IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES: FINDINGS OF THE IPCC REGIONAL ASSESSMENT OF VULNERABILITY FOR NORTH AMERICA

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INTRODUCTION

In this paper, we summarize recent findings on the effects of climate change on water resources by the International Panel on Climate Change (IPCC) Regional Assessment of Vulnerability for North America (Shriner *et al.,* 1998). This report was essentially a state-of-science review that synthesized what is currently known about climatic effects on regional resources. It concludes that water is a linchpin that integrates many geographic subregions and economic/social/ecological sectors of North America. Changes in climate resulting from increasing atmospheric concentrations of greenhouse gases could have significant effects on water resources in North America. The quantity and quality of water are likely to be directly affected by climate change. Available water supplies also are likely to be affected by changes in demand from multiple sectors competing for water resources. Changes in the hydrological cycle will cause changes in ecosystems which, in turn, affect human health (e.g., by altering the geographic distribution of infectious diseases) and biological productivity and diversity.

RECENT TRENDS AND VARIABILITY

Several reports on recent trends in precipitation and streamflow have shown generally increasing values throughout much of North America over the past several decades. Lettenmaier *et al.,* (1994) analyzed data over the period 1948-1988 and found generally increasing trends in precipitation during the months of September to December and increasing trends in streamflow during the months of November to April, particularly in the central and north-central portions of the U.S. Similarly, Lins and Michaels (1994) reported that streamflow has increased throughout much of the conterminous United States since the early 1940's, with the increases primarily occurring in autumn and winter. Mekis and Hogg (1997) reported significant increases in annual precipitation and snow for most regions of Canada over the past 50 years. Anderson *et al.*, (1991) analyzed data for 27 unregulated flow stations across Canada and showed a decrease in summer low flow, an increase in winter average and low flows, and little trend in seasonal maximum flows. In a study of unregulated rivers in Ontario and Alberta, Burn (1994) found a trend toward earlier spring snowmelt in many of the more northerly rivers. Reductions in the length of winter ice cover primarily due to earlier spring ice melts have also been observed for lakes and rivers in the northern United States. These trends are generally consistent with climate models that produce an enhanced hydrologic cycle with increasing atmospheric CO_2, although some of the streamflow trends may also be the result of water management or land use changes that reduce surface infiltration and storage.

Loss of wetlands from expansion of agricultural and urban areas in recent decades also has contributed to changes in the hydrological characteristics of many drainage basins in North America. These changes include increases in maximum river discharges from reduction in storage capacity for flood waters and reduction in groundwater levels and minimum baseflow discharges from reductions in groundwater recharge and subsequent discharge. Loss of wetlands is accompanied by the loss of ecological and cultural functions wetlands provide, including water purification, sediment reduction, carbon and nutrient sequestration, and wildlife habitat.

Recent investigations have shown how natural modes of variability at scales from seasons to years (e.g., ENSO, Pacific Decadal Oscillation) affect hydrologic variability in different regions of North America. These studies have underlined the importance of increasing our understanding of the roles these features play in influencing hydrological characteristics. The ENSO phenomenon, a predictable climate signal, affects precipitation and streamflow in the Northwestern, North-Central, Northeastern, and the Gulf Coast regions of the U.S. For example, La Ninas (the cold phase of ENSO) produce higher than normal precipitation in winter in the Northwestern U.S., while El Ninos (the warm phase of ENSO) cause drier winters in the Northwest on roughly a bi-decadal time scale. Variability in ENSO phenomena contributes natural variations in hydrology at decadal and longer time scales that are problematic for CO_2 climate change analysis. Changes in ENSO behavior related to increasing CO_2 are highly uncertain but could produce enhanced variability in precipitation and streamflow for the regions most sensitive to ENSO.

POTENTIAL IMPACTS AND VULNERABILITIES OF CLIMATE CHANGE

Important impacts and vulnerabilities of water resources to potential climate change scenarios involve changes in runoff and streamflow regimes at event, seasonal, and annual time scales, reductions in water quality associated with changes in runoff, increases in water temperatures, and increases in human demands for water supplies under a more variable climate.

