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ScienceDirect

Procedia Environmental Sciences 1 (2010) 120–129

Procedia Environmental Sciences

Application of Climate Information and Predictions in Water Sector: Capabilities

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Abstract

Climate variability and climate change have a large impact on water resources since fundamental drivers of the hydrological cycle get affected. It is beneficial to understand the processes driving these changes, the sequences of the changes and their manifestation at different spatial and temporal scales. The purpose of this paper is to explore strategies to improve water management by tracking, anticipating and responding to seasonal to interannual climate variability and climate change. Sound water management is built upon long-term hydrological and meteorological monitoring networks that provide robust, accurate, timely and consistent data that can be used to develop and access tools needed to quantify uncertainty, forecast change and create the multi-phase, multi-level climate scenarios providing reasonable and relevant management of water resources. Several water management options might be considered in consultation with hydro-climatic and social scientists and stakeholders (decision-makers) to facilitate adaptation under climate variability and/or climate change and these are illustrated with suitable examples.

Keywords: Impacts of climate change; decision support; capability assessment; integrating climate information; case studies

1. Introduction

Water resources are directly dependent on the abundance of rainfall and snow, and how we store and use the amount of water available. Precipitation, temperature, runoff, groundwater and streamflow are key variables controlling water availability. With an increasing population, a changing climate, and the expansion of human activity, water management has unique and evolving challenges. Our ability to adapt and respond to climate variability and change depends on our understanding of the climate and how we incorporate this understanding into resource management decisions by tracking, anticipating and responding to the changes. Further, there is a need to determine those countries, communities, households and individuals who will be most vulnerable to the projected impacts of climate change [1]. The capacity to adapt to climate change is dependent on a wide variety of social, political, economic, technological and institutional factors. The specific interaction of these factors differs depending on the scale of analysis – from the level of the country down to the individual. This paper focuses on the connection between the scientific ability to predict climate on seasonal-to-interannual scales and the opportunity to incorporate such understanding into decisions with particular attention to issues facing water resources managers.

Societies are vulnerable to extreme climate-related events. Reducing societal vulnerability to changes in climate depends upon our ability to bridge the gap between climate science and the implementation of scientific understanding of the water management sector. Climate data, analysis and forecasts, and regional vulnerability assessments assist water resource managers in mitigating the effects of extreme events such as droughts and floods through the use of climate information and the related decision-support resources. Understanding the complex climate–human dynamics necessarily involves interdisciplinary teams from the social, natural and physical sciences as well as decision-makers, stakeholders and resource managers as direct participants at local, regional, state, national and international levels.

2. Water sector impacts due to climate change

Climate change has the potential to affect fundamental drivers of the hydrological cycle, and consequently may have a large impact on the water sector, in which water resource managers play an active role. This in turn might affect society in many ways and particularly the sectors fully dependent on water. The major drivers are greenhouse gases and global warming impacting temperature (T), precipitation (P) and stream flow (Q) regimes and increasing global sea level and associated impacts (Figure 1). Further, many dynamic processes have impacted, and will continue to impact water resources management in addition to climate change [2]. Important changes in land cover and land use, water consumption and water resources infrastructure will affect water resources management.

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doi:10.1016/j.proenv.2010.09.009

A water manager needs tools to predict the development of a) the state of the basin's natural water resources, b) the water demands of different consumers under a changed climate and c) the state of the water supply infrastructure and its ability to provide for adequate water supply. All these predictions need to be spatially and temporally explicit.

