Stoch Environ Res Risk Assess (2011) 25:583–600
DOI 10.1007/s00477-010-0423-y

ORIGINAL PAPER

Global climate change and its impacts on water resources planning and management: assessment and challenges

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Abstract 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 and, in turn, environment, health, and economy. According to latest World Health Organization estimates, about 900 million people still lack access to safe drinking water, about 2.5 billion people lack access to proper sanitation, millions of people die every year from water-related disasters and diseases, and economic losses in the order of billions of dollars occur due to water-related disasters. With the global climate change anticipated to have threatening consequences on our water resources and environment both at the global level and at local/regional 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 our water resources 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 nation states and that there are already numerous conflicts in the planning, development, and management of water resources in these basins further complicate matters for future water resources planning. 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. These challenges are both biophysical science-related and human science-related. The biophysical science 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 human science challenges have social, political, economic, and environmental facets that often act in an interconnected manner; proper 'communication' of (or lack thereof) our climate-water 'scientific' research activities to fellow scientists and engineers, policy makers, economists, industrialists, farmers, and the public at large crucially contributes to these challenges. The present study is intended to review the current state of our water resources and the climate change problem and to detail the challenges in dealing with the potential impacts of climate change on our water resources.

Keywords Climate change · Water resources · Impact assessment · Science · Society · Policy

1 Water resource and water crisis

The need for water for the sheer survival of humans, animals, and plants, and for the overall health of our ecosystems cannot be overstated. While the importance of planning, development, and management of our water resources has always been realized ever since our ancient civilizations, unfortunately such have also been tremendously difficult. Part of this difficulty has come from our lack of scientific understanding of the numerous land, atmospheric, and ocean (e.g. hydrologic, climatic) processes that often behave in nonlinear ways, their complex interactions and feedback

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mechanisms, and their critical influence on water resources. Another part of this difficulty, however, has come from our population explosion (especially since the beginning of the twentieth century) and its many associated effects (e.g. industrialization, urbanization, water pollution, deforestation) on the availability of adequate water resources for our health, environment, and economic well-being. The fact that water resources are not evenly distributed around the globe, with rainfall and runoff apportioned in both space and time in a grossly irregular manner, only adds complications to this already difficult problem.

Notwithstanding all the scientific and technological advances we have made over the past several centuries, many of our efforts to harness water have been generally inadequate or misdirected (e.g. Gleick 1993). We remain, even in the twenty-first century, largely ignorant of the functioning of basic hydrologic and climate processes, and of the stocks, flows, and condition of our fresh water resources. At the same time, we are also increasingly contaminating our rivers, lakes, groundwater aquifers, and other fresh water resources with biological and chemical wastes. On one hand, vast numbers of people lack clean drinking water and rudimentary sanitation services; on the other hand, enormous quantities of water that become available during heavy rainfall periods are often not only wasted but also killing people and damaging the environments. Even many of the massive water developments, constructed essentially to save lives and environments, have ended up, or are, displacing millions of people from their homelands and destroying many of the world's most productive wetlands and other aquatic habitats, largely due to our inadequate planning and management at the most fundamental levels. Finally, in the current situation, the economic and environmental resources for major new water projects simply cannot be found. The following examples clearly explain the world's precarious water situation and, consequently, the need for some urgent and strong actions for its resolution.

According to latest estimates by the World Health Organization/United Nations Children's Fund (WHO/UNICEF) Joint Monitoring Programme (JMP) for Water Supply and Sanitation, about 900 million people in the world (almost one in six) still rely on unimproved drinking-water supplies (WHO/UNICEF 2008). Speaking in the specific context of water resources available for use, about one-third of the world's population lives in countries with 'moderate-to-high water stress' (According to the United Nations, 'moderate-to-high water stress' represents water consumption exceeding 10% of renewable freshwater resources). By this measure, some 80 countries, constituting about 40% of the world's population, were already suffering from water shortages by the mid-1990s (Commission on Sustainable Development (CSD) 1997; UN World Water Assessment Program (UN/WWAP) 2003). By the year 2020, water use is expected to increase by 40%, and 17% more water will be required for food production to meet the needs of the growing population (Palaniappan and Gleick 2008). These are clear indications that we are seriously skewing the very resource we are so utterly dependent upon. Marq de Villiers was apparently correct when he said (de Villiers 1999): "Water shortages are closer than they might appear." The WHO/UNICEF JMP for Water Supply and Sanitation also estimates that about 2.5 billion people in the world (more than one-third) still remain without improved sanitation facilities. Primarily because of this, but also of other associated reasons, millions of people die every year from water-related diseases (e.g. malaria, typhoid, cholera). In fact, water-related diseases are the third leading cause of death from all infectious diseases; for instance, diarrheal disease alone caused more deaths than HIV/AIDS in the year 2004 (WHO/UNICEF 2008). The calamity of this situation is clearly reflected by the fact that the majority of these deaths are among children under 5 years of age.

Although population explosion and other socio-economic factors play important roles, two types of natural hydroclimatic events are largely responsible for (and certainly further complicate) the poor water, sanitation, and health situations around the world: droughts and floods. For example, droughts are a direct reason for the decrease in water available for drinking, sanitation, and other domestic purposes, while floods often cause an increase in the transmission of communicable water-borne and vector-borne diseases (e.g. malaria, typhoid, dengue fever, cholera), especially through facilitating easy breeding of mosquitoes and other disease-spreading organisms. While these problems themselves are dangerous, the extent of impacts of droughts and floods are often realized well beyond these and at much larger scales. Droughts are one of the major threats among natural hazards to people's livelihood and socio-economic development. Droughts tend to occur less frequently than other hazards, but, when they occur, they generally affect a broad region for seasons or years at a time. This can result in a large proportion of the population being affected than when other disasters occur. For example, drought disasters account for less than 20% of all disaster occurrences in Africa, but at the same time they account for more than 80% of all people affected by natural disasters (UN International Strategy for Disaster Reduction (UN/ISDR) 2007). Disasters triggered by prolonged drought can affect millions of people and contribute to malnutrition, famine, and loss of life, and economic loss. At the global level, droughts alone accounted for 280,000 deaths between 1991 and 2000. Floods are the most reported natural disaster events around the world. Floods account for one-third of all natural disasters, affect more people (about 140 million/year on average) than all other disasters, and are responsible for about 15% of all deaths related to natural disasters and one-third of economic loss. The damages to life and property due to floods are enormous, especially considering that floods are rather of much shorter-duration events when compared to, for example, droughts.

