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Climate change impacts on water resources planning and management: scientific challenges and beyond

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Abstract: Planning and management of water resources has always been a difficult problem, since water resources are highly sensitive to the nonlinear nature of hydrologic processes and their complex feedback mechanisms. Population explosion and its many associated effects (e.g. urbanization, water pollution, deforestation) have already caused enormous stress on the world's fresh water resources, especially in the developing world. According to the latest World Health Organization estimates, about 900 million people still lack access to safe drinking water and about 2.5 billion people lack access to proper sanitation. With the global climate change (already believed to be occurring) anticipated to have threatening consequences on our environment and water resources both at the global level and at the local levels (e.g. increases in the number and magnitude of floods and droughts, increases in sea levels), a general assessment is that the future state of the world's water will be a lot worse than it is now. The facts that over 300 rivers around the world are being shared by two or more states and that there are already numerous conflicts in the planning, development and management of water resources in these basins (especially in dealing with floods and droughts) further complicate matters for future water resources planning and management.

In view of these, any sincere effort towards proper management of our future water resources and resolving potential future water-related conflicts will need to overcome many challenges (globally and locally). These challenges are both scientific (herein refers mainly to the biophysical and engineering aspects) and non-scientific (herein refers mainly to human and managerial aspects). The scientific challenges include: identification of the actual causes of climate change, development of global climate models (GCMs) that can adequately incorporate these causes to generate dependable future climate projections at larger scales, formulation of appropriate techniques to downscale the GCM outputs to local conditions for hydrologic predictions, and reliable estimation of the associated uncertainties in all these. The non-scientific challenges have social, political, economic, and environmental facets that often act in complex and interconnected ways; proper 'communication' of (or lack thereof) our climate-water scientific research activities and findings to fellow scientists and engineers, policy makers, economists, industrialists, farmers, and the public at large is also a key component in these challenges.

The present study is intended to detail the above challenges. The need for a new framework that addresses these challenges in an integrated manner is also highlighted.

Keywords: *Climate change, water resources, impact assessment, science, society*

1. INTRODUCTION

The need for water for our survival cannot be overstated. However, planning, development, and management of our water resources has always been a tremendously difficult problem. Part of this difficulty has come from our lack of scientific understanding of the various nonlinear hydrologic and climatic processes, their complex interactions and feedback mechanisms, and their influence on water resources. Another part of this problem, however, has come from our population explosion (especially since the second half of the twentieth century) and its many associated effects (e.g. urbanization, water pollution, deforestation) on the availability of water resources for our health, environment, and economic well-being.

Despite all the scientific and technological advances we have made over many centuries, we must acknowledge that many of our efforts to harness water have been inadequate or even misdirected. We remain ignorant of the functioning of basic hydrologic and climate processes. Rivers, lakes, and groundwater aquifers are increasingly contaminated with biological and chemical wastes. Vast numbers of people lack clean drinking water and rudimentary sanitation services. According to the latest WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP), 900 million people (almost one in six) still rely on unimproved drinking-water supplies and 2.5 billion people (more than one-third) still remain without improved sanitation facilites (WHO/UNICEF, 2008). Millions of people die every year from water-related diseases (e.g. malaria, typhoid, and cholera), which are the third leading cause of death from infectious diseases; for instance, in 2004 diarrhoeal disease alone caused more deaths than HIV/AIDS (WHO/UNICEF, 2008). The calamity of this situation is reflected by the fact that the majority of these deaths are among children under five years of age. On the other hand, massive water developments have also destroyed many of the world's most productive wetlands and other aquatic habitats, and the economic and environmental resources for major new water and irrigation projects simply cannot be found.

