Scienxt Journal of Environmental Sciences
Volume-2 || Issue-1 || Jan-June || Year-2024 || pp. 1-17

Climate change and water

***[1]Priti Rahangdale, [2]Farhan Khan, [3]Pawan Kumar**

[*1,2,3]Assistant professor, Department of chemistry, Bhopal Institute of Technology &science (BITS)
Bhopal 462045 M.P. India

**Corresponding Author: Priti Rahangdale*
Email: pritirahangdale00gmail.com

Abstract:

This paper explores the potential implications of climate change for the use and management of water resources. It is based on a review of simulations of changes in river flows, groundwater recharge and river water quality. These simulations imply, under feasible climate change scenarios, that annual, winter and summer runoff will decrease in southern Britain, groundwater recharge will be reduced and that water quality – as characterized by nitrate concentrations and dissolved oxygen contents – will deteriorate. In northern Britain, river flows are likely to increase throughout the year, particularly in winter. Climate change may lead to increased demands for water, over and above that increase which is forecast for non-climatic reasons, primarily due to increased use for garden watering. These increased pressures on the water resource base will impact not only upon the reliability of water supplies, but also upon navigation, aquatic ecosystems, recreation and power generation, and will have implications for water quality management. Flood risk is likely to increase, implying a reduction in standards of flood protection. The paper discusses adaptation options.

1. Introduction to climate change and water:

Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems.

Hydrologic models provide a framework in which to conceptualize and investigate the relationships between climate and water resources. These investigations can range from the evaluation of annual and seasonal stream flow variation using simple water balance models to the evaluation of variations in surface- and ground-water quantity, quality, and timing using complex distributed-parameter models that simulate a wide range of water, energy, and biogeochemical processes. The scientific literature over the past decade contains a large number of reports detailing the application of hydrologic models to the assessment of the potential effects of climate change on a variety of water resource issues. The purpose of this paper is not to review the findings of these reports but to characterize the current state of water resource modeling for use in simulating the effects of climate change and current climate variability.

Methodologies are reviewed, deficiencies are discussed, and additional research needs are identified.

2. Modal:

Climate model simulations for the 21st century are consistent in projecting precipitation increases in high latitudes (very likely) and parts of the tropics, and decreases in some subtropical and lower mid-latitude regions (likely). Outside these areas, the sign and magnitude of projected changes varies between models, leading to substantial uncertainty in precipitation projections.3 Thus projections of future precipitation changes are more robust for some regions than for others.

Projections become less consistent between models as spatial scales decrease.

By the middle of the 21st century, annual average river runoff and water availability are projected to increase as a result of climate change4 at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics

Water supplies stored in glaciers and snow cover are projected to decline in the course of the century, thus reducing water availability during warm and dry periods (through a seasonal shift in stream flow, an increase in the ratio of winter to annual flows, and reductions in low flows) in regions supplied by melt water from major mountain ranges, where more than one-sixth of the world's population currently live.

"Hydrologic modeling is concerned with the accurate prediction of the partitioning of water among the various pathways of the hydrological cycle" (Dooge, 1992). This partitioning in its simplest form is expressed by the water balance equation:

$Q = P\text{-}ET + AS$ (1)

Where Q is runoff, P is precipitation, ET is evapotranspiration, and AS is the change in system storage. Equation (1) is common to all hydrologic models. The variety and number of hydrologic models developed to solve Equation (1) reflect the wide range of modeling purposes, data constraints, and spatial and temporal scales that have influenced the conceptualization and parameterization of the processes in the equation.

Models can be classified using a number of different schemes (Woolhiser and Brakensiek, 1982; Becker and Serban, 1990; Dooge, 1992). Classification criteria include purpose of model application (e.g., real-time application, long-term prediction, process understanding), model structure (models based on fundamental laws of physics, conceptual models reflecting these laws in a simplified approximate manner, black-box or empirical analysis), spatial discretization (lumped parameter, distributed parameter), temporal scale (hourly, daily, monthly, annual) and spatial scale (point, field, basin, region, global). A variety of these types of models have been applied to the assessment of the effects of climate change. A review of some of these modeling approaches provides one measure of the state of the art of hydrologic modeling. This is not a comprehensive review of all model studies, but a review of selected models to indicate the variety of modeling approaches and range of applications. Models are grouped using the model structure and spatial discretization criteria.

2.1. Current modeling approaches:

2.1.1. Water balance models:

Water balance models originated with the work of Thornthwaite (1948) and Thornthwaite and Mather (1955). These models are basically bookkeeping procedures used with Equation (1) to account for the movement of water from the time it enters a basin as precipitation to the time it leaves the basin as runoff. The models vary in their degree of complexity based on the detail with which each component of Equation (1) is considered. Most models account for direct runoff from rainfall and lagged runoff from basin storage in the computation of total runoff

(Q). In addition, most models compute the ET term as some function of potential ET and the water available in storage (S). While water balance models can be applied at a daily, weekly, monthly, or annual time step, in climate studies they have been applied most frequently at the monthly time step.