Annual/Seasonal Changes in Runoff

Runoff is simply the area-normalized difference between precipitation and evapotranspiration, and as such is a function of watershed characteristics, the physical structure of the watershed, vegetation, and climate. Although most climate change models show increases in precipitation over much of North America, rates of evaporation and perhaps transpiration are also likely to increase with increasing temperatures. Regions that experience substantial increases in precipitation are likely to have substantial increases in runoff and river flows. Alternatively, regions in which changes in precipitation do not offset increasing rates of evaporation and transpiration may experience declines in runoff, and consequently declines in river flows, lake levels, and ground water recharge and levels. Most climate change scenarios suggest increased winter precipitation over much of North America which could result in increased runoff and river flows in winter and spring. Several climate change scenarios show declines in summer precipitation in some regions (e.g., the Southeastern U.S.) or declines in summer soil moisture levels (much of North America) which could result in significant declines in summer and autumn runoff in these regions. However, the climate change scenarios showing summer declines in precipitation or soil moisture levels are generally produced from climate model simulations with doubled CO_2 forcing alone; when aerosol forcing is included, summer precipitation and soil moisture levels increase slightly. This highlights the large uncertainty in climate change projections of runoff. Analyses of impacts on annual discharge for specific river basins using various climate model scenarios have ranged from -38% to +36%, but again, these projections are highly uncertain. Although large increases in annual runoff will affect flooding and flood management, large reductions may pose more serious threats to uses such as potable drinking water, irrigation, assimilation of wastes, recreation, habitat, and navigation. The greatest impact of declines in supply will be in arid and semi-arid regions and those areas with a high ratio of use relative to available renewable supply, as well as basins with multiple, competing uses.

In a warmer climate, the amount and seasonal timing of runoff in the mid and high latitude regions of North America could change dramatically as a result of shifts in the form of precipitation and timing of snowmelt. Warmer winters could lead to less winter precipitation as snowfall and more as rainfall, although increases in winter precipitation could also lead to greater snowfall and snow accumulations, particularly at the higher latitudes. Warmer winter and spring temperatures also could lead to earlier and more rapid snowmelt and earlier ice break-up, as well as more rain-on-snow events that produce severe flooding. In general, increases in winter and early spring temperatures under a doubled CO_2 climate could shift hydrologic regimes toward greater flows and more severe floods in winter and early spring and lower flows in summer in the mid and high latitude regions of North America. River and reservoir systems that are snowmelt fed or rely on glacier melt for spring and summer flow during the critical periods of high agricultural and municipal demand and low precipitation may have critical supply-demand mismatches. The Great Plains and Prairie regions of Canada and the U.S. and

California have been shown to be particularly vulnerable (Cohen *et al.*, 1989, Gleick 1993).

Changes in the seasonality of runoff may also affect water quality. In the mid and high latitudes the shift in the high runoff period from late spring and summer to winter and early spring might reduce water quality in summer under low flows. Extended droughts in boreal regions have been shown to result in acidification of streams due to oxidation of organic sulfur pools in soils (Schindler 1997). Reduction in summer baseflows will reduce the dilution capacity for wastewater effluents and exacerbate existing or produce new water quality problems. In general, water quality problems associated with human impacts on water resources (e.g., low dissolved oxygen levels and high contaminant concentrations resulting from wastewater effluents) will be exacerbated more by reductions in runoff, particularly during summer baseflow periods, than by other changes in hydrologic regimes.

Extreme Hydrologic Events

Changes in hydrologic variability (i.e., frequency and magnitude of extreme events) are likely to have a greater potential to impact water resources in many regions than changes in mean annual conditions. Under a warmer climate the hydrologic cycle is thought to become more intense, leading to more heavy rainfall events. Several doubled CO_2 simulations with global climate models have indicated an increase in the magnitude of mean rainfall events, particularly for central and northwest North America, even with small changes in mean annual rainfall (Cubasch *et al.,* 1995, Mearns *et al.,* 1995). In addition, these simulations indicate increases in the length of dry spells (consecutive days without precipitation). However, few model simulation analyses have addressed the issue of variability in daily precipitation, and increases in the frequency or severity of extreme hydrologic events are plausible but highly uncertain at this time.