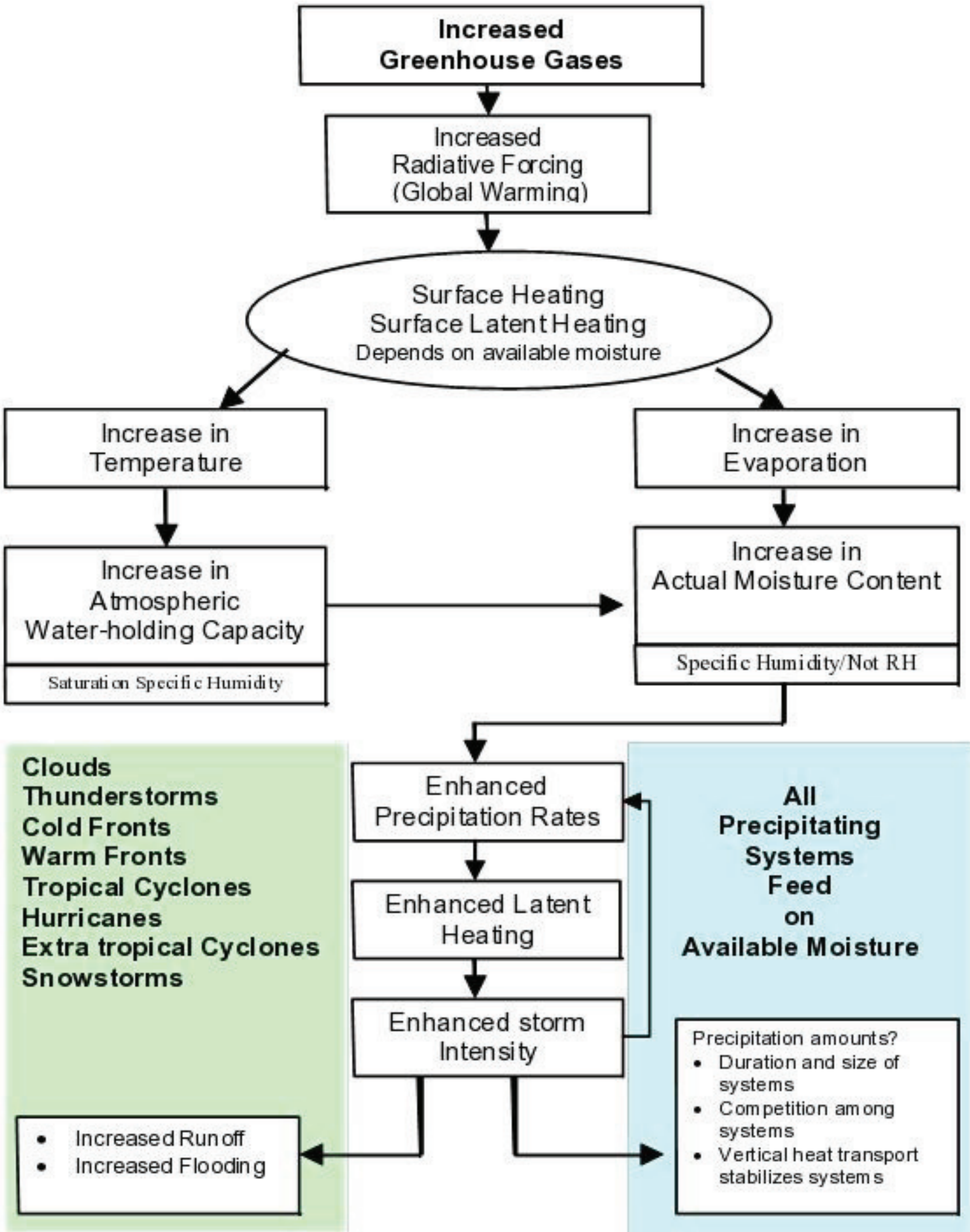

Figure 1. Conceptual model of the effect of greenhouse gases and global warming on the hydrological cycle and phenomena associated with climate extremes (Source: Ministry of Water Resources [3])

Physical models are traditionally used to predict the spatially and temporally explicit state of water resources. The traditional prediction of demand relies on data-driven methods such as trend extrapolation, regression analysis, time series analysis and rule-based and expert knowledge based systems [4]. However, to be realistic and meaningful, all methods should consider existing feedbacks between demand and supply, and the various options of adaptations the consumers have (Figure 2).

Climate change will affect not only the state of resources but also the ways and magnitude of consumption. Potential water resources management sector impacts are briefly summarized as follows:

(a) Available water resources for municipal, industrial and agricultural use, navigation support, hydropower and environmental flows is a significant concern in regions throughout the world. Potential climate change impacts affecting water availability include changes in precipitation amount, intensity, timing and form (rain or snow); changes in snowmelt timing and changes to evapotranspiration [5]. The prudent use of reservoir storage, as well as conjunctive surface water and groundwater management are strategies that water managers employ to optimize water availability.

(b) Water demand for irrigation may increase as transpiration increases in response to higher temperatures. Depending on future trends in water use efficiency and the development of new power plants, the demand for water in thermal energy generation could either increase or decrease. These changes in demand may require water managers to re-evaluate the effectiveness of current demand management.