While the present water situation itself is gloomy, global climate change is anticipated to have threatening consequences on our environment and water resources, both at the global level and at the local levels. The crux of the global climate change problem is this: Human activities over the last century have, it is believed, led to increases in the atmospheric concentration of trace gases that trap heat in the atmosphere. As the concentrations of these gases rise, the behavior of the earth's climate will be affected in ways that are only partly understood, but that will most likely include higher temperatures. With the projected global temperature increase, scientists generally agree that the global hydrologic cycle will intensify and suggest that extremes (e.g. floods, droughts) will become more frequent and with greater magnitude. Recent increases in abnormal floods and droughts have only strengthened this thought. Other ways in which global climate change could directly or indirectly influence our water resources include sea level rises and bush fires.

Looking at these future climate change projections and their potential effects, it is reasonable to make a general assessment that the future state of the world's water resources will be much worse than it is now. For example, it has been estimated that, by 2025, about 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be under 'stress' conditions. A direct consequence of this may be an increase in water-borne diseases and other related problems. Further complicating the future water situation (both at the global level and at the local levels) are the shared international river basins. As of now, over 300 rivers around the world are being shared by two or more countries (e.g. the Nile River in Africa is shared by ten countries, the Mekong River in Asia is shared by six countries, and the Jordan River in the Middle East is shared by four countries). As these rivers are the sources of numerous conflicts (or sometimes serve as a means to settle political and other differences) between the countries sharing them, adequate planning, development, and management of waters of these rivers are largely affected. It is also important to note that difficulties in planning and management and thus the possibilities for conflicts in these shared river basins are far greater during times of extreme hydrologic events, such as floods and droughts. It is particularly in this context that these river basins and the countries sharing them will likely be the most impacted regions in the future, since global climate change is anticipated to bring more frequent and more intensified floods and droughts.

In light of all these, any sincere effort towards proper planning and management of our future water resources and resolving potential future water-related conflicts in the face of global climate change will need to overcome many important challenges. These challenges, encountered both at the global level and at the regional/local levels, are both scientific and non-scientific [herein, 'scientific' refers mainly to the biophysical and engineering aspects or 'hard' sciences, while 'non-scientific' refers to the human and managerial aspects or 'soft' sciences]. The scientific challenges include: identification of the actual causes of climate change, development of Global Climate Models (GCMs) that can adequately incorporate these causes to generate dependable future climate projections at larger scales, formulation of appropriate techniques to 'transform' (i.e. downscale) the GCM outputs to regional/local conditions for hydrologic analysis and predictions, and reliable estimation of the associated uncertainties in all these. The non-scientific challenges have social, political, economic, and environmental facets that often act in interconnected ways; proper communication of our climate-water research activities to fellow scientists and engineers, policy makers, economists, industrialists, farmers, and the public at large is a particularly difficult task in this respect.

The purpose of the present study is to detail the scientific and non-scientific challenges in studying the impacts of climate change on our future water resources and to highlight the need for a new framework that addresses these challenges in an integrated manner. Although it has only been roughly two decades since we have come to know, with a reasonable degree of certainty, about the climate change issue, the serious nature of it has already resulted in a voluminous amount of literature. It is, therefore, impossible to provide all the specific details of these challenges, and only a general discussion is made.

2. SCIENTIFIC CHALLENGES

The scientific challenges involved in the assessment of climate change impacts on water resources are centered around the following aspects, a general structure of which is shown in Figure 1.