Greater hydrologic variability would have large impacts on water resources management. More frequent or larger floods could lead to increased expenditures for flood management and place significant strains on public finances or on the insurance industry. Increases in the frequency or magnitude of extreme rainfall events would likely have greatest impacts on water resources if they occurred in the winter and spring when the ground is frozen or soil moisture levels are high, producing more rapid runoff and greater flooding. Flood control structures might require modifications to accommodate larger probable maximum flow events. Alternatives to structural flood control measures can be instituted to reduce risk at a lower cost to society, but these nonstructural methods of risk reduction are often slow to be accepted. Navigation might be impacted by changes in hydrologic variability, as illustrated by severe restrictions on navigation in the Mississippi River during the drought of 1988. Hydropower generation also could be severely restricted during droughts. More severe summer droughts could also increase agricultural irrigation demands and exacerbate current drinking water supply problems in some large urbanized areas, as shown for California and Houston, Texas.

Deterioration of water quality could result from an increase in hydrologic variability. An increase in the frequency or magnitude of floods could result in increased erosion of the land surface and stream channels, higher sediment loads and increased sedimentation of rivers and reservoirs, and increased loadings of nutrients and contaminants from agricultural and urban areas. More severe droughts, particularly in summer, could result in reduced water quality (e.g., lower dissolved oxygen concentrations, reduced dilution of effluents) and impaired biological habitat (e.g., drying of streams, expansion of zones with low dissolved oxygen concentrations, water temperatures exceeding thermal tolerances).

Changes in Lake Levels and Wetland Areas

Lake levels and wetland distributions are sensitive to changes in precipitation and evaporation which lead to changes in streamflow and groundwater flow. Several analyses have shown that lake levels and wetland areas decline or fluctuate more widely in climate change scenarios in which annual precipitation is reduced or soil moisture levels decline as a result of warming-induced increases in evaporation. Water level declines would be most severe in lakes in dry evaporative drainage basins and basins with small catchments. The semi-permanent prairie sloughs in the north-central U.S. and Canada, fed primarily by ground water, precipitation and spring snowmelt, are among the most sensitive to changes in climate that produce drier conditions. Loss of prairie pothole wetlands would have a substantial negative effect on waterfowl populations, as this area accounts for over half of the waterfowl produced each year in North America.

Potential water level changes in the Great Lakes are of particular concern because of their great economic and social importance. Analyses conducted as part of the Great Lakes-St. Lawrence Basin Project by Environment Canada suggest declines in water levels from 0.2 to 2.5 m in the Great Lakes under several doubled CO_2 climate change scenarios (Mortsch and Quinn 1996, Mortsch and Mills 1996). These water level changes were based on climate change scenarios from models that produced global temperature increases that are at least twice as large and precipitation changes that are generally greater than the most recent climate change simulations with aerosols included. Nonetheless, although highly uncertain at this time, the potential declines in Great Lakes water levels could have large negative effects on wetlands, fish spawning, recreational boating, commercial navigation, and municipal water supplies in the Great Lakes. Also of concern is the exposure of toxic sediments and their remediation with declines in lake levels. In contrast, climatic warming that produced a shorter period of winter ice cover would benefit commercial navigation on the Great Lakes as well as on other mid- and high-latitude water bodies.

Direct Effects of Warming

The direct effects of climatic warming will be both positive and negative, depending on the resource in question. Analyses of climate change effects on fish in deep, thermally-stratified lakes in the mid and high latitudes, including the Great Lakes, winter survival, growth rates, and thermal habitat generally increase under doubled CO_2 climate simulations (Magnuson and DeStasio 1996). However, in smaller mid-latitude lakes, particularly those that do not stratify or are more eutrophic, warming may reduce habitat for many of the cool-water and cold-water species because deep-water thermal refuges in summer are not present or become unavailable as a consequence of declines in dissolved oxygen concentrations (Stefan *et al.*, 1996). In general, climatic warming will produce a general shift in species distributions northward, with extinctions and extirpations of cold water species at lower latitudes and range expansion of warm-water and cool-water species into higher latitudes. For example, Eaton and Scheller (1996) project that the suitable habitat for cold- and cool-water fish species would be reduced by over 50% in streams of the conterminous U.S. by summer mean air temperature increases of 2-6°C derived from simulations of a doubled CO_2 climate model. In contrast, a 4°C increase in mean air temperature is projected to expand the ranges of smallmouth bass and yellow perch northward across Canada by about 500 km (Shuter and Post 1990).