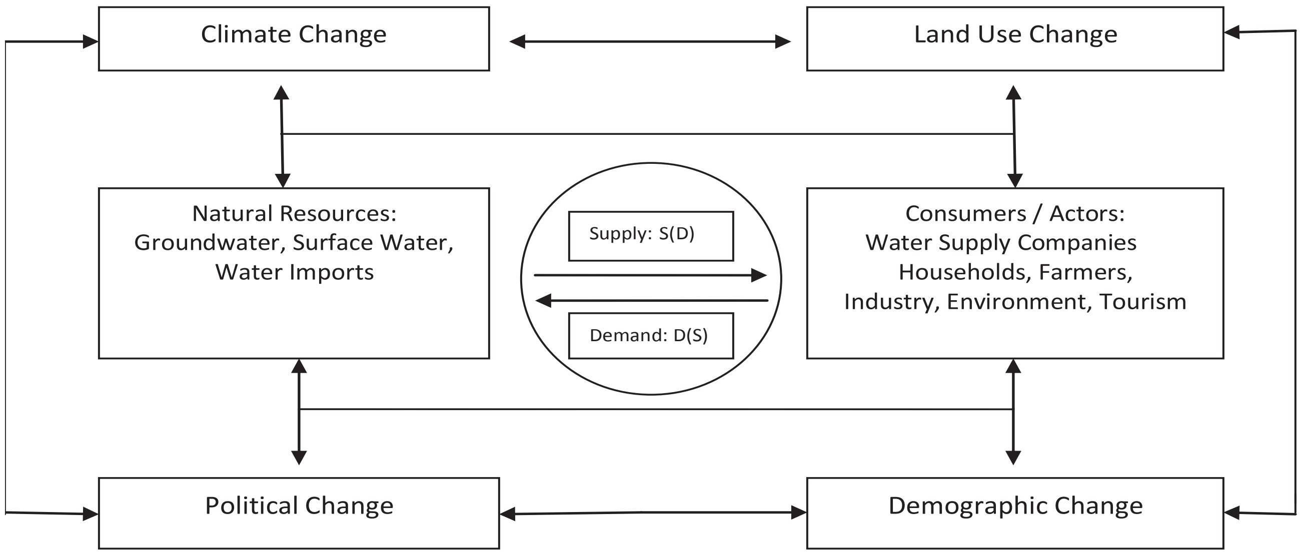

Figure 2. Influences of global change on the demand/supply relationship in a river basin where demand is a function of supply and vice versa (Source: Barthel et al. [4])

(c) Water quality is impacted by changing precipitation and temperature resulting from climate change [2]. Changes in water resources may affect chemical composition of water in rivers and lakes. Changes to precipitation intensity and frequency influence non-point source pollution. Areas with melting glacial ice may become susceptible to soil erosion.

(d) Storm-water and wastewater infrastructure may need to include climate change effects in their design and evaluation to improve performance under changing water availability, water demand and water quality conditions.

(e) Flood risk reduction structures, water system operational strategies and resource management decisions may face more intense rainstorms, more events of rain or snow, and greater portions of watersheds participating in rainfall runoff generation creating more frequent and more severe flooding. The design and evaluation of flood risk reduction infrastructure should use the most recent available data and consider possible future climate conditions, including shifts in the seasonal timing of typical high flows. Reservoir water control plans may need to be adjusted to reflect new flood regimes.

(f) Drought results when precipitation is significantly below normal, causing serious hydrological imbalances that adversely affect land resource production systems. The Intergovernmental Panel on Climate Change [5] concluded with high confidence (90 per cent probability) that the extent of drought-affected areas will likely increase. The climate change projections indicate that even though farmers have largely adapted to dryland agriculture, increased demand and consequent water stress could severely jeopardize livelihoods and diminish agricultural productivity. Much has been done to address water shortages with a particular focus on supply- and demand-side remedies including large water storage infrastructure, watershed development, rainwater harvesting, efficiency in groundwater use, water conservation and a host of community initiatives.

(g) Rising sea levels would have a profound effect on coastal systems, including wetland loss, loss in the productivity of estuaries, changes in barrier islands, changes in groundwater systems and increased vulnerability to coastal erosion and flooding [2]. Given that estimates of future rates of sea-level rise remain uncertain, planning and design studies should consider designs that are most appropriate for a range of possible future rates of rise [6].

(h) Hydropower generation will be affected by changes in water resources where impacts have already been reported. Hydropower production at facilities that are operated to meet multiple objectives of flood risk reduction, irrigation, domestic and industrial water supply, flow augmentation and water quality may be especially vulnerable to climate change.

3. Why decision support ?

Networking between climate and hydrological scientists is getting stronger as they now more frequently collaborate to create forecast products. While much progress has been made conveying climate and hydrological forecasts in a form useful to real world decision-making, complications get introduced that call upon the skills of not only climate scientists, hydrologists, and water resources experts, but also social scientists with the capacity to understand and work within the dynamic boundaries of organizational and social change.

The concept of decision support has evolved over time. Making climate science useful to stakeholders involves a process in which climate scientists, hydrologists and the potential users of their products engage in an interactive dialogue during which trust and confidence is built at the same time that climate information is exchanged. Well-designed tools, institutions and processes can clarify the necessary trade-offs of short- and long-term gains and losses of potentially competing values associated with water allocation and management. Decision-support experiments employing climate-related information have had varying levels of success in integrating their findings with the needs of water resource managers.