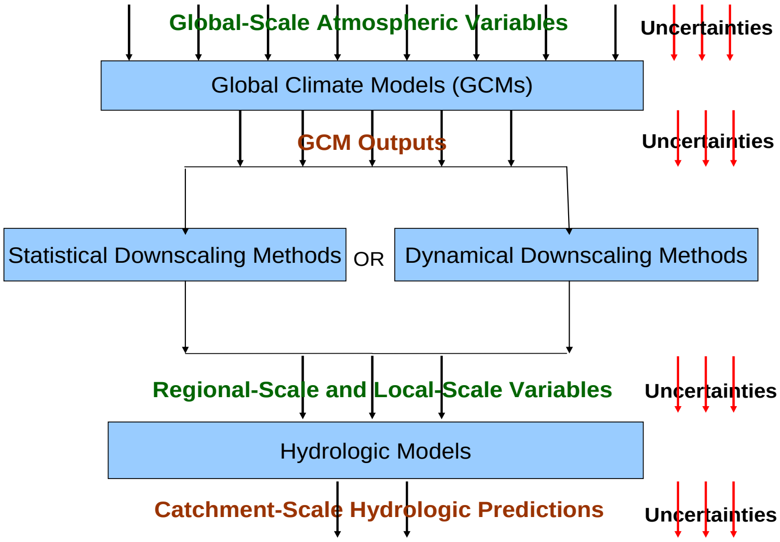

Figure 1. Important steps in the assessment of climate change impacts on water resources and the associated uncertainties.

2.1. Identification of Causes and Assessment of Future Levels

It is now generally accepted that human activities during the last century, mainly through increases in the atmospheric concentration of trace gases, have most likely caused, or at least exacerbated, the changes in global climate. Studies over the last two decades or more have indeed provided a good amount of evidence to support this view [see, for example, IPCC (2007) for details]. Nevertheless, debates and discussions on this issue are still continuing, albeit indications that critics have considerably receded recently.

Even if it is accepted that increases in the atmospheric concentration of trace gases are the causes of climate change, important questions remain on their extent of influence and on their future levels. These questions cannot be answered with any degree of certainty, especially since their answers lie in the future. Although observations of recent increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level provide some indications, it may still be far too early to adequately comprehend on their extent of influence, considering the fact that a century is a negligible period in the Earth's history and the associated climate phenomena; in fact, this 'negligible period' is used as a basis to argue in favor of our exorbitant contributions to atmospheric concentration of trace gases within just a century and thus to climate change! Similarly, while the various 'emission scenarios' assumed are reasonable under some situations, the future levels of atmospheric concentration of trace gases depend on numerous factors (some may not even be foreseen today) that interact in a multitude of ways in a complex web of social, political, economic, and environmental settings; for instance, one may ask (perhaps sarcastically): do these emission scenarios take into consideration the number of people that will potentially be 'killed by climate changes' in the next 40 years in the population projection and thus emission level determination for 2050 and, even if they do, how reliable are they?

2.2. Global Climate Models and Future Climate Projections

With the identification of relevant factors influencing the climate and also the emission scenario, global climate models can be used to make future climate projections. Climate models are mathematical representations of the climate system, expressed as computer codes and run on powerful computers. There is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above (IPCC, 2007). This confidence comes from the foundation of the models in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes. Experience with climate models indicates that they have consistently provided a robust and unambiguous picture of significant climate changes, including warming in response to increasing greenhouse gases.

Despite the confidence they offer, climate models also show significant errors. While these errors are generally greater at smaller scales, important large-scale problems also exist; for instance, deficiencies remain in the simulation of tropical precipitation, the El Niño-Southern Oscillation (ENSO) and the Madden-Julian Oscillation (an observed variation in tropical winds and rainfall with a time scale of 30 to 90 days). The fundamental reason for these errors is concerned with our inability to explicitly represent, in these models, the many important small-scale processes, which can thus be included only in approximate form as they interact with large-scale features. While this is partly due to limitations in computing power, our lack of scientific understanding and/or lack of detailed observations of some physical processes also contributes to this. As a result, significant uncertainties are associated with, for example, the representation of clouds and in the resulting cloud responses to climate change. In the specific context of water resources, a particularly disheartening observation is that confidence in climate model estimates is low for precipitation when compared to some other climate variables (e.g. temperature).

Another important thing to note is that almost all of the climate processes and their interactions are inherently nonlinear and also often chaotic in their dynamics (e.g. Lorenz, 1963; Sivakumar, 2000). It is possible, therefore, that exclusion of even a single relevant factor (however small its influence is believed to be) or observational errors (however small they appear to be) can significantly affect the workings and outcomes of these models. Considering our limited understanding of the climate system and our inability to make accurate observations, this problem could turn out be far more significant than one might tend to believe.