Further complicating these water-related problems (both at the global level and at the local levels) are the many shared international river basins. As of now, over 300 rivers around the world are being shared by two or more countries; for instance, the Nile River in Africa is shared by ten countries, the Danube River in Europe flows through 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 (five, if Palestine is considered as a nation state of its own). 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 and, thus, adequate planning, development, and management of waters of these rivers are already severely impeded. It is important also 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.

While the present situation on water planning and management is itself bleak, the future looks even bleaker for at least two important reasons: demands due to population increase and impacts due to global climate change. As for population, according to some estimates (UN Economic & Social Affairs (UN/ESA) 2007), the world population will likely increase by 2.5 billion in 2050, passing from the current 6.7 billion to 9.2 billion. This increase, equivalent to the overall number of people in the world in 1950, will be absorbed mostly by the less-developed regions, whose population is projected to rise from 5.4 billion in 2007 to 7.9 billion in 2050. As these regions are precisely the ones that are already most affected by the lack of water and sanitation facilities, there will be enormous consequences for the future. Also, according to latest estimates by the United Nations Environment Programme (UNEP), 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 conditions of ‘water stress’ (UNEP 2007).

On the other hand, the global climate change—the so-called greenhouse effect—is one of the most severe environmental issues we are facing today. It is anticipated to have threatening consequences on our water resources and environment, both at the global level and at the local levels. Although the exact impacts of climate change are hard to predict, there is a general consensus among scientists that the global hydrologic cycle will intensify and that extremes (e.g. floods, droughts) will occur more frequently and often with greater magnitudes. In fact, recent increases in abnormal floods and droughts around the world have only strengthened this thought. Since, water resources planning and management is more difficult with the occurrence of floods and droughts, the global climate change will bring additional challenges to the already existing difficulties. It is also particularly in this context that the shared river basins and the countries sharing them will likely be the most impacted regions in the future.

In light of these, any sincere effort towards proper planning and management of our future water resources and resolving potential future water-related conflicts must address the impacts of global climate change on water resources. The challenges in doing so, however, are very many, ranging from those encountered in the specific field of climate science all the way to those concerned with our general social settings and water uses. These challenges may broadly be grouped under ‘biophysical science’ challenges and ‘human science’ challenges (The term ‘biophysical science’ is used herein to refer to ‘hard’ sciences and engineering, while the term ‘human science’ refers to ‘soft’ sciences and arts). The biophysical science challenges include: identification of the actual causes of climate change, development of Global Climate Models or General Circulation 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 and local conditions for hydrologic analysis and predictions, and reliable estimation of the associated uncertainties in all these. The human science challenges have social, political, economic, and environmental facets that often act in complex and interconnected ways; proper communication of our climate-water ‘scientific’ research activities to fellow scientists and engineers, policy makers, economists, industrialists, farmers, and the public at large is also a particularly difficult task in this respect.

The purpose of the present study is twofold: (1) to review the global climate change problem, including its impacts observed in the past and projected for the future; and (2) to detail the biophysical science and human science challenges in studying the impacts of climate change on our future water resources and highlight the need for a new framework to address such 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 this issue has already resulted in a voluminous amount of literature, especially the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC 2001, 2007a, b, c). It is, therefore, impossible to provide all the specific details of the climate change problem and the challenges. In view of this, only a general discussion and possible ways to address them is made.

The rest of the paper is organized as follows. In Sect. 2, the global climate change problem is briefly reviewed, with some specific observations that already reflect the change. Section 3 highlights the already observed impacts of global climate change and also the projected future ones, with focus on water resources. Section 4 discusses the biophysical science challenges, while the human science challenges are discussed in Sect. 5. Closing remarks are made in Sect. 6, with emphasis on the need to formulate an integrated framework to deal with these challenges.

2 Climate system and climate change

The climate system is a complex, interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface, and the biosphere. The term ‘climate’ normally refers to the ‘average weather’ condition, where ‘weather’ is the fluctuating state of the atmosphere around us and described by the variables temperature, precipitation, and wind, among others. Therefore, climate is the average state of these variables over a long period of time (ranging from months to millions of years; the classical period is 30 years), and is most obviously characterized by the atmospheric component of the climate system.

The climate system evolves in time under the influence of its own internal dynamics and due to changes in external factors that affect climate, called ‘forcings.’ The external forcings include natural phenomena (e.g. solar variations, volcanic eruptions) as well as human-induced ones (e.g. changes in atmospheric concentration). Solar radiation powers the climate system. The radiation balance of the Earth can be modified in three fundamental ways: (1) by changing the incoming solar radiation (e.g. by changes in the Earth’s orbit or in the Sun itself); (2) by changing the fraction of solar radiation that is reflected or ‘albedo’ (e.g. by changes in cloud cover, atmospheric particles, vegetation); and (3) by changing the longwave radiation from Earth back towards space (e.g. by changing the greenhouse gas concentrations). Climate responds directly to such alterations, and also indirectly through a variety of feedback mechanisms.

Human activities contribute to climate change by causing changes in Earth’s atmosphere in the amounts of greenhouse gases, aerosols (small particles), and cloudiness. Greenhouse gases and aerosols affect climate by altering incoming solar radiation and outgoing infrared (thermal) radiation that are part of Earth’s energy balance. Changing the atmospheric abundance or properties of these gases and particles can, therefore, lead to a warming or cooling of the climate system. Scientific observations indicate that, since the start of the industrial era (about 1750), the overall effect of human activities on climate has been a warming influence (with a net radiative forcing of $+1.6\ \mathrm{W/m^2}$), a possible implication that the role of greenhouse gases has been greater than that of the aerosols and clouds. The observations also indicate that atmospheric concentrations of greenhouse gases (e.g. carbon dioxide, methane, nitrous oxide) now far exceed pre-industrial values (with a combined radiative forcing of $+2.30\ \mathrm{W/m^2}$) determined from ice cores spanning many thousands of years (IPCC 2007a). There have also been increases in the concentrations of some non-greenhouse gases (e.g. nitrogen oxides, carbon monoxide), which nevertheless play a role in the atmospheric chemistry and have led to a significant increase (about 40%) in tropospheric ozone, a greenhouse gas, since pre-industrial times.