Over the course of the 1980s, scientists achieved remarkable advances in probabilistic forecasting of seasonal and interannual variation in climate conditions associated with the El Niño–Southern Oscillation (ENSO). Probabilistic climate forecast information about seasonal and interannual climate variability is increasingly being incorporated into regional water resources decision-making to assess opportunities for improving decisions for the benefit of affected communities, regions and economic sectors. Better hydrological management strategies may not only improve viability of local water supplies but also help mitigate conflicts in areas where there is competition for water rights.

4. Capability assessment

Current projections of climate change and its potential impacts encompass many uncertainties unlikely to be dissipated in the real term. In this context, a strategy that balances detecting and adjusting to changes, and that includes modelling, will be most prudent. Thus, monitoring of climatic and hydrological characteristics plays an important role in addressing potential climate change.

4.1 Tracking climatic and hydrological sensitivities

Data on the components of the natural hydrological system (such as precipitation, snowpack, streamflow, groundwater and water quality) from long-term monitoring networks are essential for establishing baseline conditions and tracking long-term changes over time, and for detecting hydrological changes due to climate change. Rational standards for data collection may be employed so that datasets maintain consistency and relevancy. Monitoring networks are also required for understanding the hydrological processes leading to change in water resources and for validating models used to project future conditions. Information about likely future changes to climate improves the effectiveness of planning and development and implementation of strategies for adapting to a changing climate.

Surveillance and monitoring networks include a tiered approach starting with general inventories using remote-sensing technologies such as radar and satellites, and progressing through several levels to intensive studies at selected locations. Further, to be useful for climate change studies, monitoring networks need to be in place in locations relevant to water managers. In addition, data on human water use can be useful in planning for climate change.

Monitoring networks for detecting change are especially valuable when they are regional or involve local networks that are integrated to allow regional analyses. A comprehensive set of parameters that characterize current and future climate conditions is required for planning and for operational analysis. A number of federal, state and local agencies operate observation networks that are valuable for climate change studies. However, the varying data collection methods limit their utility for evaluating demand interactions with climate.

The continuous long-term meteorological and streamflow data are critical for detecting trends and shifts in the statistics of historical hydro-climatic variables. The non-stationarity in hydro-climatic conditions would answer how trends manifest themselves [7]. While the magnitude of a trend may be easy to quantify, its significance may be ambiguous because of natural climate variability and long-term persistence causing oscillatory patterns in long-term hydro-climatic records [8]. Trend analysis should be conducted over large areas to consider cross-correlation among the stations in a region [9]. It is also important to identify whether a trend occurs as a gradual change or as an abrupt shift. Finally, it is important to understand the cause of the trend to allow modelling of the future events using future development plans as input [10].

Surveillance and monitoring networks provide the basis for evaluating the hydrological models that are routinely used in water resources, including the hydraulic models that are used to route flood flows, or the watershed models that are used to estimate streamflow and water quality conditions under current land use, or the complex models of nonlinear hydrological systems, or the statistical models that are used to estimate water availability. The continued usefulness of these models under a changed climate also requires continued collection of observational data.

Recommendation 1. Continued operation of long-term monitoring networks and improved sensors deployed in space, in the atmosphere, in the oceans and on the Earth's surface are essential for understanding the climate variability, its impacts and the effectiveness of adaptation and mitigation strategies.

4.2 Relating climate information to decision-making

Long-term, long-range water management planning and decisions typically focus on questions about physical and operational system changes. Climate information is reflected in studies through assumptions made about water supplies, demands and operational constraints (Figure 3). Water supply assumptions are a direct reflection of the expected climate and are based on available historical data with the premise that the range of observed supply variability (including but not limited to changing averages or shifts in annual hydrograph shapes) is a reasonable proxy for future supply possibilities. Physical assessments are used to estimate water demands relative to climate and other drivers; the objective might be to identify demand limits relative to available supplies, constraints and required system performance. The final category of assumptions involves the various operational constraints affected by an underlying climate assumption (for example, flood risk evaluations and reservoir operation for flood control).