A simple three-parameter monthly water balance model was applied by Aruell (1992) to 15 basins in the United Kingdom to estimate changes in the monthly river flow regimes and to investigate the factors controlling the effects of climate change on river flow regimes in a humid temperate climate. The three parameters, which were fitted to each individual basin, represent (1) the fraction of precipitation that contributes directly to runoff; (2) the maximum storage capacity of the basin; and (3) the basin lag for converting the water available for runoff to stream flow. Arndell (1992) also compared the water balance model with four different empirical models for the assumed climate changes. No one empirical formulation gave a consistently closer match to the water balance model estimates of climate change effects, and differences among empirical models for the same scenario were large. It was noted that the results suggest that "estimates of possible change based on annual empirical models should be treated with extreme caution."

Water balance models provide the ability to simulate average runoff for given precipitation over a range of basin conditions and to simulate the year to year variation in runoff as precipitation varies.

Limitations include the need to calibrate parameters to observed conditions and the inability to adequately account for possible changes in individual storm runoff characteristics at the time steps they are applied.

2.1.2. Conceptual lumped-parameter models:

Conceptual lumped-parameter models are developed using approximations or simplifications of fundamental physical laws and may include some amount of empiricism. They attempt to account for the linear and nonlinear relations among the components of Equation (1). As with water balance models, conceptual lumped parameter models attempt to account for the movement of water from the time it enters the basin until it leaves as runoff. However, flow paths and residence times of water are considered in much greater detail and normally at time steps on the order of minutes, hours, or one day. Vertical and lateral flow processes may be considered. Vertical processes may include interception storage and evaporation, infiltration, soil moisture storage; evapotranspiration, ground-water recharge, and snow pack accumulation and melt. Lateral flow processes may include surface runoff, subsurface flow, ground-water flow, and stream flow. In addition, some models include the capability to simulate some associated sediment, chemical, and biological processes.

The Erosion Productivity Impact Calculator (EPIC) is a coupled model that simulates hydrology, erosion and sedimentation, nutrient cycling, plant growth, tillage, soil temperature, and crop management (Williams et al., 1984). EPIC was modified to enable it to simulate the effects of atmospheric CO2 and climate change on crop photosynthetic efficiency and water use (Stockle et al., 1992a, b). This modified version was used to investigate the effects of rising atmospheric CO2 concentrations and climate change on agricultural productivity in the four state region of Missouri, Iowa, Nebraska, and Kansas (Easterling et al., 1992a, b). Applications were made at the single hectare scale for 49 different representative sites throughout the region.

2.1.3. Process-based distributed-parameter models:

These models are firmly based in the understanding of the physics of the processes that control basin response. Process equations involve one or more space coordinates and have the capability of forecasting the spatial pattern of hydrologic conditions in a basin as well as basin storages and outflows (Bevan, 1985). Spatial discretization of a basin to facilitate this detail in process simulation may be done using a grid-based approach or a topographically based delineation. In each case, process parameters are determined for each grid cell or topographic element.

Major limitations to the application of these models are the availability and quality of basin and climate data at the spatial and temporal resolution needed to estimate model parameters and validate model results at this level of detail. These data requirements may pose a limit to the size of basin in which these models are applied. However, the System Hydrologique European (SHE) model (Abbott et al., 1986) is said to have been successfully applied to basins ranging from 30 m 2 to 5000 km 2 (Bathurst and O'Connell, 1992).

Increased precipitation intensity and variability are projected to increase the risks of flooding and drought in many areas.

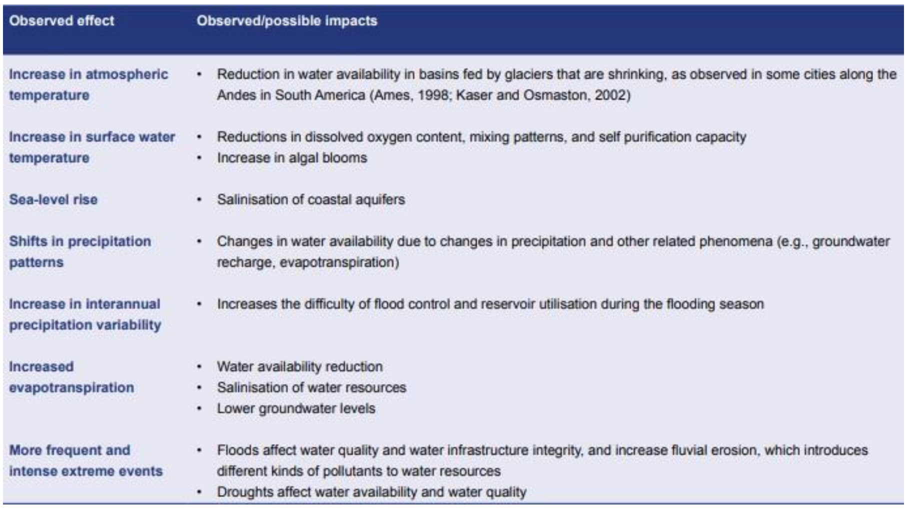
3. Observed and projected changes in climate as they relate to water:

