became stronger in the last two assessment reports. The Third Assessment Report (TAR – IPCC, 2001) stated that „most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations", while the Fourth Assessment Report (AR4 – IPCC, 2007) conveyed the message that „most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations". The qualifiers „likely" and „very likely" in the last two statements were defined to correspond to the probability in excess of 66% and 90%, respectively.

Indeed, human activities have changed the chemical composition of the atmosphere and the land surface, and have exerted an identifiable effect on global climate. The dominant mechanisms to which recent climate change has been attributed are: increasing atmospheric concentrations of greenhouse gases (GHGs); global changes to land surface, such as deforestation; and changing atmospheric concentrations of aerosols. The first two mechanisms enhanced the warming potential, while the third mechanism exerted a cooling effect. Model-based "fingerprint" studies show that observed climate changes over the past 50 years cannot be explained by natural factors alone.

General Circulation Models (GCMs), based on rigorous equations of mathematical physics, have been developed to relate GHG forcing to future potential climate states, in order to project the future behaviour of the climate system. These models account external drivers, such as solar activity, the Earth's orbit, volcanic eruptions, properties of the atmosphere (therein concentrations of GHGs and aerosols) and land surface, and internal feedbacks in the system, diminishing or amplifying the effects of GHGs and generating variability. Advanced climate models mimic essential physical mechanisms and internal feedbacks and have been found to reproduce broad observed features of recent and past climate at larger scales (continental and above). For instance, it is possible to reconstruct essential, large-scale, characteristics of the 20th century temperature. Hence, it was attempted to use these tools to produce projections for the future, but there are a plethora of uncertainties related to this process. Climate models do not cope well with reproduction of temporal details of global temperature. Unfortunately, precipitation, the principal input to freshwater systems, is not adequately simulated in present climate models (Kundzewicz et al., 2008) and models largely disagree in the projection of changes over many areas, even if areas of stronger consensus do exist.

In general, despite the considerable progress achieved, GCMs still cannot reconstruct the important details of the climate at smaller scales (regional to local). They cannot resolve sub-grid processes, e.g. related to land use. Hence, such techniques as regional climate models (RCMs) or downscaling methods, have been developed. Statistical downscaling is based on relationships linking large-scale atmospheric variables (predictors) and local/regional climate variables (predictands), cf. Wilby (2010).

Some processes are still missing, or poorly represented in the model. Complex nonlinear feedbacks are difficult to grasp; some are possibly unknown. More comprehensive data on the aerosols, atmosphere, oceans, land surface and soil moisture, and vegetation state are necessary for model validation.

It should be understood that RCMs operate under a set of boundary conditions set by a GCM. Hence, if the GCM does not do an adequate job of reproducing the climate of a particular region, the RCM will simply mimic those inaccuracies and biases, and propagate the uncertainties even further, albeit at a regional scale. Bias reduction, being a kind of curve-fitting exercise, does not really help in improvement of our interpretation.

There are many sources of uncertainty in climate change impact projections. Scenarios of population and pathways of socioeconomic and technological development are uncertain. They, in turn, drive scenarios of emissions (and hence atmospheric concentrations) of greenhouse gases, hence uncertainty grows. It grows even more in the process of application of global climate models (with different global climate sensitivities). A large increase in uncertainty is related to producing regional scenarios (e.g., with the help of downscaling). Finally, there is another considerable increment in uncertainty, related to determination of a range of possible future impacts (with and without adaptation). Hence, the initial uncertainty, related to future human development, has considerably grown along the chain from socio-economy to climate change impacts.

A call to reduce uncertainties was issued in the IPCC First Assessment Report in 1990, but since then the uncertainties have actually grown (even if the main attribution statement has been gradually less uncertain in the subsequent IPCC reports). There will be more knowledge, but less certainty – states Trenberth (2010). Ha also soberly assesses the transient deficiency related to model improvement: “Adding complexity to a modelled system when the real system is complex is no doubt essential for model development. It may, however, run the risk of turning a useful model into a research tool that is not yet skilful at making predictions.” There are inherent, possibly irreducible, uncertainties of the climate system, so that a shift of emphasis from ‘‘reduce uncertainties’’ to ‘‘risk reduction’’ tends to be necessary.