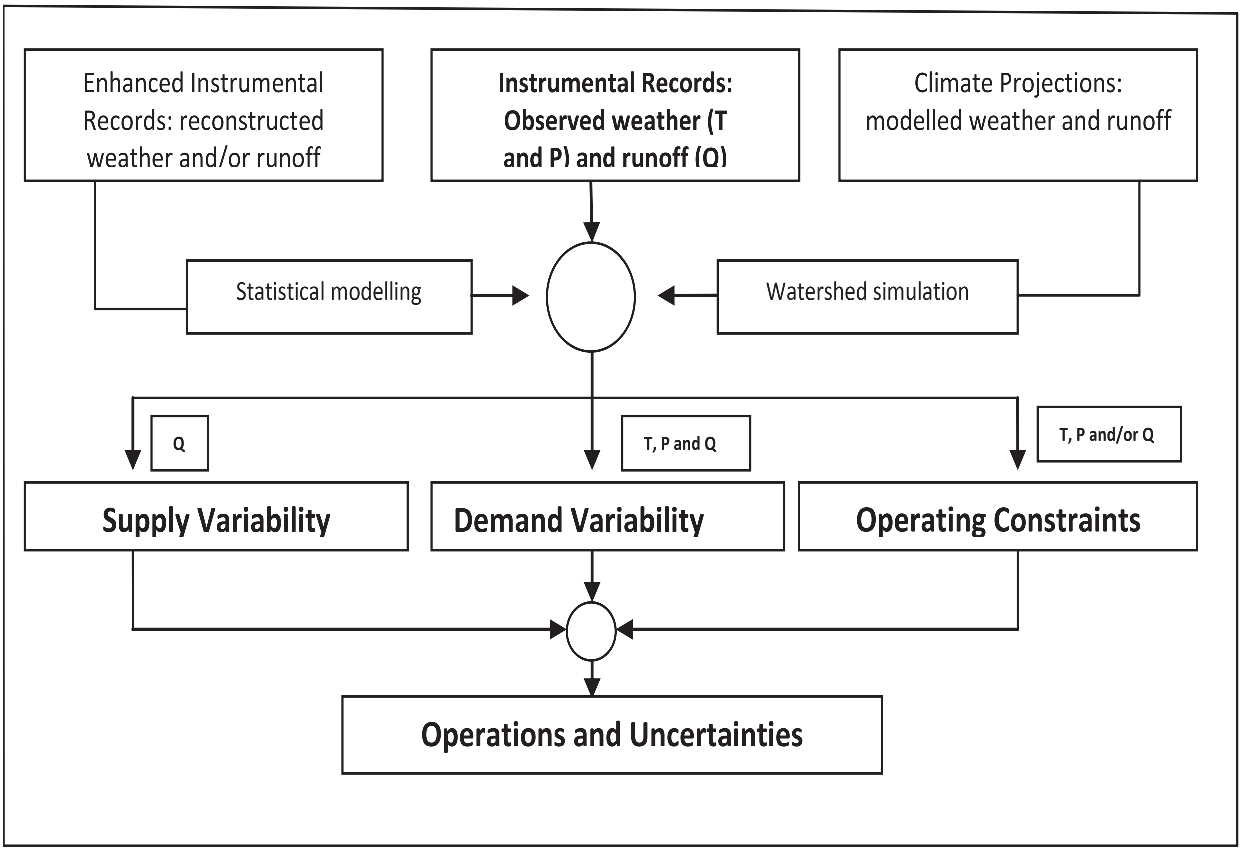

Figure 3. Analytical framework for relating climate to water supplies, demands and constraints (Source: Brekke et al. [11])

To expand on the historical record basis for planning, statistics of the instrumental record are to be preserved while allowing for possible changes in the sequencing of conditions. This gives rise to developing synthetic hydro-climatic time series using stochastic modelling. The instrumental record offers one reference period to support stochastic modelling. Further, the paleo-climatic information may indicate a wider range of hydro-climatic variability prior to the instrumental records [12].

Given the evidence of recent climate trends and projected future climate conditions, the recent attempts are intended to relate planning assumptions to projections of future temperature and precipitation [5]. These climate projections are based on global climate modelling that represents our current understanding of cause and effect in the climate system. Global climate modelling groups generally report monthly values of temperature and precipitation. Temporal disaggregation techniques are then required to provide the needed daily weather data on temperature and precipitation projections to drive hydrological simulations, currently a matter of research.

Recommendation 2. Paleo-climatic information, instrumental records and stochastic modelling can be blended for developing climate scenario for water management planning and decision-making. Opportunities also exit to blend paleo-climatic and projected future climatic information using global climate modelling and disaggregation techniques.

4.3 Scaling decision-making processes

Water management decisions are made at a variety of space and timescales and are informed by assumptions about supplies, demands, weather, climate and operational constraints at those scales. Spatial scales for decision-making range from local, to state, to regional, to national and to international – from stream corridors to multistate regions. Temporal scales range from hours to days to multiple decades impacting policy, operational planning and management, and near real-time operational decisions. Resource managers often make multi-dimensional decisions spanning various parallel and temporal frames. Decision-makers need to understand the types of predictions that can be made, and the trade-offs between longer-term prediction of information at the local or regional scale on one hand, and potential decreases in accuracy on the other. Often decision-makers, scientists and stakeholders need to work together in formulating research questions relevant to the spatial and temporal scales of the problems to be managed.