3.1. Observed changes in climate as they relate to water:

The hydrological cycle is intimately linked with changes in atmospheric temperature and radiation balance. Warming of the climate system in recent decades is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. Net anthropogenic radioactive forcing of the climate is estimated to be positive (warming effect), with a best estimate of 1.6 Wm−2 for 2005 (relative to 1750 pre-industrial values). The best-estimate linear trend in global surface temperature from 1906 to 2005 is a warming of 0.74°C (likely range 0.56 to 0.92°C), with a more rapid warming trend over the past 50 years. New analyses show warming rates in the lower- and mid-troposphere that are similar to rates at the surface. Attribution studies show that most of the observed increase in global temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. At the continental scale, it is likely that there has been significant anthropogenic. Warming over the past 50 years averaged over each of the continents except Antarctica. For widespread regions, cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent over the past 50 years.

Understanding and attribution of observed changes also presents a challenge. For hydrological variables such as runoff, non-climate-related factors may play an important role locally (e.g., changes in extraction). The climate response to forcing agents is also complex. For example, one effect of absorbing aerosols (e.g., black carbon) is to intercept heat in the aerosol layer which would otherwise reach the surface, driving evaporation and subsequent latent heat release above the surface. Hence, absorbing aerosols may locally reduce evaporation and precipitation. Many aerosol processes are omitted or included in somewhat simple ways in climate models, and the local magnitude of their effects on precipitation is in some cases poorly known. Despite the above uncertainties, a number of statements can be made on the attribution of observed hydrological changes, and these are included in the discussion of individual variables in this section, based on the assessments

Table. 3.1: Observed effects of climate change and its observed/possible impacts on water services



Observed effect	Observed/possible impacts
Increase in atmospheric temperature	• Reduction in water availability in basins fed by glaciers that are shrinking, as observed in some cities along the Andes in South America (Ames, 1998; Kaser and Osmaston, 2002)
Increase in surface water temperature	• Reductions in dissolved oxygen content, mixing patterns, and self purification capacity • Increase in algal blooms
Sea-level rise	• Salinisation of coastal aquifers
Shifts in precipitation patterns	• Changes in water availability due to changes in precipitation and other related phenomena (e.g., groundwater recharge, evapotranspiration)
Increase in interannual precipitation variability	• Increases the difficulty of flood control and reservoir utilisation during the flooding season
Increased evapotranspiration	• Water availability reduction • Salinisation of water resources • Lower groundwater levels
More frequent and intense extreme events	• Floods affect water quality and water infrastructure integrity, and increase fluvial erosion, which introduces different kinds of pollutants to water resources • Droughts affect water availability and water quality

3.1.1. Precipitation (including vapor extremes) and water

3.1.2. Snow and land ice (Snow cover, frozen ground, lake and river ice, Glaciers and ice caps)

3.1.3. Sea level

3, .1.4. Evapotranspiration

3.1.5. Soil moisture

3.1.6. Runoff and river discharge etc….

4. Linking climate change and water resources: impacts and responses:

4.1. Observed climate change impacts:

4.1.1. Observed effects due to changes in the cryosphere:

Effects of changes in the cryosphere have been documented in relation to virtually all cryospheric components, with robust evidence that they are, in general, a response to the reduction of snow and ice masses due to enhanced warming.

4.1.2. Hydrology and water resources:

Changes in surface and groundwater systems Since the TAR there have been many studies related to trends in river flows during the 20th century at scales ranging from catchment to global. Some of these studies have detected significant trends in some indicators of river flow, and some have demonstrated statistically significant links with trends in temperature or precipitation; but no globally homogeneous trend has been reported. Many studies, however, have found no trends, or have been unable to separate the effects of variations in temperature and precipitation from the effects of human interventions in the catchment, such as land-use change and reservoir construction. Variation in river flows from year to year is also very strongly influenced in some regions by large-scale atmospheric circulation patterns associated with ENSO, NAO and other variability systems that operate at within-decadal and multi-decadal time-scales