2.3. Transformation of Large-scale GCM Outputs to Smaller Scales

Since global climate models produce outputs at much larger spatial scales than those required for regional or catchment scale hydrologic and water resources analysis, transformation of data between these scales (i.e. downscaling) becomes essential. For this purpose, numerous downscaling techniques have been developed, which may be put under two broad categories: (1) Statistical downscaling – this approach uses an equation to represent the relationship between small-scale phenomena and the large-scale model behavior, which may be obtained from change factors, regression models, weather typing schemes, and weather generators; and (2) Dynamical downscaling – in this approach, a high-resolution climate model is embedded within a GCM, in the form of a regional climate model (RCM) or a limited area model (LAM). Extensive details on these approaches and their advantages and disadvantages are presented in several studies (e.g. Fowler et al., 2007).

Either of these approaches can provide reasonable downscaled simulations, but the accuracy achieved depends strongly on the quality of the GCM simulations used as well as the nature of the transformation function adopted. An alternative to these approaches is the use of a nonlinear dynamic system to formulate the downscaling framework. However, the utility of such an option depends on the extent of consideration, especially the system’s nonlinear and chaotic dynamic nature. Another important limitation with GCM outputs, especially when it comes to downscaling for water resources applications, is that rainfall is only a secondary output from GCMs but is the primary input for water resources studies. This necessitates identification of primary GCM outputs that are reliable as the basis of ascertaining catchment-scale rainfall, which is often a challenging task. In view of these, the current downscaling approaches have some serious drawbacks, and thus there is indeed a need for a new approach to overcome such drawbacks.

2.4. Hydrologic Analysis and Prediction at Catchment Scales

Despite the significant advances we have made during the last century, our ability to model hydrologic systems and forecast hydrologic processes is still far from adequate. An important (and also inevitable, as it has turned out) outcome of our technological and methodological developments are highly complex rainfall-runoff models. It is true that additional model complexity oftentimes helps towards a better understanding of hydrologic systems and processes. However, complex models also bring with them many difficulties, such as requirements of more data, time, and computational resources, and the associated uncertainties. Extensive details of these issues are already available in the literature (e.g. Beven, 2002; Sivakumar, 2008a, b).

One particularly important problem in hydrology and water resources (and in most other fields) is our inability to model and forecast the extreme events, such as floods and droughts. This problem will have enormous implications in the future in the face of climate change, since extreme events are anticipated to happen not only more frequently but also with much greater magnitudes. What additional hydrologic factors will come into play as a result of climate change, what kind of data/parameters will be needed to represent them, and how will they be incorporated in hydrologic models are extremely relevant questions to ask, but the answers are not at all clear. In fact, we do not seem to have even seriously considered asking these fundamental questions in the first place, especially in a coherent manner that is required to find the answers.

2.5. Estimation of Uncertainties

The above observations clearly indicate the existence of many uncertainties in the assessment of climate change impacts on water resources planning and management. As shown in Figure 1, these uncertainties arise in each and every step of the ladder, starting from the identification of actual causes of climate change, to future emissions scenarios, to future climate projections at large scales, to downscaling, and finally to hydrologic analysis and predictions at catchment scales. Still further uncertainties may arise during the disaggregation procedure often required to obtain rainfall data at high temporal resolutions (e.g. hourly) from the more reliable monthly or daily data derived from the downscaling step, especially for flood forecasting purposes. The hydrologic models that are used for representing the rainfall-runoff process have their own uncertainties too, a topic of intense debate in hydrology at the current time. Further, the uncertainties are of various types and their levels are also often different, depending upon our knowledge of the system (or sub-system), the model, data, and computational resources.