Among others, human activities have resulted in emissions of four principal greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the halocarbons (a group of gases containing fluorine, chlorine, and bromine). These gases accumulate in the atmosphere, causing concentrations to increase with time. Significant increases in all these gases have occurred in the industrial era, and all of these increases are attributable to human activities. Carbon dioxide is the most important anthropogenic greenhouse gas. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 to 379 ppm in 2005 (about 35%), and is still increasing at an unprecedented rate of about 0.5% per year. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years (180 to 330 ppm) as determined from ice cores (IPCC 2007a). The primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial period results from fossil fuel use (in transportation, building heating and cooling, and the manufacture of cement and other goods), with land-use change providing another significant but smaller contribution (deforestation releases CO_2 and reduces its uptake by plants); carbon dioxide is also released in natural processes, such as the decay of plant matter. Methane has increased, from a pre-industrial value of about 715 to 1774 ppb in 2005, as a result of human activities related to agriculture, natural gas distribution, and landfills; it is also released from natural processes that occur, for example, in wetlands. Nitrous oxide is also emitted by human activities, such as fertilizer use and fossil fuel burning; natural processes in soils and the oceans also release nitrous oxide. It has increased from a pre-industrial value of about 270 ppb to about 319 ppb in 2005. Halocarbon gas concentrations have increased primarily due to human activities; natural processes are also a small source. Principal halocarbons include the chlorofluorocarbons (e.g. CFC-11, CFC-12), which were used extensively as refrigeration agents and in other industrial processes before their presence in the atmosphere was found to cause stratospheric ozone depletion.

The above observations offer very high confidence towards an interpretation that the human impact on climate during the industrial era greatly exceeds that due to known changes in natural processes, such as solar changes and volcanic eruptions, and that the overall effect has been warming; for example, the global total temperature increase from 1850–1899 to 2001–2005 is 0.76°C. A wide range of studies on climate change patterns, including those incorporating multiple variables in climate models, suggest that the observed climate changes cannot be explained by natural factors alone (e.g. Santer et al. 1995, 2004; Hegerl et al. 1996; Hasselmann 1997; Barnett et al. 1999; Tett et al. 1999; Stott et al. 2000, 2001; Levitus et al. 2001). For recent reviews on this, the reader is directed to IPCC (2007a) and Keller (2008), among others.

Despite these observations, there have and continue to be debates and discussions about climate change (both on its occurrence and on the causes), albeit indications that critics are considerably receding in number. There are several reasons for this situation: (1) the complexity of the climate system and the multiple interactions that determine its behavior impose limitations on our ability to understand fully the course of the global climate; (2) there is still an incomplete physical understanding of many components of the climate system and their role in climate change; and (3) there are key uncertainties, including the roles played by clouds, the cryosphere, the oceans, land use, and couplings between climate and biogeochemical cycles. In addition to these, another criticism against the global climate change is that the roughly two centuries of the industrial era is a ‘negligible period’ of the Earth’s history and the climate dynamics and that any changes in climate could just be attributed to the natural cycle of events. The importance of this criticism must be viewed especially in the context that this same ‘negligible period’ is, in fact, also used as a basis to argue in favor of our ‘exorbitant’ contributions to atmospheric concentration of greenhouse gases and, thus, to climate change.

With our inadequate understanding of the climate system and dynamics and also the associated uncertainties, criticisms on the climate change issue must be given due consideration, rather than simple rejection. Further, since science is most often stimulated by argument and debate, such criticisms certainly deserve attention and need to be addressed. At the same time, science generally advances through clear formulation of hypotheses and their objective testing, and a statement, to be genuinely scientific, must be susceptible to testing that could potentially show it to be false (Popper 1934). Obviously, this should apply not only to studies that positively report climate change but also to studies that argue against it. The following statement by de Villiers (1999) clearly reflects the nature of our scientific progress, especially with respect to the debates on the occurrence/causes of climate change: “… there are still arguments as to whether the temperature of the atmosphere is rising (early studies said no; subsequent studies claimed to have found an error and that the answer was yes; further studies said the error might be an error).” Nevertheless, as discussed earlier, recent and more extensive reviews of the climate studies (IPCC 2007a; Keller 2008) present very high confidence regarding the occurrence of climate change and the human-induced causes. These studies, and the future projections therein, form the basis for the rest of the discussion in this paper.

3 Climate change impacts: observations and projections

While some debates persist on whether climate change is occurring and, if it indeed is, on its causes (natural cycle or human induced), most recent and current studies provide overwhelming evidence of its occurrence and of the human causes (e.g. Santer et al. 1995; Hegerl et al. 1996, 1997; Barnett et al. 1999; Tett et al. 1999; Stott et al. 2000, 2001; Levitus et al. 2001; IPCC 2007a). In view of this, the current perception among (at least a majority of) scientists on this issue seems to be that ‘the issue is mostly settled,’ similar to the view of Keller (2008) on ‘global warming.’ As a matter of fact, most people around the world (not just scientists, but also others, including politicians) have already moved beyond asking ‘if’ climate change is occurring and ‘if’ it is human induced; rather, people are now talking about its impacts: what kind? how much?

The exact impacts of climate change have and continue to be hard to predict. However, it is expected that climate change will have threatening consequences on our water resources, which will also serve as the operating medium for many of the other anticipated impacts of climate change (e.g. environment, health, agriculture, economy). At the global level, the overall impacts of climate change on freshwater resources are expected to be negative. With the projected global temperature increase, scientists generally agree that the global water cycle will intensify and also suggest that extremes (e.g. hurricanes/typhoons, floods, droughts, sea level rises) will become more frequent and often with greater magnitude. Recent increases in abnormal typhoons, floods, and droughts around the world (especially in the Asia–Pacific region) have only strengthened this thought. As a result, studies on the impacts of climate change on our water resources are at the forefront of scientific research today (e.g. Gleick 1993; Wilby et al. 2000; Bergstrom et al. 2001; Chiew and McMahon 2002; Prudhomme et al. 2002; Sullivan et al.

2003; Barnett et al. 2004; Christensen et al. 2004; Wood et al. 2004; Sullivan and Meigh 2005; Wilby and Harris 2006; IPCC 2007a, b; Kilsby et al. 2007). In what follows, a brief account of the 'water-related changes' (starting with 'temperature changes' that have important implications for water) that have already been observed around the world and also those projected for the future, as reliably assessed impacts of climate change and reported by the IPCC in particular, is presented.