Climatic warming could result in substantial changes in the mixing properties of many mid- and high-latitude lakes which, in turn, would produce large effects on deep-water dissolved oxygen concentrations and on primary productivity via effects on nutrient supplies and exposure of phytoplankton to light. Although these effects are expected to be highly dependent on the morphometric characteristics of individual lakes and are difficult to predict, at high latitudes the effects are likely to be generally beneficial. Development of summer stratification under a warmer climate could increase primary productivity and reduction in the duration of ice cover could reduce winter fish mortality from the development of anoxic conditions. Climate changes that result in decline in runoff also may have substantial effects on mixing in small lakes that are highly influenced by fluxes from their catchments. For example, the surface mixed layer of boreal lakes in northwest Ontario has deepened over the past 20 years as a result of a long-term drought that reduced inputs of colored humic compounds from the catchment and thus increased water clarity and light penetration (Schindler *et al.*, 1996).

In Arctic regions permafrost maintains lakes and wetlands above an impermeable frost table and limits subsurface water storage. Some climate change scenarios indicate that discontinuous and continuous permafrost boundaries could move poleward by about 500 km, reducing the area of permafrost to less than 80% of its present coverage. Thawing of permafrost increases active layer storage capacity, and alters peatland hydrology. Although climatic warming could have a large effect on Arctic hydrology, the changes are highly uncertain at this time.

A warmer climate could increase the demand for water for irrigation and for industrial cooling at the same time that urban growth will be increasing the demand for municipal water supplies. In addition, higher water temperatures will reduce the efficiency of cooling systems, and might make it increasingly difficult to meet regulatory requirements for downstream water temperatures, particularly during summer heat waves. Further, instream flow requirements to protect aquatic ecosystems are increasing in many basins and could increasingly constrain future available water supplies. Improved management of water infrastructure, pricing policies, and demand-side management of supply have the potential to mitigate some of the impacts of increasing water demand (Frederick and Gleick 1989).

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The impacts of climate change on water resources are potentially large and could result from increases in temperature and from changes in mean annual values and the variability of precipitation. However, our ability to predict climate change impacts on water resources and plan for adaptation and amelioration is hindered by the lack of good predictions of future climate at regional scales and a lack of fundamental understanding of many of the effects of climate variability on the physical, chemical, and biological characteristics of water resources. Several areas of future research are critical for improving our understanding of and our ability to predict effects of climate change on water resources. These include the development of better regional climate models, studies of relationships between climate variability and physiological and ecosystem processes, initiation of integrated assessment of impacts, and analyses that define viable response options for future changes in climate. Many water bodies are highly managed and changes in water resources management (infrastructure, operations, and administration) can potentially ameliorate some of the impacts of climate change. Adaptation will be necessary in many cases, however, and it is only through an improved understanding of climate and its effects on water resources that we can begin to plan the adaptation strategies that will be needed.

This review covers only the state-of-science on climatic effects on North American water resources through mid-year 1997 when the IPCC report was completed. Much additional research has been completed since that time. This newer information is currently being incorporated into the Water Sector Assessment of the U.S. National Assessment on the Potential Consequences of Climate Variability and Change that will be completed in 1999. For additional information on the on-going water sector assessment, see Dresler *et al.*, (this volume) and the U.S. Global Change Research Program's Web site at: www.nacc.usgcrp.gov.

REFERENCES

Anderson, J., S. Shiau, and D. Harvey. 1991. Preliminary Investigation of Trend/Patterns in Surface Water Characteristics and Climate Variations, pp. 189-201. In: *Using Hydrometric Data to Detect and Monitor Climatic Change*, Kite, G., and K. Harvey (eds.), Proceedings of NHRI Workshop, National Hydrology Research Institute, Saskatoon, Saskatchewan, Canada.

Burn, D. 1994. Hydrologic Effects of Climate Change in West-Central Canada. *Journal of Hydrology* 160:53-70.