It is clear that uncertainty in hydrology is not restricted to projections for the future. Indeed, the notion had been recognized in hydrologic sciences a long time ago, before climate projections became available. The very concept of a 100-year flood is loaded with uncertainty. A rigorous statistician would demand at least 100 years of observation records, in order to reliably estimate a 20-year (5%) flood in stationary situation. Unfortunately, frequently the problem to be solved is very much different – the situation is nonstationary and one only has 20 years of observation records, while being asked to construct a 100-year (1%) flood. This is indeed a kind of ‘‘mission impossible.’’ Long time series of data records are rare and challenging data quality issues have to be addressed (e.g. spotting and fixing problem of nonuniformity of observations, solving the problem of missing data, outliers). Economic constraints cause interruption of observations at many stations, globally. Even stations with long existing data records are being closed down, due to lack of funding. But even if the data have been collected and included into a database, access to them can be difficult. Observation records – particularly at national and regional levels – may be available at (sometimes prohibitively high) cost.

4. Are projections ready for prime-time?

Temperature projections based on GCMs agree on the sign of change: ubiquitous warming is projected (cf. IPCC, 2007). However, in contrast to straightforward temperature changes, model-based projections of future precipitation, of crucial importance to water resources, are considerably less clear and much more uncertain. There is a strong inter-model uncertainty. Over large areas, climate models disagree even as to the direction of change of future precipitation, spanning a broad uncertainty range. For instance, some climate models project decrease of summer precipitation over much of Europe, while other models project increase (cf. IPCC, 2007). There are areas of model agreement (e.g. projections of precipitation decrease in the Mediterranean basin and in southern Africa), where results are relatively robust, but there are also areas of much disagreement between models.

Generally, precipitation extremes are likely to be impacted more than the means by the changing climate. Heavy precipitation is on the rise in the warmer world, and this can be interpreted by physical reasoning (Clausius-Clapeyron law). Yet, existing climate models are not good at reproducing local climate extremes, of crucial importance for water resources, due to, inter alia, inadequate (coarse) resolution.

Nevertheless, there are many studies using climate change projections in hydrology and water resources, and determining impacts. Some studies have been based on results of one climate model (e.g. the one that was available to the analyst), others – have been using multi-model ensemble simulations. These studies span possible and plausible futures, but it is not possible to assess probability of their realization.

Milly et al. (2005) presented mean runoff change until 2050 for the SRES A1B scenario from an ensemble of twenty-four climate model runs (from twelve different GCMs). Almost all model runs agree at least with respect to the direction of runoff change in the high latitudes of North America and Eurasia, with increases of 10 to 40%. With higher uncertainty, runoff can be expected to increase in the wet tropics. Prominent regions, with a rather strong agreement between models, of decreasing runoff (by 10 to 30%) include the Mediterranean, southern Africa, and western USA/northern Mexico. In general, between the late 20th century and 2050, the areas of decreased runoff expand. Milly et al. (2008) presented a map of projections of river runoff change for countries and smaller units of large countries. A very robust finding of hydrologic impact studies is that warming leads to changes in the seasonality of river flows where much winter precipitation currently falls as snow (Kundzewicz et al., 2007).

Hirabayashi et al. (2008) produced a global map of changes in recurrence intervals (return periods) corresponding to a 100-year flood in the control period (i.e., flood with a recurrence interval of 100 years during 1961-1990), compared to projections for the end of the 21st century (2071-2100). Over

30% of the area of Europe, the mean recurrence interval of the 100-year flood in the control period is projected to decrease to below 50 years in 2071-2100.

With respect to drought, projections obtained by Burke et al. (2006) show a net overall global drying trend. Globally by the 2090s, the land surface suffering from extreme drought is projected to increase in extent, while the proportion of the land surface in extreme drought at any one time is predicted to increase 10-fold from the present. The number of extreme drought events per 100 years and mean drought duration are projected to increase by factors of two and six, respectively, by the 2090s. The overall drying trend is projected with a decrease in global average value of the PDSI (Palmer Drought Severity Index) of 0.3 and 0.56 per decade, respectively, for the first and the second half of the 21st century (Burke et al., 2006). Lehner et al. (2006) analyzed projections of droughts in Europe, concluding that what used to be a 100-year drought in the control period (1961-1990) is projected to be exceeded much more frequently in 2020s, and even more so in 2070s, over much of Europe.