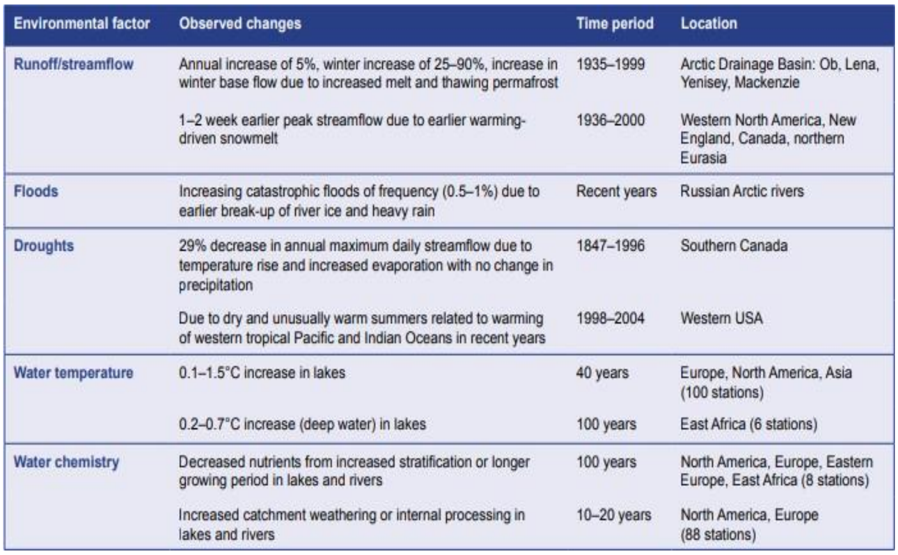
4.1.3. Water quality a climate:

Related warming of lakes and rivers has been observed over recent decades. As a result, freshwater ecosystems have shown changes in species composition, organism abundance, productivity and phenological shifts (including earlier fish migration). [WGII Also due to warming, many lakes have exhibited prolonged stratification with decreases in surface layer nutrient concentration, and prolonged depletion of oxygen in deeper layers. Due to strong anthropogenic impacts not related to climate change, there is no evidence for consistent climate-related trends in other water quality parameters (e.g., salinity, pathogens or nutrients) in lakes, rivers and groundwater.

4.1.4. Floods:

As discussed in Section, heavy precipitation events are projected to become more frequent over most regions throughout the 21st century. This would affect the risk of flash flooding and urban flooding. Some potential impacts are shown in Table

In a multi-model analysis, Palmer and Räisänen (2002) projected a considerable increase in the risk of a very wet winter over much of central and northern Europe, this being due to an increase in intense precipitation associated with mid-latitude storms. The probability of total boreal winter precipitation exceeding two standard deviations above normal was projected to increase considerably (five- to seven-fold) for a CO2 -doubling over large areas of Europe, with likely consequences for winter flood hazard. An increase in the risk of a very wet monsoon season in Asia was also projected (Palmer and Räisänen, 2002). According to Milly et al. (2002), for 15 out of 16 large basins worldwide, the control 100-year peak volumes of monthly river flow are projected to be exceeded more frequently for a CO2 -quadrupling. In some areas, what is given as a 100-year flood now (in the control? run), is projected to occur much more frequently, even every 2–5 years, albeit with a large uncertainty in these projections. In many temperate regions, the contribution of snowmelt to spring floods is likely to decline (Zhang et al., 2005)



Environmental factor	Observed changes	Time period	Location
Runoff/streamflow	Annual increase of 5%, winter increase of 25–90%, increase in winter base flow due to increased melt and thawing permafrost	1935–1999	Arctic Drainage Basin: Ob, Lena, Yenisey, Mackenzie
	1–2 week earlier peak streamflow due to earlier warming-driven snowmelt	1936–2000	Western North America, New England, Canada, northern Eurasia
Floods	Increasing catastrophic floods of frequency (0.5–1%) due to earlier break-up of river ice and heavy rain	Recent years	Russian Arctic rivers
Droughts	29% decrease in annual maximum daily streamflow due to temperature rise and increased evaporation with no change in precipitation	1847–1996	Southern Canada
	Due to dry and unusually warm summers related to warming of western tropical Pacific and Indian Oceans in recent years	1998–2004	Western USA
Water temperature	0.1–1.5°C increase in lakes	40 years	Europe, North America, Asia (100 stations)
	0.2–0.7°C increase (deep water) in lakes	100 years	East Africa (6 stations)
Water chemistry	Decreased nutrients from increased stratification or longer growing period in lakes and rivers	100 years	North America, Europe, Eastern Europe, East Africa (8 stations)
	Increased catchment weathering or internal processing in lakes and rivers	10–20 years	North America, Europe (88 stations)

4.1.5. Droughts:

It is likely that the area affected by drought will increase. [WGI SPM] There is a tendency for drying of mid-continental areas during summer, indicating a greater risk of droughts in these regions. [WGI 10.ES] In a single-model study of global drought frequency, the proportion of the land surface experiencing extreme drought at any one time, the frequency of extreme drought events, and the mean drought duration, were projected to increase by 10- to 30-fold, two-fold, and six-fold, respectively, by the 2090s, for the SRES A2 scenario (Burke et al., 2006). [WGI 10.3.6; WGII 3.4.3] A decrease in summer precipitation in southern and central Europe, accompanied by rising temperatures (which enhance evaporative demand), would inevitably lead to both reduced summer soil moisture (cf. Deauville et al., 2002; Christensen et al., 2007) and more frequent and intense droughts. [WGII 3.4.3] As shown in Figure 3.3, by the 2070s, a 100-year drought16 of today's magnitude is projected to return, on average, more frequently than every 10 years in parts of Spain and Portugal, western France, Poland's Vistula Basin and western Turkey (Lehner et al., 2005)