Many decisions involve application horizons ranging from days to years, such as daily reservoir release scheduling, monthly operations scheduling to determine annual water allocations and hydropower marketing strategies. These decisions occur at timescales that are shorter than those required for detecting climate change [5]. Instead of being informed by future climate projections, these decisions are informed by climate information from the past. The past information is used to calibrate water supply forecast models and to provide a basis for demands and operating constraints during upcoming months and seasons.

Because climate change is traditionally detected over a period that spans multiple decades [5], decisions with application horizons greater than 20 years might reasonably be informed by climate change information. Examples of such decisions include general planning studies exploring feasibility, economic benefits and costs and estimation of risks to decide alternative actions, infrastructure or a long-term operations criterion; expected benefits and impacts of proposed actions; environmental conditions and aquatic species likely to be affected by proposed actions; etc.

In many planning studies, it is necessary to conduct a multi-objective analysis that compares the economic costs with the benefits of alternative plans. The planning process is supposed to explicitly consider future conditions during the planning horizon; this step could include a forecast of climate change impacts [13]. Planners identify areas, risk and uncertainty and describe them clearly so that decisions can be made with knowledge of the degree of reliability of the estimated benefits and costs.

Recommendation 3. Decision-makers need to understand the types of climate predictions to be made, and the trade-offs between longer-term prediction of climate information at the local or regional scale on one hand, and potential decrease in accuracy or increase in vulnerability on the other.

5. Decision-support tools and modelling systems

Sensitivity analysis and scenario planning are tools for understanding the uncertainty in decision-making. Scenario analysis is one method to deal with complex, uncertain systems. The scenarios could be defined relative to climate projections, demographic outlooks and other planning drivers. Such scenarios might be called top-down and may include climate and socio-economic scenarios, global circulation model output, regional downscaling, projected responses, identification of vulnerabilities, development of adaptation options and the assessment of alternatives [11]. These contrast with bottom-up scenarios defined with a sensitivity analysis where thresholds of operations flexibility are revealed by incrementally adjusting planning drivers. These approaches include assessing alternatives, projecting responses, regional downscaling, developing adaptation options, identifying drivers and identifying vulnerabilities, and are generally not exclusive [11].

Water resources agencies have generally employed statistical models to estimate the likelihood of future hydrological events. Hydrologists recognize that there are multiple sources of uncertainty in these estimates due to sampling errors and measurement errors. Model uncertainty is much more difficult to identify. The underlying assumption behind using a statistical model may be wrong when past data are stationary and unrepresentative of the future. Another approach is to estimate probabilities based on subjective judgement to assess the likelihood of future climate change. However, probability estimates using these approaches could give misleading results that do not consider the full range of uncertainty.

Recommendation 4. Adopting alternatives that perform well over a wider range of future scenarios could improve system flexibility, an approach that requires an appreciation of existing and potential uses of water resources.

Robust decision criteria try to choose plans that perform well over a wider range of possible future scenarios. Robustness is an alternative decision criterion for planning. Brekke et al. [11] discussed an approach that features robust decision criterion and named it “Robust Decision-making”; its four elements are:

(a) Consider a large number of scenarios that contain a range of plausible futures that are as diverse as possible;

(b) Seek robust rather than optimal strategies that do well across a broad range of plausible futures;

(c) Employ adaptive strategies evolved over time in response to new information to achieve robustness;

(d) Use computer tools for interactive exploration of the multiplicity of plausible futures.

Robustness methods are superior to sensitivity analysis. The robust policy performs well across a wider range of plausible futures. Robust decision criteria are compatible with other decision criteria and could be an additional piece in a multi-criteria problem [14].

Adaptive management is a sequential decision process for dealing with climate change, and promotes flexible decision-making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood [15]. Adaptive management offers a framework where robust decision criteria may be considered. Adaptive management is an iterative process of six steps: 1) assess the problem, 2) design, 3) implement, 4) monitor, 5) evaluate, and 6) adjust. Adaptive management can be used for any dynamic system where there is uncertainty about the future. For example, adaptive management has been used for evaluating alternative reservoir releases in order to improve downstream aquatic habitat [15].

Adaptive management is more suited to guiding operational or institutional changes than to the construction of new water facilities. Structural solutions may be hard to reverse unless they are designed to anticipate alternative future conditions with planned upgrades. The adaptive management approach toward climate uncertainty would follow a course of monitoring conditions and adjusting policies as changes are observed or uncertainty is reduced [15].