It is impossible to account for all these uncertainties, because some (or all) are either not known or not well-defined. A huge volume of literature on this issue is already available (e.g. Beven, 2002; Sivakumar, 2008a); due to space limitations, details are not reported herein. Even if the specific uncertainties involved at each of the above steps are known, there is no guarantee that we can know the overall uncertainty at the end. This is because, the uncertainties (e.g. errors) propagate in a nonlinear manner (often in unknown ways) as we move from one step to another. Looking at the difficulties we are already having in the uncertainty estimation in the existing hydrologic models, one can confidently surmise that the future, with many uncertainties in the face of climate change, will only bring far more scientific difficulties.

3. NON-SCIENTIFIC CHALLENGES

While the scientific challenges themselves are complicated enough, the non-scientific are even more complicated. The non-scientific challenges have many different facets, such as social, political, economic, and environmental, that often act in complex and interconnected ways. In each of these facets, the challenges are concerned with the development and implementation of appropriate strategies for awareness, preparedness, adaptation, and mitigation of climate change impacts on water resources.

3.1. Social Challenges

From the beginning of our civilization, we have established various traditions and practices around the world, depending upon the region, culture, race, reglion, and other aspects. Although some universal laws, moral codes, and practices have been developed over the last few centuries, strong traditional beliefs, values, and practices (oftentimes in contradiction to the universal ones) still exist around the world. It is particularly in this context that the enormity of the social challenges may be realized. Looking at the future projections of the impacts of climate change on water resources, it seems that significant changes to our water uses (e.g. agriculture) and thus to our lifestyles will be required. These changes are pertinent both to the developed countries and to the developing countries, although likely in different ways and magnitudes. How far our communities are willing to compromise and sacrifice their established practices and lifestyles for the overall global community and environment is not at all clear. The essential first step in dealing with these challenges is to bring sufficient awareness of the climate change problem to the communities around the world and encourage their participation in formulating appropriate adaptation and mitigation strategies. This, however, is a formidable task, which we have not addressed in any adequate measure yet.

3.2. Political Challenges

Since people’s perceptions and opinions (must) play vital roles in the establishment and functioning of governments (especially democratically elected ones), the political facet of the climate change problem cannot be separated from the social one. At the same time, it is also possible that some governments may act in their own ways without any serious consideration to the public perceptions and opinions (as is the case often with non-democratic ones). Either of these situations can be good or bad, depending upon the public opinions and the governments. For example, if both the public and the government are in favor of or against taking appropriate measures for dealing with climate change impacts, then there are no political complications; however, enormous complications may arise when one of these is for and the other is against. The difficulties that have been faced over the past few years in the ratification of the Kyoto Protocol reveal some ugly sides of these complications that have arisen in many individual countries and thus at the global level. For example, Australia had long refused to ratify the Kyoto Protocol under the previous Liberal Coalition Government, but then changed stance and ratified the same after the election of the Labor Government in 2007. The fact that the United States, the most powerful country in the world (both economically and militarily), has not yet ratified the Kyoto Protocol should provide a clear indication as to the enormous political challenges in dealing with the climate change impacts on water resources.

3.3. Economic Challenges

In a similar vein, the economic facet of the climate change impacts on water resources cannot be separated from the social and political facets. Addressing the climate change issues, starting from bringing awareness to the society to the development of adaptation and mitigation strategies and finally to their implementation, has enormous economic implications for individuals and governments. For example, the development of new technologies for water saving in the agricultural sector could result in massive costs, especially when they are to be implemented in large countries that are dominated by generally remote rural areas, such as in India and China. Similarly, efforts to mitigate the impacts of abnormal floods that are anticipated due to climate change will likely require enormous structural measures (e.g. flood control dams), which will also incur huge costs. In view of these, an important question is: to what extent are we (as individuals, communities, and governments) willing to invest and sacrifice in the present time for the potential well-being of the global community in the future, especially considering the uncertainties associated with climate change?