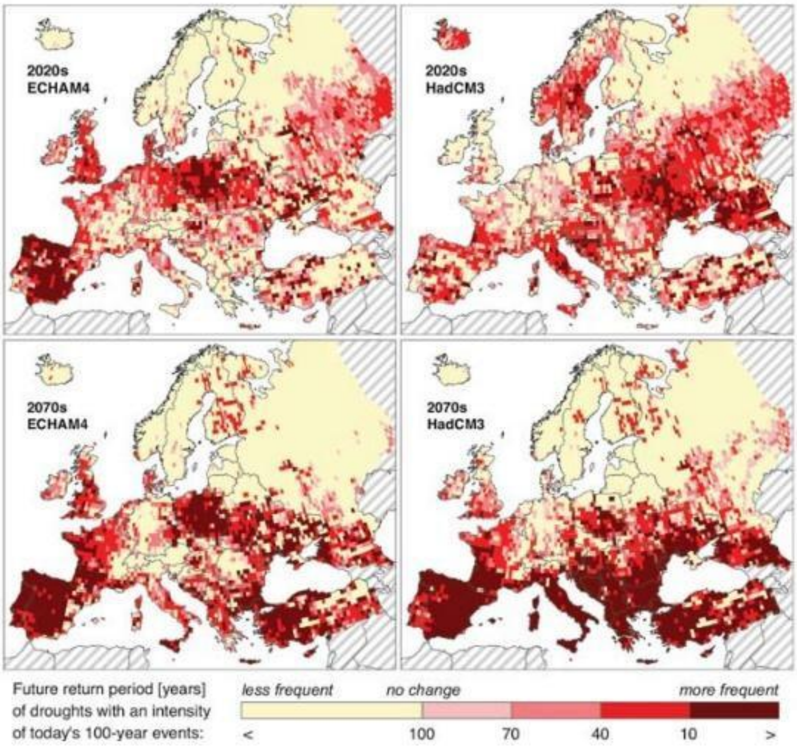


Figure. 4.1.5: Change in the future recurrence of 100-year droughts, based on comparisons between climate and water use in 1961–1990 (Lehner et al., 2005)

4.2. Future changes in water availability and demand due to climate change

4.2.1. Climate-related drivers of freshwater systems in the future

4.2.2. Non-climatic drivers of freshwater systems in the future

4.2.3. Impacts of climate change on freshwater availability in the future

4.2.4. Impacts of climate change on freshwater demand in the future

4.2.5. Impacts of climate change on water stress in the future

4.2.6. Impacts of climate change on costs and other socio-economic aspects of freshwater

4.2.7. Freshwater ‘areas and sectors highly vulnerable to climate change

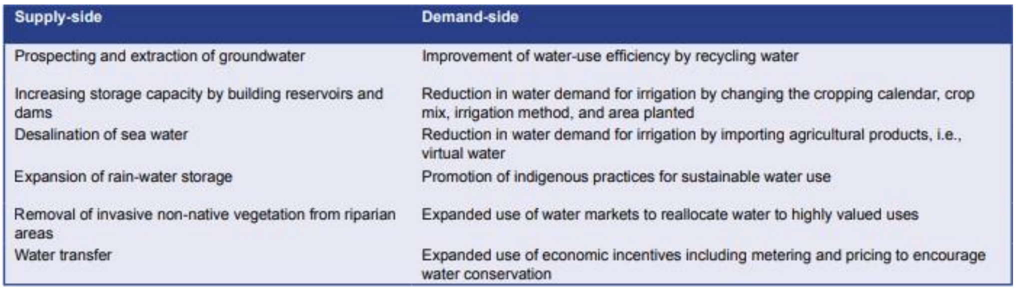
4.2.8. Uncertainties in the projected impacts of climate change on freshwater systems

4.2. Water-related adaptation to climate change: an overview:

Water managers have long dealt with changing demands for water resources. To date, water managers have typically assumed that the natural resource base is reasonably constant over the medium term and, therefore, that past hydrological experience provides a good guide to future conditions. Climate change challenges these conventional assumptions and may alter the reliability of water management systems. Management responses to climate change include the development of new approaches to system assessment and design, and non-structural methods through such mechanisms as the European Union Water Framework Directive