Climate change projections are highly uncertain – in fact the unknowns about climate change dynamics go beyond our understanding of classical risk and uncertainty analysis. There are true unknowns. Hence no combinations of clever statistical methods can reveal what those unknowns may be. Definitely, there is a need for more research on climate dynamics and feedback loops (Kundzewicz and Stakhiv, 2010). We know increasingly well that we do not know enough.

Climate models were designed to provide a broad assessment of the response of the global climate system to GHG forcings, and to serve as the basis for devising a set of GHG emission reduction policies to slow down the rate of growth of atmospheric concentration of GHGs, and, by this, to mitigate global warming impacts. However, there has been a key change in perspective of climate scenarios – the examination of the utility of climate models has shifted from the modellers concerned with mitigation options and policies to the adaptation side of the ledger – to the prospective users dealing with realistic adaptation (and smaller-scale, e.g. regional or local) strategies, including the hydrologic and water management community (Kundzewicz and Stakhiv, 2010).

There are pragmatic concerns, raised by hydrologists and water management practitioners, about how useful the GCMs are for the detailed level of analysis (and predictability) required for site-specific water management decisions (infrastructure planning, design and operations) even if the current suite of climate models were not developed to provide the level of accuracy required for adaptation-type analysis. There is a discrepancy between what the models were designed for, and their potential extended uses. To expect more from these models is simply unrealistic at this time.

It is expected that there should be some degree of practically useful correspondence between the spatial average of station data and the results of climate modelling in the past-to-present range (hindcasting). If the correspondence is poor, improvement of these features should be one of the major research priorities. Present climate models contain considerable biases in their climatology and do not fit gridded station data well; hence, a need for bias correction comes about. Yet these “bias corrections” merely represent an ad hoc curve-fitting exercise of convenience, rather than a result of impeccable physically-based theory (Kundzewicz and Stakhiv, 2010).

Even though the purpose of climate models is to mimic gross climate changes corresponding to changing emissions scenarios (emissions, land use, etc.), they should still be expected to reproduce the recent past 30 years of climate reasonably well. Verification of performance of climate models is important for evaluating model utility. Koutsoyiannis et al. (2008) tried to estimate a point value based on a linear combination of model-simulated values for surrounding grid cells and then to compare a station data value of temperature or precipitation. They analysed eight stations and showed that models perform poorly at large temporal (30-year climatic) scale. The best linear unbiased estimate (BLUE) of a point value based on a linear combination of neighbouring cells, while possibly being the best (as suggested by the name), is still far from being good. Anagnostopoulos et al. (2010) extended that study to larger spatial scales. They aggregated the observation values both spatially (to a large area of the contiguous USA) and temporally (to shifted 30-year climate standard normal period), and compared them with climate model simulations. The match between model simulations and station data was not found to be satisfactory.

Anagnostopoulos et al. (2010) show that present climate models, on their own, cannot accurately reconstruct the past even at sub-continental to continental scales, and perform poorly at regional scales. Comparison of model performance with station (data-based cell vs model-based cell) data is relatively poor, being somewhat better for temperature, and worse for precipitation. Actually, climate modelers warn the users that confidence in models decreases at smaller scales. If this is indeed true, then can the use of RCMs and statistical downscaling improve our insight as part of suggested vulnerability analyses (Kundzewicz and Stakhiv, 2010)? Hagemann et al. (2006) evaluated precipitation at the regional scale by comparing model simulations corresponding to various resolutions with observational data in selected catchments representing major river systems on Earth, in different climate zones. They found that precipitation bias was low in the catchment of the Mississippi, but very high (in excess of 80%) at the Ganges and Brahmaputra, for all resolutions considered.

The paper by Anagnostopoulos et al. (2010) contains a warning that one should not use GCMs simulations uncritically, taking them at face value. Without bias correction, model simulations cannot mimic reality.