3.1 Past observations

Generally speaking, past observations offer convincing evidence on increasing global average air and ocean temperatures, increasing snow and ice melt, and rising global average sea level (IPCC 2007a). Numerous long-term changes in climate have been observed also at continental, regional, and ocean basin scales. These changes, both independently and in combination, have (had) enormous implications for our water resources, especially in the form of changes in precipitation and, consequently, in river flow, floods, and droughts.

3.1.1 Temperature

Increase in global temperature has been one of the most pronounced observation attributed to climate change. Eleven of the 12 years during 1995–2006 rank among the 12 warmest years in global surface temperature (average of near-surface air temperature over land and sea surface temperature) since 1850 (IPCC 2007a). The 100-year linear trend of 0.74°C (0.56–0.92°C) for the period 1906–2005 is larger than the corresponding trend of 0.6°C (0.4–0.8°C) for the period 1901–2000. And even during 1906–2005, the linear warming trend of 0.13°C (0.10–0.16°C) per decade over the latter 50 years (1956–2005) is nearly twice that over the entire 100 years. The total temperature increase from 1850–1899 to 2001–2005 is 0.76°C (0.57–0.95°C). Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Average arctic temperatures increased at almost twice the global average rate in the past 100 years. Widespread changes in extreme temperatures have been observed over the last half a century. Cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent.

3.1.2 Snow and ice melt

Mountain glaciers and snow cover have declined on average in both hemispheres. Satellite data since 1978 show that annual average arctic sea ice content has shrunk by 2.7% (2.1–3.3%) per decade, with larger decreases in summer of 7.4% (5.0–9.8%) per decade. The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with a decrease in spring runoff up to 15%. Spring peak river flows have been occurring 1–2 weeks earlier during the last 65 years in North America and northern Eurasia, and there is also evidence for an increase in winter base flow in these regions. These have important implications for water resources planning and management, in particular managing floods during the winter season (with heavy rainfall) and managing water supply during the summer season (with scant rainfall).

3.1.3 Sea level rise

Global average sea level rose at an average rate of 1.8 mm (1.3–2.3 mm) per year over 1961 to 2003; widespread decreases in glaciers and ice caps have contributed to sea level rise. The rate was faster over 1993 to 2003, at about 3.1 mm (2.4–3.8 mm) per year; data show that losses from the ice sheets of Greenland and Antarctica have *very likely* contributed to sea level rise during this period. There is *high confidence* that the rate of observed sea level rise increased from the nineteenth to the twentieth century. The total twentieth-century rise is estimated to be 0.17 m (0.12–0.22 m).

3.1.4 Precipitation (cyclones, river flow, floods, and droughts)

Long-term trends from 1900 to 2005 have been observed in precipitation amount over many regions around the world. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe, and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa, and parts of southern Asia. The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapor. More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought. Changes in sea surface temperatures, wind patterns, and decreased snowpack and snow cover have also been linked to droughts. There is also observational evidence for an increase in intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures. At the global scale, there is evidence of a broadly coherent pattern of change in annual runoff, with some regions experiencing an increase at higher latitudes and a decrease in parts of West Africa, southern Europe, and southern Latin America (Milly et al. 2005).

3.2 Future projections

Many studies that attempt projections of future climate changes consider the end of this century as a reasonable timeframe. However, this timeframe may be a bit too long for reliable results, especially considering the generally chaotic nature of the climate system on the one hand and the ever-changing global/regional/local socio-politico-economic landscape on the other (with important implications for greenhouse gas emissions, for example). There also remain serious doubts on the ability of the existing climate and socio-economic models (and even the models that are foreseen to be developed in the future) to take into account all the important factors for reliable future projections (see below for further details). In view of these, it is reasonable to contend that, for example, projections made for the 2030–2050 timeframe would be far more reliable than those made for the 2080–2100 timeframe; in fact, even projections of the population, arguably the most fundamental factor in all these, cannot reliably be made beyond the 2030–2050 timeframe. Nevertheless, some important climate change projections and their potential impacts, regardless of how far they are made for from now, are mentioned here.

3.2.1 Temperature

For the next two decades, a warming of about 0.2°C per decade is projected for a range of IPCC Special Report Emissions Scenarios (SRES) provided in the year 2000 (IPCC 2000). Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year-2000 levels, a further warming of about 0.1°C per decade would be expected. Since the IPCC's first report in 1990 (IPCC 1990), assessed projections have suggested global average temperature increases between about 0.15 and 0.3°C per decade for 1990–2005. This can now be compared with observed values of about 0.2°C per decade, strengthening confidence in near-term projections. Projected warming in the twenty-first century shows scenario-independent geographic patterns similar to those observed over the past several decades. Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean. It is *very likely* that hot extremes and heat waves, and heavy precipitation events, will continue to become more frequent.

3.2.2 Snow and ice melt

Snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions. Sea ice is projected to shrink in both the Arctic and the Antarctic under all SRES scenarios. In some projections, Arctic late-summer sea ice disappears almost entirely by the latter part of the twenty-first century.

3.2.3 Sea level rise

Global average sea level rise at the end of the twenty-first century (2090–2099) is projected to rise anywhere from 0.18–0.38 m (B1 emission scenario) to 0.26–0.59 m (A1F1 emission scenario); this projection excludes any rise that may occur due to future rapid dynamic changes in ice flow. Contraction of the Greenland Ice Sheet is projected to continue to contribute to sea level rise after 2100. Sea level rise (especially due to anthropogenic warming) would continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized.

3.2.4 Precipitation (cyclones, river flow, floods, and droughts)

Based on a range of models, it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period. Since the IPCC's Third Assessment Report (IPCC 2001), there is an improving understanding of projected patterns of precipitation. Increases in the amount of precipitation are *very likely* in high latitudes, while decreases are *likely* in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100), continuing observed patterns in recent trends. The proportion of the land surface in extreme drought, globally, is predicted to increase by the factor of 10 to 30; from 1–3% for the present day to 30% by the 2090s. The number of extreme drought events per 100 years and mean drought duration are likely to increase by factors of two and six, respectively, by the 2090s (Burke et al. 2006). A decrease in summer precipitation in southern Europe, accompanied by rising temperatures, which enhance evaporative demand, would inevitably lead to reduced summer soil moisture (Douville et al. 2002) and more frequent and more intense droughts. Runoff projections until 2050 suggest an increase of 10–40% in the high latitudes of North America and Eurasia and a decrease by 10–30% in the Mediterranean, southern Africa, and western USA/northern Mexico.