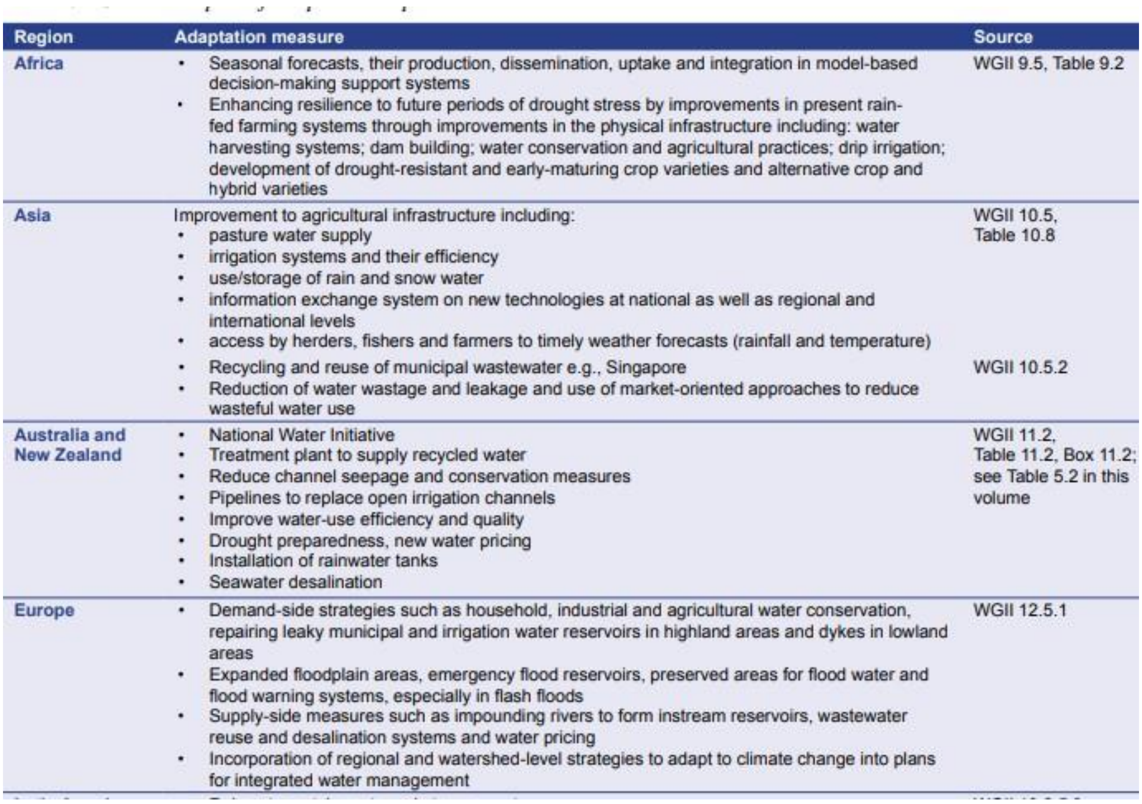
Table. 4.2. summarizes some supply-side and demand-side adaptation options, designed to ensure supplies during average and drought conditions. Supply-side options generally involve increases in storage capacity or abstraction from water courses and therefore may have adverse environmental consequences. Demand-side options may lack practical effectiveness because they rely on the cumulative actions of individuals. Some options may be inconsistent with mitigation measures because they involve high energy consumption, e.g., desalination, pumping.

Table. 4.2: Some adaptation options for water supply and demand (the list is not exhaustive). (Table4.3)



Supply-side	Demand-side
Prospecting and extraction of groundwater	Improvement of water-use efficiency by recycling water
Increasing storage capacity by building reservoirs and dams	Reduction in water demand for irrigation by changing the cropping calendar, crop mix, irrigation method, and area planted
Desalination of sea water	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water
Expansion of rain-water storage	Promotion of indigenous practices for sustainable water use
Removal of invasive non-native vegetation from riparian areas	Expanded use of water markets to reallocate water to highly valued uses
Water transfer	Expanded use of economic incentives including metering and pricing to encourage water conservation