Cohen, S. J., L. E. Welsh, and P. Y. T. Louie. 1989. *Possible Impacts of Climate Warming Scenarios on Water Resources in the Saskatchewan River Sub-Basin.* CCC Report No. 89-9, Atmospheric Environment Service, National Hydrology Research Centre, Saskatoon, Saskatchewan, 87 pp.

Cubasch, U., J. Waszkewitz, G. Hegerl, and J. Perlwitz. 1995. Regional Climate Changes as Simulated Time-slice Experiments. *Climatic Change* 31:273-304.

Eaton, J. G., and R. M. Scheller. 1996. Effects of Climate Warming on Fish Thermal Habitat in Streams of the United States. *Limnology and Oceanography* 41:1109-1115.

Frederick, K. D., and P. H. Gleick. 1989. Water Resources and Climate Change, pp. 133-143. In: *Greenhouse Warming: Abatement and Adaptation*, Rosenberg, N. J., W. E. Easterling III, P. R. Crosson, and J. Darmstadter (eds.), Resources for the Future, Washington, D. C., USA.

Gleick, P. H. 1993. *Water in Crisis.* Oxford University Press, Oxford, United Kingdom, 473 pp.

Lins, H. F., and P. J. Michaels. 1994. Increasing U.S. Streamflow Linked to Greenhouse Forcing. *EOS Transactions* 75:281-283.

Magnuson, J. J., and B. T. DeStasio. 1996. Thermal Niche of Fishes and Global Warming, pp. 377-408. In: *Global Warming - Implications for Freshwater and Marine Fish*, Wood, C. M., and D. G. MacDonald (eds.), Society for Experimental Biology Seminar Series 61, Cambridge University Press, Cambridge, UK.

Mearns, L. O., F. Giorgio, L. McDaniel, and C. Shields. 1995. Analysis of Daily Variability of Precipitation in a Nested Regional Climate Model: Comparison with Observations and Doubled CO_2 Results. *Global and Planetary Change* 10:55-78.

Mekis, E., and W. Hogg. 1997. Rehabilitation and Analysis of Canadian Daily Precipitation Time Series. In: 10th Conference on Applied Climatology, 20-24 October 1997, Reno, Nevada, USA (in press).

Mortsch, L. and F. Quinn. 1996. Climate Change Scenarios for Great Lakes Basin Ecosystem Studies. *Limnology and Oceanography 41*: 903-911.

Mortsch L. D., and B. N. Mills (eds.). 1996. 1996: Great Lakes - St. Lawrence Basin Project Progress Report #1: Adapting to the Impacts of Climate Change and Variability. Environment Canada, Burlington, Ontario, 160 pp.

Schindler, D. W. 1997. Widespread Effects of Climatic Warming on Freshwater Ecosystems in North America. *Hydrological Processes* 11:1043-1067.

Schindler, D. W., P. J. Curtis, P. Parker, and M. P. Stainton. 1996. Consequences of Climatic Warming and Lake Acidification for UV-B Penetration in North American Boreal Lakes. *Nature* 379:705-708.

Shriner, D. S., R. B. Street, R. Ball, D. D'Amours, K. Duncan, D. Kaiser, A Maarouf, L. Mortsch, P. Mulholland, R. Neilson, J. A. Patz, J. D. Scheraga, J. G. Titus, H. Vaughan, and M. Weltz. 1998. North America, pp. 253-330. In: Watson, R. T., M. C. Zinyowera, and R. H. Moss (eds.), *The Regional Impacts of Climate Change, An Assessment of Vulnerability*. Special Report of International Panel on Climate Change, Working Group II, Cambridge University Press, Cambridge, United Kingdom.

Shuter, B. J., and J. R. Post. 1990. Climate, Population Viability, and the Zoogeography of Temperate Fishes. *Transactions of the American Fisheries Society* 119:316-336.

Stefan, H. G., M. Hondzo, X. Fang, J. G. Eaton, and J. McCormick. 1996. Simulated Long-Term Temperature and Dissolved Oxygen Characteristics of Lakes in the north-central United States and Associated Fish Habitat Limits. *Limnology and Oceanography* 41:1124-1135.