Although controversial, the use of indicators and indices is one means of quantifying adaptive capacity for the use of policymakers. While the theoretical driving forces of adaptive capacity are similar, they manifest themselves differently depending on scale: using the same indicators at both national and sub-national level is not feasible. Vincent [1] utilized two different indices of adaptive capacity developed for national and household scales for uncertainty analysis in decision-making.

The approaches outlined above to deal with uncertainty due to climate change are not incompatible and can be used in conjunction with current water management planning methods that primarily employ cost-benefit analysis and sensitivity analysis. All of these approaches present options and then try to assess their performance under a range of conditions. The value of each approach lies in its application to a specific problem. Each approach can be helpful, but may give a false notion that much more known about the future than actually is.

Recommendation 5. Adaptive management allows adjustments to be made as more information is known. This approach could be useful in dealing with the additional uncertainty introduced by potential climate change.

6. Responding to climate change

There are several water management options that might be considered to facilitate adaptation to climate change including operational changes, demand management and infrastructure changes. Climate change may translate into changed design and operational assumptions for determining resource supplies, system demands, system performance requirements and operational constraints. The strategy options available for consideration will vary from system to system.

In the following paragraphs, available options are presented for adapting to climate change as it occurs across various temporal and spatial scales. These options include the incorporation of lessons from responses to climate variability into longer-term vulnerability reduction efforts and within governing mechanisms from communities and watersheds to international agreements.

Operational changes make better use of existing water resources by building more flexibility into the response to climate change. Existing operating plans are based on the historical climate such as flood control rules based on historical flood risk evaluations that have a climate context. There may be benefits from revising reservoir storage rules and authorized purposes as the climate and social values change. Adaptation to climate change also includes making coordinated use of surface water and groundwater to optimize the use of both sources, also referred to as conjunctive use.

In the short term, water managers could increase the adaptive capacity to climate change through increased operational flexibility. One way could be through the use of intra-seasonal to interannual climate forecasts. Much of the seasonal forecast skill is due to predictions of the El Niño-related floods and the La Niña-related droughts which generally led to severe socio-economic impacts.

Demand management is a strategy to make better use of water, reducing waste and increasing economic efficiency. Reducing the demand for water has been advocated as a way to reduce the vulnerability of managed water systems to climate change. Demand side management balances water demands with limited available supplies by employing a more efficient allocation of existing supplies. Thus, water that is saved reduces the need for costly infrastructure.

One adaptation strategy is to enhance mechanisms for market-based transfers of water among users. Transfers can either be permanent by purchasing water rights or temporary by having contracts to purchase water during dry years. Markets and higher prices provide an incentive to adopt water conservation during periods of limited supply and drought. Another strategy is to reduce overall water consumption through conservation and efficiency improvements. However, most measures to reduce demand are implemented at the local or state level.

Infrastructure modifications include up-to-date maintenance, rehabilitation and upgrades to ensure flexibility to a wider range of potential climate variability. One important adaptation to a changing climate is the evaluation of the potential risk to existing infrastructure, such as dams and levees, caused by possible increases in the magnitude, frequency and duration of large floods. Alternative strategies for meeting project goals may need to be evaluated and may result in modification to infrastructure.

All of these options have to be based on comprehensive studies, including in particular:

(a) Developing and improving comprehensive monitoring of climate observations, hydrological parameters, water resources and their use;

(b) Developing more reliable and detailed climatic scenarios for the near future, and adapting the scenarios to different regions.

Challenges frequently crop up in evaluating and implementing the adaptation options. There is uncertainty about the hydrological impacts of climate change. Resources are limited and there are many competing demands for funding. There are also legislative and regulatory requirements that could limit adaptation options. Agencies may also need to adopt a decision-making framework that encourages robust solutions that can be updated over time. Finally, effective adaptation to climate change will require collaboration and coordination among individuals and federal, state, regional and local agencies.

Recommendation 6. Water management options, including operational changes, demand management and infrastructure changes, should be considered to facilitate adaptation to climate change. Decision-making frameworks using robust solutions should be encouraged.

7. Integrating climate information with societal needs

Scientific understanding of climate variability and climate change has expanded dramatically. Much of that information is lost on the public and on the water managers who urgently need it to reduce risk and increase economic opportunities but are reluctant to innovate and use data and tools from new sources. Most scientists have a limited understanding of the information needs of stakeholders and of the political, institutional and economic contexts of decisions. Educating stakeholders regarding characteristics of future climate change relevant to their resource management activities has become an increasingly pressing need over the last few years. In order to successfully meet this need, the scientific community must understand the stakeholders' vulnerabilities to prospective climate change (both natural and human caused); the impacts on water resources, demand and relevant quality characteristics; the response options available to them; and the types of information needed for incorporation into their longer-term decision-making processes. Networks of researchers, including hydro-climatic and social scientists, should actively seek more integrated involvement with the water resources management community, adapt their research agenda and activities to address the needs of stakeholders, and commit to develop practical products and decision-support tools.