Table. 4.3: Some examples of adaptation in practice



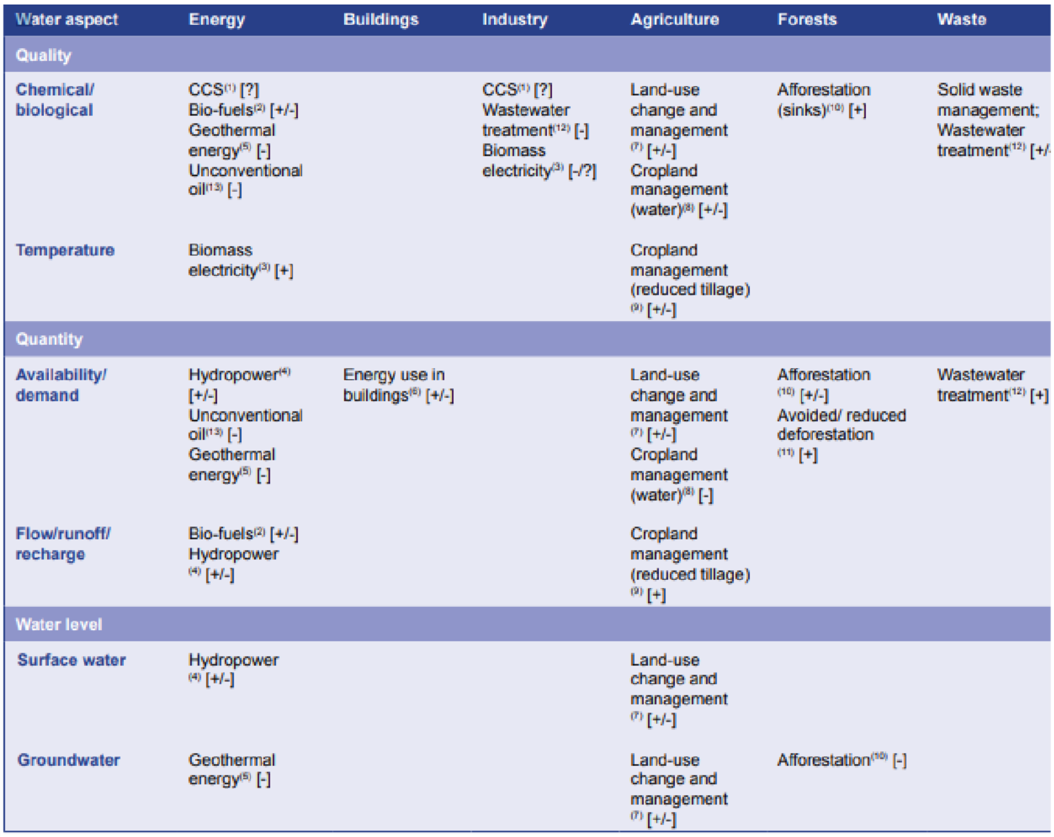
Region	Adaptation measure	Source
Africa	• Seasonal forecasts, their production, dissemination, uptake and integration in model-based decision-making support systems • Enhancing resilience to future periods of drought stress by improvements in present rain-fed farming systems through improvements in the physical infrastructure including: water harvesting systems; dam building; water conservation and agricultural practices; drip irrigation; development of drought-resistant and early-maturing crop varieties and alternative crop and hybrid varieties	WGII 9.5, Table 9.2
Asia	Improvement to agricultural infrastructure including: • pasture water supply • irrigation systems and their efficiency • use/storage of rain and snow water • information exchange system on new technologies at national as well as regional and international levels • access by herders, fishers and farmers to timely weather forecasts (rainfall and temperature)	WGII 10.5, Table 10.8
	• Recycling and reuse of municipal wastewater e.g., Singapore • Reduction of water wastage and leakage and use of market-oriented approaches to reduce wasteful water use	WGII 10.5.2
Australia and New Zealand	• National Water Initiative • Treatment plant to supply recycled water • Reduce channel seepage and conservation measures • Pipelines to replace open irrigation channels • Improve water-use efficiency and quality • Drought preparedness, new water pricing • Installation of rainwater tanks • Seawater desalination	WGII 11.2, Table 11.2, Box 11.2; see Table 5.2 in this volume
Europe	• Demand-side strategies such as household, industrial and agricultural water conservation, repairing leaky municipal and irrigation water reservoirs in highland areas and dykes in lowland areas • Expanded floodplain areas, emergency flood reservoirs, preserved areas for flood water and flood warning systems, especially in flash floods • Supply-side measures such as impounding rivers to form instream reservoirs, wastewater reuse and desalination systems and water pricing • Incorporation of regional and watershed-level strategies to adapt to climate change into plans for integrated water management	WGII 12.5.1

5. Climate change mitigation measures and water:

The relationship between climate change mitigation measures and water is a reciprocal one. Mitigation measures can influence water resources and their management, and it is important to realize this when developing and evaluating mitigation options. On the other hand, water management policies and measures can have an influence on greenhouse gas (GHG) emissions and, thus, on the respective sect oral mitigation measures; interventions in the water system might be counter-productive when evaluated in terms of climate change mitigation.

Sector-specific mitigation measures can have various effects on water, which are explained in the sections below (see also Table 6.1). Numbers in parentheses in the titles of the sub-sections correspond to the practices or sector-specific mitigation options described in Table 5.1.