3.4. Environmental Challenges

One of the notable developments during the last century is our vastly improved scientific knowledge of the environment and our efforts to save it from potential dangers, both natural and man-made. However, it is the same period that has also witnessed enormous exploitation of the environment for our individual and societal benefits, one of the supposed reasons for climate change. Therefore, the environmental challenges in dealing with climate change are mainly concerned with the assessment of our technological developments needed to deal with climate change (i.e. benefits) and the potential negative alterations such developments would likely bring to the environment (i.e. costs). For example, if we prefer the nuclear technology to the coal technology to reduce the carbon emissions, we should also make sure to completely safeguard the nuclear plants and eliminate all the associated dangers to humans, animals, plants and the environment. Similarly, if we decide to construct a flood control dam in a specific location, then we should also make sure that there will be no significant ecological and environmental dangers in that location and surrounding areas. Since these assessments require both biophysical and socio-economic considerations, they are far more difficult.

3.5. Communication

Proper communication of our scientific endeavors and findings to the rest of the society is a key component in dealing with climate change impacts on water resources. The other stakeholders in the climate-water issue include fellow scientists/engineers, policy makers, economists, industrialists, farmers, non-governmental organizations, and the public at large. These stakeholders are to be ‘kept in the loop’ of our scientific efforts.

While the desirable ‘media’ for communication with these stakeholders are visual (television), audio (radio), and general print (newspapers and magazines), our focus continues to be on publications in scientific journals and conferences in ‘specialized’ topics. A ‘balance’ between these two (notwithstanding their often contrasting interests and goals) is essential for any hope of proper communication. The only medium where we seem to have relatively succeeded in communicating our climate-water science with the others is the ‘internet.’ However, how effective even this can be remains a relevant question, since a good majority of the population that will likely be affected by climate change (in developing and under-developed regions) are also the one that will likely **not** have this medium, at least in the near-future.

On the actual communication itself, we should be able to clarify and translate the true state of the climate-water science, so that the decision makers and the larger public can appropriately interpret the findings and focus the political process on a constructive debate to deal with the climate change impacts on water. Unfortunately, however, our ability to do this continues to be poor. Part of this problem arises due to difficulties in ‘translating’ to the other stakeholders the somewhat sophisticated mathematics involved. However, our inclination to specialize in individual mathematical techniques and models, each having its own jargon, also contributes to this problem. Unfortunatley, we are not even doing nearly enough to change this situation anytime soon (e.g. Sivakumar, 2008a).

4. CONCLUSION: NEED FOR AN INTEGRATED APPROACH

Since the challenges in studying the impacts of climate change on our water resources are both scientific and non-scientific in nature, any hope for significantly advancing our climate-water research lies in our ability to formulate an approach that addresses these scientific and non-scientific challenges in an integrated manner. Despite some recent attempts (e.g. Sullivan et al., 2003; Sullivan and Meigh, 2005), formulation of such an integrated approach continues to be a tremendously difficult task, for at least two reasons: (1) the inherent ‘complexities’ in our scientific as well social settings; and (2) the noticeable ‘disconnection’ (either intentional or unintentional) between scientists/engineers and the rest of the society.

In the scientific setting, in addition to the pure scientific challenges discussed above, difficulties arise because of the lack of collaboration not only among the different scientific disciplines involved (e.g. climatologists, hydrologists, civil engineers) but also within a given discipline (with different specializations). These difficulties may be overcome relatively easily, since we can attempt to understand each other’s language, despite coming from different backgrounds and possessing different specializations. In the non-scientific setting, the difficulties arise because of the (often different) vested interests of each of the stakeholders (e.g. policy makers, industrialists, economists, general public). Although the contributions that we (climate-water researchers) can make to overcome these difficulties do not seem to be significant, we can still play an influencing role because of our association with the different stakeholders at various levels.

As for the ‘disconnection’ between climate-water researchers and the rest of the society, the difficulties may largely be attributed to our inability to communicate *our* science to the others in *their* language. This unfortunate situation is essentially because of our focus (understandably) on publications in ‘scientific’ journals rather than on communications with the larger public. This problem can be overcome by making appropriate modifications to our existing communication modes, without significant compromises.

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