In general, impacts of hydroclimatic extremes on human welfare are likely to occur disproportionately in countries with low adaptation capacity. The flooded area in Bangladesh is projected to increase at least by 23–29% with a global temperature rise of 2°C (Mirza 2003). Up to 20% of the world's population live in river basins that are likely to be affected by increased flood hazard by the 2080s in the course of global warming (Kleinen and Petschel-Held 2007).

4 Climate change impact assessment: biophysical science challenges

The biophysical science-related challenges in the assessment of climate change impacts on water resources are centered around the following steps involved therein: (1) identification of the actual causes of climate change and assessment of their future levels; (2) development of GCMs to incorporate these causes and projections of future climates at larger spatial scales; (3) formulation of downscaling techniques to transform the GCM outputs to regional- and local-scale hydroclimatic variables; (4) hydrologic analysis and predictions at regional and local scales; and (5) estimation of uncertainties in all of these. A general structure of these steps is shown in Fig. 1. A more detailed account of these steps is presented next.

4.1 Identification of causes and assessment of future levels

As mentioned earlier, studies over the last two decades or so have provided a good amount of evidence and high level of confidence as to the role of human activities during the last century, mainly through increases in the atmospheric concentration of trace gases, as the most likely causes of global climate change (or at least they have exacerbated the change). This is now a generally accepted view, at least by a majority of climate scientists. Nevertheless, debates and discussions on this issue are still continuing, and there certainly are critics. To be fair, the critics may also have a point, since important questions still remain on the 'extent of influence' of greenhouse gases on climate change and also on their future levels. These questions cannot be answered with any degree of certainty, especially since their answers mainly lie in the future.

It may be true that 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 of climate change. At the same time, however, it may also be far too early to adequately comprehend on the extent of influence of change, especially considering the fact that a century is a 'negligible period' in the Earth system's history and the associated climate phenomena; in fact, as mentioned above, 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. The point is: could the recent change in climate be just a 'blip' in the natural climate cycle? Similarly, while the various 'emission scenarios' assumed are reasonable under certain situations, the future levels of atmospheric concentration of trace gases depend on numerous factors (some may not even be foreseen today or in the near future) that interact in a multitude of ways in a complex web of social, political, economic, and environmental settings. Therefore, the question 'how reliable are they?' is inevitable.

The importance of this kind of questions and criticisms may easily be realized from the fundamental assumptions,

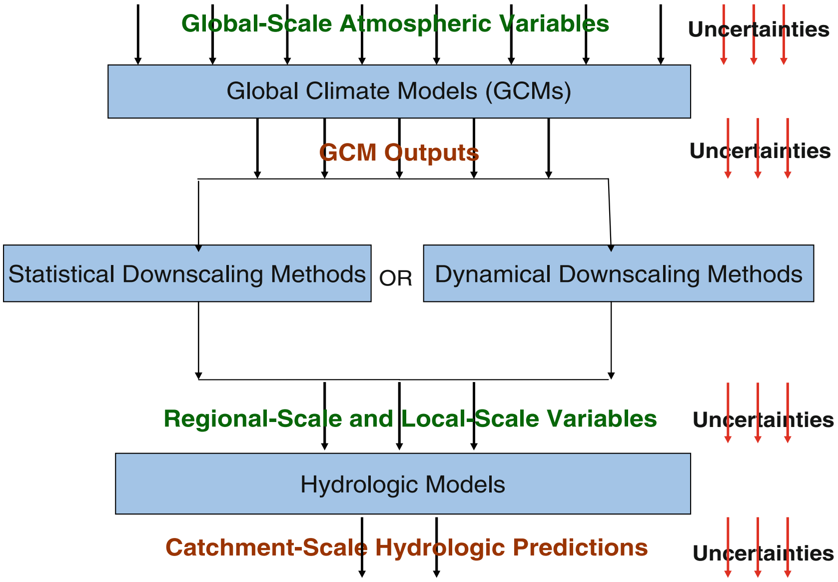

Fig. 1 Important steps in the assessment of climate change impacts on water resources and the associated uncertainties

uncertainties, and limitations that inherently exist in our models and projections. For instance, studies on climate change impact assessment generally consider the population projections and, thus, the emission scenarios provided by the SRES (IPCC 2000). However, such projections may be outdated and not be appropriate anymore, since population projections that are made now are generally lower than those provided by the SRES; one reason for this is new data indicating that birth rates in many parts of the world have fallen sharply. In fact, these new population projections have thus far not been implemented in many of the new emission scenarios in the literature. The studies that have incorporated them, however, result in more or less the same overall emission levels, due to changes in other driving forces, such as economic growth (IPCC 2007c), again a factor that may not have been foreseen earlier. Further, virtually all emission scenarios assume that technological and structural changes occur during this century, leading to relative reduction of emissions compared with the hypothetical case of attempting to 'keep' the emission intensities of GDP (Gross Domestic Product) and economic structures the same as today. How far such an assumption would continue to hold true is something to ponder. Finally, one may ask (perhaps sarcastically): if the climate change problem and its impacts are as serious as they are made out to be (with potentially tens or hundreds of millions of deaths), do these emission scenarios take into consideration also the number of people that will potentially be 'killed by climate change' in the next 40 years (or 90 years) in the population projection and thus emission level determination for 2050 (or 2100)? And, even if they do, how reliable are they?

Although the above questions have important implications for climate change research, it must also be noted that some of these are not even within the realm of climate scientists (let alone that of water researchers/managers); in fact, many of these have deep roots in our socio-politico-economic settings. This situation makes the task of water researchers/managers to deal with the potential impacts of climate change even far more complicated and challenging.

4.2 Global climate models and future climate projections

With the identification of relevant factors influencing the climate and also the appropriate emission scenario (A1, A2, B1, B2, and their sub-sets), GCMs can be used to make future climate projections. Climate models are simply 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 2007a). 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 timescale 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 thus must be included only in approximate form as they interact with large-scale features. While this is partly due to limitations in computing power (notwithstanding our increasing realization that additional computer power cannot solve all the problems), 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.