The debate is now about – are the GCM-based scenarios “ready for prime time”? – i.e. can they be used in real applications in the water management sector and infrastructure planning and design realm?
Kundzewicz and Stakhiv (2010) responded to this question as follows: while climate models are getting better, they are not (up to) ready for “prime time” yet, at least for direct application to water management problems. Water managers understand that climate models are improving, but are not good enough yet for the types of analyses that they routinely undertake. Much more research needs to be done, and models need to be further, and considerably, improved before they can be used effectively for adaptation planning and design: “Significant improvements of GCMs to the point where their output can be input directly into water utilities planning models without bias correction and downscaling will

likely take more than a decade or two" (Water Utility Climate Alliance, 2009). Kundzewicz and Stakhiv (2010) estimate that these models may begin to provide useful information, at least for vulnerability assessments, at some point in the future, but unlikely earlier than after a decade.

Stakhiv (2011) demonstrated inadequacy of results currently available from multiple GCM simulations for application for planning and design decisions related to water. In a paper by Angel and Kunkel (2009), focusing on the Great Lakes system, authors tested 565 scenarios generated by 23 GCMs. They obtained a wide array of highly variable outcomes (lake levels) for any selected GCM. Even with the assistance of robust decision-making procedures, effective use of this result in water management remains a very difficult challenge. Water managers are not satisfied from a proliferation of 23 GCMs that they have to contend with, as part of their analyses, each generating countless scenarios. Why should the burden be on the user community to reconcile the disparate outcomes of 23 GCMs? The spread of outcomes in these models is often used, incorrectly, as a form of uncertainty analysis, and the central characteristic (average or median) of the ensemble of model projections is often advocated as a useful representation of future climate. However, it is not at all clear how to interpret the widely disparate results of climate models in the water field, even if these models had some useful predictive capabilities, possibly for temperature increase (Stakhiv, 2011).

5. Adaptation challenges

Adaptation in the water sector involves measures to alter hydrologic characteristics to suit human demands, and measures to alter demands to fit conditions of water availability (Kundzewicz et al., 2007).

Detection of changes in long time series of hydrologic records is an important scientific issue, fundamental for planning and management of water resources and protection from water-related disasters. If a trend is detected, and possibly attributed with the help of modelling, projections for the future can be made. (However, the author subscribes to the opinion by Wilby et al. (2008), who stated that, in some areas, statistically significant trends are unlikely to be found for several decades more). If predictions indicate, in a reliable way, a significant increase in the frequency, duration, and intensity of hydrologic extremes (floods and droughts) in the changing climate, then the consequences for the existing water resources design procedures, traditionally based on the assumption of stationarity of river flow, would be severe (Kundzewicz, 2011). For instance, in some areas, one would have to better manage hypothetical increased flood risks, that is to design and build higher levees and larger storage volumes, at higher costs, to accommodate larger future flood waves. Existing infrastructure may not guarantee the adequate level of protection against impacts of climate changes and may need to be re-adjusted (Milly et al., 2008). Without this, systems will be over- or under-designed and will either not serve their purpose adequately, or will be overly costly.

Information on increasing variability of river flows and stages would be of primary importance for designing flood protection infrastructure - dams and reservoirs, dikes, spillways, culverts, by-pass channels, polders. If design flood is, according to existing regulations, a 100-year event (i.e. such ´flood safety level has to be maintained in the future), then it would be necessary to know how a 100-year flood from the control period would change in the future in order to dimension a levee and to determine a 100-year flood plain. Also such water management issues as reservoir operation, dam safety, water allocation, or reliability of water supply would benefit of a (presently non-existent) reliable climate scenario in a small spatial scale.

Unfortunately, uncertain scenarios generated by climate models of current generation do not provide an adequate foundation for the design of hydraulic infrastructure. Downscaling and bias correction cannot compensate for the basic inadequacies of the climate models (Kundzewicz and Stakhiv, 2010). Hence a question: ‘‘Adapt to what?’’ comes about. Since uncertainty of projections is not likely to be reduced soon, it is necessary to make rational decisions without being able to know the future with adequate precision. Hence, robust adaptation procedures, which do not rely on precise projections of changes, need to be developed. There is no doubt that good adaptation to the present climate and its variability augurs better for adaptation to the future, changed (and not precisely known) climate.

There are many questions related to adaptation: What to do? When to start action? How fast to proceed? How to incorporate the updating mechanism? What are the costs of action, as compared to the cost of inaction? Responses that are more costly or long-term would be applicable once uncertainties are reduced. Expensive structural adaptation actions should not be realized unless economically justified (i.e. unless the expected cost of inaction is very high). Flexibility (keeping options open) is always an advantage.