Many of the uncertainties regarding future climate change will not be reduced before decisions are made for planning purposes across a wide range of human activities such as resource management, human health management and mitigation plans. Given this basic condition, new protocols are necessary for managing uncertainty and for making decisions in the near term for long-term water management. Miller and Yates [16] developed a protocol for linking the research on uncertainty assessments within climate forecasts and impact analyses with work on decision-making and policymaking. The ultimate goal of this integration effort is to ensure that scientific information effectively connects with the needs of the stakeholders. The components of such a protocol could be described in a seven-level process: 1) identify the stage in the decision process where climate science could enter; 2) ensure that scientific input is truly useful; 3) identify the type of programme the stakeholder faces; 4) identify the specific decision challenge; 5) identify necessary uncertainty analyses; 6) conduct identified uncertainty analyses; and 7) communicate uncertainties back to the stakeholder. Steps are being taken to ensure that the protocol meets the goals of usefulness and applicability for all kinds of climate-sensitive decisions and in a variety of contexts.

All water users need to have the ability to obtain climate information in real time in order to understand risks and to be able to plan accordingly. Risk perception, analysis and management as well as specific socio-economic and institutional aspects of climate variability and change are necessary for an understanding of how a jurisdiction plans to respond to water demand in the face of decreasing availability. Of particular interest is the understanding of how decisions are made to allocate water given competing demands from the residential, agricultural and environmental sectors. An essential element in moving away from an ad hoc response to preparedness and mitigation is more sophisticated impact information. The socio-economic impacts of climate change encompass the costs of extreme events (droughts or floods) and the effects of collective mitigation efforts. The context for analysis includes the institutional constraints and any innovations in the area of preparedness, as well as the data and information needs related to reducing vulnerability to climate impacts. Water management in river basins should include an inventory of relevant research, an assessment of ongoing activities of government agencies, a synthesis of the present use of climate information including data and forecasts, an accounting of gaps in information and approach and recommendations for future opportunities and activities.

Recommendation 7. Hydro-climatic and social scientists should actively seek more integrated involvement with the water resources management community; adapt their research agenda and activities to address the needs of stakeholders; and commit to develop practical products, innovations and decision-support tools.

8. Case studies of adaptation strategies

In recent years, governmental organizations have explored the use of expanded climate information to support various water resources planning efforts. In the two case studies listed below, the planning focus involves evaluating proposed or anticipated plans for long-term operations and water control. Stakeholders in these studies wanted the impact and outcomes to be related to projected climate information and climate variability.

A Colorado River Basin study used nonparametric stochastic modelling with paleo-climatic information to guide water supply variability assumptions in operations planning for the Colorado River storage system [17].

The purpose of the proposed action was to improve management of the Colorado River by considering tradeoffs between the frequency and magnitude of reduction of water deliveries on water supply, power production, recreation and other environmental resources, particularly under drought and low reservoir conditions.

In developing assumptions about hydrological variability two climate regimes were referenced in the study: a) the climate of instrumental record during 1906-2005, and b) the climate from a 1244-year annual reconstructed streamflow based on tree ring records [18]. Stochastic modelling was used to develop synthetic hydrological and water supply sequences consistent with either reference climate. The resultant Colorado River Simulation System was used to look at a range of future river conditions through 2060 under each action alternative.

A water resources planning case study in the east of England follows a structure that considers all of the components of a company's water balance for each year until the planning horizon of 2030 [14]. This involves evaluating the amount of water available for supply as well as all of the demand on this water. Climate change is expected to exacerbate drought-like conditions because of increasing temperatures and drier summers.

Methods employed to elicit the adaptation options included extensive literature reviews, elite interviews with water managers and in-depth examination of planning documents. The next stage linked options with changes in climate variables (temperature and/or precipitation) by combining climate change scenarios with observed climate records, which served as input to a hydrological-yield model (impact model) giving water yield change as output. Using these results it is possible to link changes in climate variables with impacts and subsequently with adaptation options required to maintain a certain level of service.

9. Way forward

The preparation for managing unpredictable future changes is to put in place a water resources infrastructure and management system that is driven to a much greater degree by knowledge (including but not limited to hydrological knowledge) and that is designed and operated to be much more flexible and adaptive.

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