There exist numerous GCMs. Some popular ones are: HadCM3 (Hadley Center Coupled Model, Version 3), BCCR-BCM2.0 (Bjerknes Center for Climate Research-Bergen Climate Model, Version 2), CCCma CGCM2 (Canadian Center for Climate Modeling and Analysis Coupled Global Climate Model), CSIROMk3.5 (Commonwealth Scientific and Industrial Research Organization, Australia Mark3.0), ECHAM5 (Max Planck Institute of Meteorology Model, Version 5), GFDL CM2.0 (Geophysical Fluid Dynamics Laboratory Climate Model, Version 2), NCAR-CCSM (National Center for Atmospheric Research Community Climate System Model), and CCSR/NIES (University of Tokyo, Center for Climate System Research/National Institute for Environmental Studies). Each of these models has its own advantages and limitations and may also give importance to specific regions, climate processes, and associated factors. Therefore, selection of the best model among these continues to be a challenge, and what factors should be considered in the selection also remains a question. In fact, an even more fundamental question to ask is: whether such a selection is possible at all? Further, regardless of the GCM, confidence in estimates is low for precipitation when compared to some other climate variables (e.g. temperature), not to mention precipitation is only a secondary output from GCMs. This is a particularly disheartening observation in the specific context of water resources, since precipitation is the primary input for water resource studies.

Another important thing to note is that almost all of the processes in the hydroclimate system and their interactions are inherently nonlinear and also often chaotic in their dynamics (e.g. Lorenz 1963; Tsonis and Elsner 1988; Elsner and Tsonis 1993; Abarbanel and Lall 1996; see also Sivakumar (2000, 2004a, 2009) for extensive reviews on nonlinear and chaotic dynamic behaviors in hydroclimate). 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 also our inability to make accurate observations, this problem could turn out be far more significant than one might tend to believe.

4.3 Transformation of large-scale GCM outputs to smaller-scale climate variables

Since GCMs produce outputs at much larger spatial scales than those required for regional- or catchment-scale hydrologic and water resource analysis, transformation of data between these scales (i.e. downscaling) becomes essential. Indeed, downscaling of GCM outputs has, in recent years, become one of the most important research topics in hydrology and water resource studies. Such research has, consequently, resulted in the development of numerous techniques and their applications (Hewitson and Crane 1996; Wilby 1998; Wilby et al. 1998; Charles et al. 1999; Huth 1999; Zorita and von Storch 1999; Bergstrom et al. 2001; Prudhomme et al. 2002; Wood et al. 2004; Bardossy et al. 2005; Bürger and Chen 2005; Coulibaly et al. 2005; Gangopadhyay et al. 2005; Salathé 2005; Dibike and Coulibaly 2006).

With the exception of a few (perhaps those based on, for example, neural networks and genetic programming), these downscaling techniques may be grouped 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 (e.g. Wilby 1998; Zorita and von Storch 1999; Hanssen-Bauer et al. 2005; Diaz-Nieto and Wilby 2005; Gangopadhyay et al. 2005); 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) (e.g. Arnell et al. 2003; Frei et al. 2003, 2006; Leung et al. 2003, 2004; Hagemann et al. 2004). Many studies have also presented comparison of statistical and downscaling techniques as well as comparison of different methods within each of these techniques (e.g. Wilby et al. 1998; Murphy 1999, 2000; Benestad 2001; Busuioc et al. 2001; Salathé 2003; Hagemann et al. 2004; Diaz-Nieto and Wilby 2005; Hanssen-Bauer et al. 2005; Maurer and Hidalgo 2008). Extensive details on these techniques and their advantages and disadvantages are already available in the literature (e.g. Wilby and Wigley 1997; Xu 1999; Fowler et al. 2007) and, therefore, are not reported herein.

As the outcomes of the above studies indicate, either of these two techniques 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. Nevertheless, an alternative technique that overcomes the inherent limitations of these techniques is required if more reliable and realistic downscaled data are preferred. One possible means to achieve this is by coupling the two techniques. A preliminary effort to this end was made by Fuentes and Heimann (2000), who proposed a statistical–dynamical technique that combines weather classification with RCM simulations. The results are encouraging, but much more work needs to be done to further improve this technique. Despite all these advances, a technique that can explicitly take into account and adequately represent the inherent nonlinear, and particular chaotic, dynamic nature of the climate system and the associated processes seems to be missing. To this end, application of a chaotic dynamic-based approach, perhaps along the lines of the one proposed by Sivakumar et al. (2001) but in a spatial sense, and its extensions for downscaling GCM outputs could be worth an attempt.

Another important limitation with the current state of GCMs, especially when it comes to downscaling for water resources applications, is that precipitation is only a secondary output from GCMs but is the primary input for hydrologic models, as mentioned earlier. This situation also necessitates identification of primary GCM outputs that are reliable as the basis of ascertaining catchment-scale rainfall. Such identification, however, is often a challenging task.

4.4 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, as it has turned out, also inevitable) outcome of our technological and methodological developments is the highly complex rainfall-runoff and other hydrologic models. It is true that additional model complexity oftentimes helps towards a better understanding of hydrologic systems and processes. Unfortunately, however, ‘more is better’ is not always true, and many studies have discussed the positives and negatives of more complex models (e.g. Jakeman and Hornberger 1993; Young et al. 1996; Grayson and Blöschl 2000; Perrin et al. 2001; Beven 2002; Young and Parkinson 2002; Sivakumar 2004b, 2008a, c). Common sense and experience clearly indicate that complex models bring with them many additional difficulties to the modeling endeavor. These include estimation of more parameters and requirements of additional data (not to mention the time and computational resources), which, in turn, oftentimes give rise to additional uncertainty in the model outcomes.