It is important to do things that make sense anyway. It is always good to save water (hence prospect for water demand management) and improve water use efficiency in agriculture (“more crop from a drop”). Other common-sense slogans like “learning to live with floods and droughts”, creating “room for the rivers”, “keeping water where it falls” (enhancing storage via watershed management), and “making risk taker pay” deserve to be broadly applied.

There is a focus on the ‘‘soft path’’ to climate adaptation (e.g., Gleick, 2002). The soft path may include non-structural measures, such as water conservation; demand management (e.g., through water pricing); floodplain zoning; disaster relief and emergency preparedness – flood forecasting, warning, and evacuation plans; flood and drought insurance; optimization of existing systems (e.g. optimization of reservoir operation rules); modification of cropping systems towards water conservancy; adjustments in protecting water quality; adjustment in river transportation; modification (enhancement) of water storage and other water augmentation measures; adjustments in protecting water quality in rivers and reservoirs; utilization of hydropower. However, the ‘‘soft path’’ alone would not be sufficient for the needs of most of the developing world.

Risk sharing and risk transfer mechanisms can increase resilience to water-related extremes. Risk transfer can provide means to finance relief, recovery of livelihoods, and reconstruction, to reduce vulnerability, and incentives for reducing risk. Mechanisms include flood and drought insurance, reinsurance, and national and international risk pools.

Low-regrets measures for managing water problems have the potential to produce co-benefits, e.g., they help addressing other development goals (e.g. improvements in livelihoods, human well-being, and biodiversity conservation), and help minimize the scope for maladaptation.

It is always worthwhile to continue augmenting the data base important for informing the decision and adaptation process (inventorying, monitoring, assessment, transfer of information and technology, and financial assistance).

As noted by Stakhiv (2011), the water resources management sector has developed a variety of strategies to deal with periods of high demand and low water availability. They consist of longer term infrastructure ‘‘adaptation’’ to stationary climate signals and shorter term ‘‘adaptive management’’ measures that center mostly on flexible operations, forecasting and innovative uses of existing delivery and supply infrastructure to meet unexpected demands and match changing extremes. There are five ways that water managers have of adapting to climate variability and change, and different water management strategies employ various combinations of all the categories listed below:

- Planning new investments, or for capacity expansion (reservoirs, irrigation systems, levees, water supply, wastewater treatment).
- Operation, monitoring and regulation of existing systems to accommodate new uses or conditions (e.g., ecology, climate change, population growth).
- Maintenance and major rehabilitation of existing systems (e.g., dams, barrages, irrigation systems, canals, pumps, etc.).
- Modifications in processes and demands (water conservation, pricing, regulation, legislation) for existing systems and water users.
- Introducing new efficient technologies (desalination, drip irrigation, wastewater reuse, recycling).

In some developed countries, components of existing systems are resilient and could accept moderate climatic change without dramatic damages. Existing, well designed and maintained, engineering structures and systems cope well with natural variability and uncertainty. It is important to carry out life-cycle management of aging infrastructure, to increased frequency of inspections, oversight and regulation of infrastructure during operation and maintenance and to perform vulnerability assessment of existing water infrastructure. Risk-averse societies may be willing to pay for a safety factor in order to avoid failures, even if this may lead to overdesign. This situation, however, does not hold universally. There are considerable problems in many developing countries, where the water infrastructure is inadequate, but financial resources are scanty.

Anticipatory policies would be necessary if the project life time is long enough to deal with possibly changed climate. Water storage reservoirs undoubtedly belong to this category. It may be anticipated that a dam will be needed in several decades. If such a dam is being built now, it may be useful to "design-in" the possibility of further augmentation. This is again a call for flexible design, with possible variants, depending on the development of situation, to accommodate realization of various scenarios.

Studies of impact of climate change on damages caused by hydrologic extremes may determine the costs of avoided loss if adaptation were in place. Regional studies devoted to the impact of climate change on flood damages are scarce, but Feyen et al. (2009) arrived at expected annual damages at the European Union (EU) and country level. It was simply assumed that the flood protection level depends on the country's GDP (protection up to 100-year, 75-year, and 50-year flood for countries with GDP above 110%; in the range from 55 to 110%; and below 55% of the average GDP level in 27 EU Member States, respectively). Also assumptions of no adaptation to increasing flood levels and no growth in exposed values were made. Under these simplifying assumptions, useful and interesting indicative results were obtained, thereby the present expected annual damage was projected to nearly treble in 2071-2100. Out of 25 countries with nonzero flood damages in the control period, increase (up to 80%) is projected in 20 and decrease (even by 85%) is projected in five countries.