The uncertainty problem may become a particularly serious one as far as future rainfall inputs are concerned, since there are already many unknowns and uncertainties in downscaling of coarse-scale GCM outputs to catchment-scale rainfall data, as explained earlier. Parameter estimation and uncertainty in hydrologic models have been hot topics in recent years, extensive details of which are already available in the literature (e.g. Sorooshian and Gupta 1983; Beven and Binley 1992; Duan et al. 1992, 2002; Beven 1993, 2002, 2006; Kavetski et al. 2002; Vrugt et al. 2002, 2009; Beven and Young 2003; Gupta et al. 1998, 2003; Sivakumar 2008b). Furthermore, almost all the hydrologic models in existence require adequate calibration with data for the region of interest, but this can become a serious problem in the face of climate change, since we may not have representative and good quality data for calibration. There are also many regions around the world where the catchments are still ‘ungaged’ (especially in terms of streamflow). Predictions in ungaged basins (PUB) is currently an important area of research in hydrology (e.g. Sivapalan et al. 2003), and several ideas, including regionalization and classification of catchments, are being proposed for dealing with ungaged basins and also for a general modeling framework in hydrology (e.g. McDonnell and Woods 2004; Sivakumar et al. 2007; Wagener et al. 2007).

One particularly important problem that we continue to have in hydrology and water resources (and also in 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? How will they be incorporated in hydrologic models? How much more complex will the models be then? What will be the level of uncertainty in the outcomes? These 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 right answers (e.g. Kirchner 2006; Sivakumar 2008a).

4.5 Estimation of uncertainties

The above observations clearly indicate the existence of far too many uncertainties in the assessment of climate change impacts on water resources planning and management. As shown in Fig. 1, these uncertainties arise in each and every step of the ladder, starting from the identification of actual causes of climate change, to future emission 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 commonly available and more reliable monthly or daily data derived from the downscaling step, especially for flood forecasting purposes. Further, hydrologic models that are used for representing the rainfall-runoff process have their own uncertainties too. These 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 or not supported adequately by the data. There is an extensive amount of literature on this aspect; for example, Konikow and Bredehoeft (1992) argue that the existing quantity/quality of data are not sufficient for calibration of groundwater models, and Sivakumar (2008b) discusses the difficulties in estimating the uncertainty in hydrologic models with particular reference to our lack of knowledge on the ‘unpredictability of Nature.’ 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 only surmise that the future, with even more uncertainties in the face of climate change, will bring far more difficulties in this aspect.

5 Climate change impact assessment: human science challenges

While the biophysical science challenges themselves are complicated enough, the human science challenges are even more complicated. The human science 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 and its impacts on water resources, among others. There are also important challenges in communicating our scientific endeavors and findings to the other stakeholders in the climate-water science. Figure 2 presents some of these components and their interconnections, which are discussed next.

5.1 Social challenges

From the beginning of human civilization, we have established various traditions and practices around the world, depending upon the region, culture, race, religion, and many other factors. 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 are our communities around the world willing to compromise and sacrifice for the good of the overall global community and environment is a vital question. The essential first step in dealing with these challenges is to bring sufficient awareness of the climate change problem to the communities and encourage their participation in formulating appropriate adaptation and mitigation strategies. This, however, is a formidable task, which we have not started to address in any adequate measure yet. A particularly important area of concern in dealing with social (as well as other) challenges is transboundary waters, especially those shared by countries with very different traditions and cultural practices. Planning and management of transboundary waters is already a very difficult task, especially during periods of floods and droughts. Since climate change is anticipated to bring more floods and droughts, the task will be far more challenging.

5.2 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-democratically (s)elected 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 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 (despite the people's generally good support for ratification), but then changed stance and ratified the same after the election of the Labor Government in the

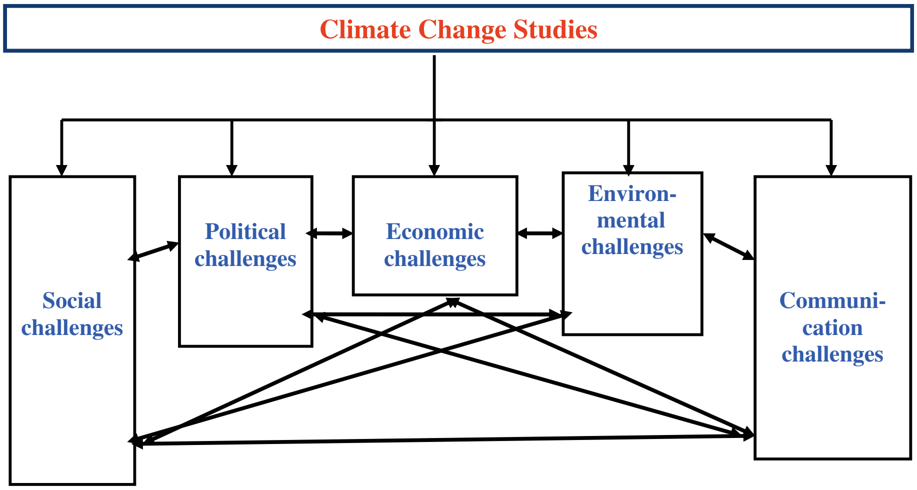

Fig. 2 Components of human science challenges in the assessment of climate change impacts on water resources and their interconnections

year 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 of the enormous political challenges in dealing with the climate change impacts on water resources; the United States is one of the major emitters of greenhouse gases, and indeed the largest per capita emitter. In the specific context of water resources, the climate change problem, with anticipated increases in floods and droughts, will bring far more complications to the already complex transboundary water management issues. The politics of transboundary waters and other water issues (hydropolitics) has already been extensively discussed in the literature (e.g. Ohlsson 1995; Elhance 1999; Turton and Henwood 2002) and, therefore, details are not reported herein.

5.3 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 (and more so when the necessary technologies/equipments are to be imported and transported). 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. On a broader spectrum of the climate change problem, reduction of greenhouse gases, for example, most likely necessitates invention of new technologies and/or modification of existing ones, which will require huge economic investment for technology research and development as well as for their construction and maintenance. In this respect, obviously, the developing and under-developed countries are at a major disadvantage. This explains why countries like China and India, catering to huge populations, are forcefully arguing their case for their continued large greenhouse gas emissions and for the developed countries to assume major responsibility in reducing their emissions. On the other hand, the abundance of certain resources in some countries may give an extra incentive for continuation of the status quo, rather than developing new technologies that may or may not turn out to be effective and efficient in the long-term; the case of Australia, with vast mining resources, is a good example for this situation. In view of these, an important question to ask 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?

5.4 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. There is obviously a connection between these two; population explosion and associated factors have played a major role in the latter, which, in turn, has significantly contributed to the former. The climate change problem is an excellent example for this. Therefore, the environmental challenges in dealing with climate change are mainly concerned with the assessment of our technological developments needed to tackle the 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 to the atmosphere, 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. Unfortunately, however, reliable assessments of environmental benefits and costs are oftentimes very difficult, especially when we have had no prior experience with the technologies and industries that are under consideration. In fact, we are today dealing with some of the environmental problems most likely due to our earlier inadequate knowledge and failure to make reliable assessments on the environmental benefits and costs of the energy industry, automobile industry, large dams, and so on. The question now is: will we be wiser this time?

5.5 Communication challenges

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 and engineers, water managers, policy makers, economists, industrialists, environmentalists, non-governmental organizations (NGOs), the media, and the public at large. Figure 3 presents these channels of communication of climate change science (for simplicity, only the channels between the scientific community and the other stakeholders are shown, rather than the entire web of connections among all the stakeholders). 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 print (newspapers and magazines), our focus continues to be on publications in scientific journals and on conferences in ‘specialized’ topics. A ‘balance’ between these two (notwithstanding their often contrasting interests and goals) is essential for any hope of proper communication between us and the rest of the society. 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 ones 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 is due to difficulties in ‘translating’ the somewhat sophisticated mathematics involved in climate-water science to the other stakeholders in a language that they can understand. However, our inclination to ‘specialize’ in individual mathematical techniques and models, each having its own ‘jargon,’ also contributes to this problem. In fact, we sometimes have difficulties explaining our (mathematical) sciences even to our fellow scientists/engineers. An excellent account of the lack of clarity of terminologies used in hydrologic modeling and possible ways to achieve some general guiding principles is presented in Refsgaard and Henriksen (2004). It is also relevant to note, at this point, that at the recent IAHS-IAH Meeting in Hyderabad, India, concerns were raised on the lack of a clear definition of an ‘ungaged basin,’ especially in the context of ‘Predictions in Ungaged Basins;’ in fact, I had raised such a question at the MODSIM 2005 Conference in Melbourne, Australia, and my guess is that the question may have been raised in many other places as well. Although there has been some progress in addressing these issues, it is also fair to say that we are not even doing nearly enough to change this situation anytime soon [see, for example, Sivakumar (2008a) for some details].

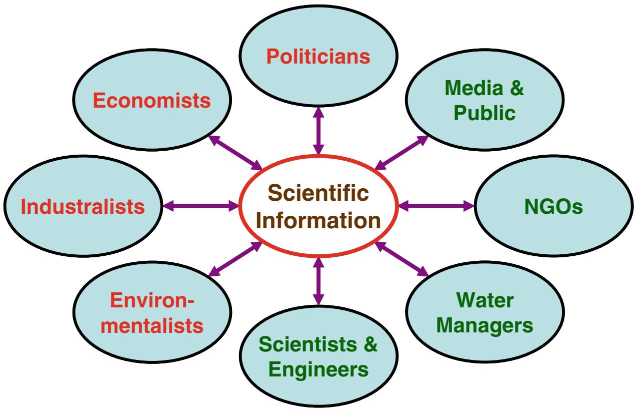

Fig. 3 Channels of communication of scientific information to the various stakeholders in the assessment of climate change impacts on water resources

6 Closing remarks: need for an integrated approach

Since the challenges in studying the impacts of climate change on our water resources are both biophysical science-related and human science-related in their nature, any hope for advancing our climate-water research endeavors lies in our ability to formulate an approach that addresses such challenges in an integrated manner. Formulation of such an integrated approach, however, is a tremendously difficult task, because of at least two reasons: (1) our biophysical systems as well as our socio-politico-economic settings are inherently highly ‘complex’ with numerous uncertainties; and (2) there is generally a noticeable ‘disconnection’ (either intentional or unintentional) between scientists/engineers and the rest of the society.

As for the biophysical science challenges, apart from the pure ‘scientific’ challenges, such as the ones discussed earlier, difficulties also arise because of the lack of communication and collaboration among the different scientific disciplines involved (e.g. climatology, hydrology, civil and environmental engineering) as well as within a given discipline with different ‘specializations’ (e.g. surface hydrology, subsurface hydrology, water resource systems). These difficulties can be overcome with only moderate efforts, since we (can) generally understand each other’s research activities and ‘language’ reasonably well enough, despite coming from different scientific/engineering backgrounds and possessing different specializations.

In the human science settings, the difficulties normally arise because of the often different vested interests of each of the stakeholders in the climate-water problem (e.g. policy makers, industrialists, economists, general public). Overcoming these difficulties may oftentimes be a formidable challenge, and it may also seem that our contributions to change this situation are not that significant, especially considering the dominant roles of politics and economics. However, we can still play an influencing role, because of our close association with the different stakeholders at various levels. Indeed, the establishment of the IPCC in itself, with scientists and engineers (among others) from many different disciplines coming together and sharing their expertise and experience, is an excellent example for the influencing role we can play in shaping the future course of climate change impact assessment on our water resources (and other areas). It is also appropriate to note, at this point, that discussions among the different stakeholders have and do happen all the time at various levels (e.g. local, provincial, national, international) and on various matters (e.g. environment, health, economy, policy), and there have been numerous great successes too. Therefore, we are not really in a totally new territory by any means. The only thing is that, with climate change, we may potentially be dealing with a far greater problem than what we have had to deal with so far.

Nevertheless, to say that there continues to be a general 'disconnection' between climate-water scientists and the rest of the society is a fair statement. While the different vested interests of some of the stakeholders and their lack of knowledge about our 'biophysical science' certainly contribute to this situation, our lack of ability to 'communicate' *our* science to the other stakeholders in *their* language is also an important reason. This unfortunate situation may have even been exacerbated because of our focus on publications in 'scientific' journals (which is certainly understandable) rather than on communications aimed at reaching the larger public. This problem can indeed be overcome by making appropriate modifications to our existing 'communication' modes, without significantly compromising our 'scientific' publications; the role of visual and audio media are examples for these. This, however, requires some fundamental changes to the way we conduct and disseminate our climate-water education, research, and practice. Whether or not we are willing to make the necessary sacrifices and compromises to make this happen is an open question. It is my hope that we will make some good progress in this direction in the near future.

Acknowledgments Part of the work leading to this article was carried out while I was visiting Inha University, Korea. Support from the Korea Science and Technology Societies (through the Brainpool fellowship) and Inha University is acknowledged.

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