Existing water resources infrastructure in developed countries was designed to accommodate variability and standard engineering practices account for those structural failure uncertainties by explicitly designing project redundancy for numerous features. Hence, ''levee freeboard'' was added to account for a ''standard project flood,'' which itself was calculated to accommodate the uncertainties associated with hydrologic variability that is inherent in a relatively short hydrologic record (Stakhiv, 2011).

Due to the difficulty in isolating the greenhouse signal in the observation records and the large uncertainty of projections for the future, no precise quantitative information can be delivered from academia to practitioners as to accommodating the uncertainties. However, increasingly risk-averse societies of the EU undertake simple, common sense, efforts to increase safety margins based on climate change impact scenarios. Water managers in a few countries have begun to consider the implications of climate change explicitly in flood management. In the UK and in some German federal states (e.g. Bavaria) design flood magnitudes have been increased by 20% and 15%, respectively, to reflect the possible effects of climate change. Measures to cope with the increase of the design discharge for the Rhine in the Netherlands from 15 000 to 16 000 m^3/s must be implemented by 2015 and it is planned to increase the design discharge to 18 000 m^3/s in the longer term due to climate change. A ''climate change factor'' shall be taken into account in any new plans for flood control measures in the Netherlands (EEA, 2007). One can expect that in those areas where 100-year floods become lower and the adequate, and properly maintained, protection systems are already in place, the existing defenses will provide higher-than-standard protection level.

There are critical limits on adaptation to changes (Arnell and Delaney, 2006). One being a physical limit: it may not be possible to prevent adverse effects through technical or institutional procedures. For example, during prolonged drought it may be impossible to reduce demands for water further without seriously threatening health or livelihoods. It may physically be very difficult to react to the water quality problems associated with higher water temperatures. In the extreme case it is impossible to adapt where rivers dry up completely. However, whilst it may be physically feasible to adapt, there may be economic constraints to what is affordable. There may be political or social limits to the implementation of adaptation measures. For instance, it can be difficult (if not impossible) to construct new reservoirs due to strong environmental opposition. It may be politically very difficult to adapt to reduced reliability of supplies by reducing standards of service. Finally, the capacity of water management agencies and the water management system as a whole may act as a limit on which adaptation measures (if any) can be implemented (Arnell and Delaney, 2006).

6. Concluding remarks

Climate change affects the function and operation of existing water infrastructure as well as water management practices. Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, land-use change and urbanization.

Despite the uncertainty in projections, it is plausible to expect that the negative impacts of climate change on freshwater systems may outweigh its benefits. Areas in which runoff declines are facing a reduction in the value of the services provided by water resources. The beneficial impacts of increased annual runoff in other areas may be tempered by negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality and flood risks. Increases in runoff are concentrated in the most populous parts of the world and mainly occur during high flow seasons. Therefore, they may not alleviate dry season problems if the extra water is not stored and would not ease water stress in other regions.

It is difficult to disentangle the climatic change component from strong natural variability and direct human impacts on river flow, hence a question „adapt to what?“ comes about. Robust adaptation procedures, which do not rely on precise projections of changes, need to be developed. Adaptation procedures and risk management practices for the water sector are being developed in some countries that recognize the uncertainty of projections. There are common-sense changes to design rules, based on precautionary principle rather than robust science.

There is a focus on the ‘‘soft path’’ to climate adaptation and seeking low regret options. Responses that are more costly or long-term, in areas of much uncertainty of projections, would be applicable once uncertainties are reduced. Water project justification is based on the balance of cost-benefit considerations, being adjusted by societies, with account of climatic and nonclimatic changes, and reflecting economic, social, and environmental components.

It may take decade to decades before statistically significant trends in river flow can be found in some areas, and GCMs are improved to the point where their output can be input directly into water utilities planning models without bias correction and downscaling, or at least for vulnerability assessments.

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