Table. 5.1: Influence of sector-specific mitigation options (or their consequences) on water quality, quantity and level. Positive effects on water are indicated with [+]; negative effects with [−]; and uncertain effects with [?]. Numbers in round brackets refer to the Notes



Water aspect	Energy	Buildings	Industry	Agriculture	Forests	Waste
Quality						
Chemical/ biological	CCS(1) [?] Bio-fuels(2) [+/-] Geothermal energy(5) [-] Unconventional oil(13) [-]		CCS(1) [?] Wastewater treatment(12) [-] Biomass electricity(3) [-/?]	Land-use change and management (7) [+/-] Cropland management (water)(8) [+/-]	Afforestation (sinks)(10) [+]	Solid waste management; Wastewater treatment(12) [+/-
Temperature	Biomass electricity(3) [+]			Cropland management (reduced tillage) (9) [+/-]		
Quantity						
Availability/ demand	Hydropower(4) [+/-] Unconventional oil(13) [-] Geothermal energy(5) [-]	Energy use in buildings(6) [+/-]		Land-use change and management (7) [+/-] Cropland management (water)(8) [-]	Afforestation (10) [+/-] Avoided/ reduced deforestation (11) [+]	Wastewater treatment(12) [+]
Flow/runoff/ recharge	Bio-fuels(2) [+/-] Hydropower (4) [+/-]			Cropland management (reduced tillage) (9) [+]		
Water level						
Surface water	Hydropower (4) [+/-]			Land-use change and management (7) [+/-]		
Groundwater	Geothermal energy(5) [-]			Land-use change and management (7) [+/-]	Afforestation(10) [-]	

Notes:

(1) Carbon capture and storage (CCS) underground poses potential risks to groundwater quality; deep-sea storage (below 3,000 m water depth and a few hundred meters of sediment) seems to be the safest option.

(2) Expanding bio-energy crops and forests may cause negative impacts such as increased water demand, contamination of underground water and promotion of land- use changes, leading to indirect effects on water resources; and/or positive impacts through reduced nutrient leaching, soil erosion, runoff and downstream siltation.

(3) Biomass electricity: in general, a higher contribution of renewable energy (as compared to fossil-fuel power plants) means a reduction of the discharge of cooling iiiwater to the surface water.

(4) Environmental impact and multiple benefits of hydropower need to be taken into account for any given development; they could be either positive or negative.

(5) Geothermal energy use might result in pollution, subsidence and, in some cases, a claim on available water resources.

(6) Energy use in the building sector can be reduced by different approaches and measures, with positive and negative impacts.

(7) Land-use change and management can influence surface water and groundwater quality (e.g., through enhanced or reduced leaching of nutrients and pesticides) and the (local) hydrological cycle (e.g., a higher water use).

(8) Agricultural practices for mitigation can have both positive and negative effects on conservation of water and on its quality.

(9) Reduced tillage promotes increased water-use efficiency.

(10) A forestation generally improves groundwater quality and reduces soil erosion. It influences both catchment and regional hydrological cycles (a smoothed hydrograph, thus reducing runoff and flooding). It generally gives better watershed protection, but at the expense of surface water yield and aquifer recharge, which may be critical in semi-arid and arid regions.

(11) Stopping/slowing deforestation and forest degradation conserve water resources and prevent flooding, reduce run-off, control erosion and reduce siltation of rivers.

(12) The various waste management and wastewater control and treatment technologies can both reduce GHG emissions and have positive effects on the environment, but they may cause water pollution in case of improperly designed or managed facilities.

(13) As conventional oil supplies become scarce and extraction costs increase, unconventional liquid fuels will become more economically attractive, but this is offset by greater environmental costs (a high water demand; sanitation costs).

6. Conclusion:

Numerous models and modeling approaches are currently being used to assess the impacts of climate change on water resources. Studies to date have been generally limited to the use of operational models that have been tested in a wide variety of geographic regions or extensively in the region of interest. Model choice is normally a function of problem objectives, data constraints, and the spatial and temporal scales of application. Empirical and water-balance type models have generally been applied to large-basin and regional analyses at time scales of months to seasons to years. More detailed conceptual lumped-parameter and process-based distributed-parameter models have generally been applied to smaller basins at time scales of 24 hr or less.

A review of current modeling studies also indicates a number of problem areas common to the variety of models applied. These problem areas are related to a number of modeling issues, including parameter estimation, temporal and spatial scale of application, validation, climate-scenario generation, data, and modeling tools. Solutions to these problems would significantly improve the capability of models to assess the effects of climate change. Research needs to address these problems include:

1. A more physically based understanding of hydrologic processes and their interactions is needed. The complexities of the hydrologic system are such that process parameterizations will always represent an integration of the spatial heterogeneity of the factors that control these processes. However, when these parameterizations are based on the physics of the process, the ability to measure or estimate parameter values from climate and basin characteristics is improved. It is only through the use of parameterizations that do not require calibration that the problems of climatic and geographic transferability will be resolved.
2. Parameter measurement and estimation techniques must be developed for application over a range of spatial and temporal scales. In moving from the points to hill slopes to grid cells or small basins, different sets of physical laws may dominate at each of these scales. The variability and applicability of parameters and process formulations must be understood across the wide range of scales over which climate change impacts will be assessed.
3. Quantitative measures of uncertainty in model parameters and model results are needed. Uncertainty measures could provide an estimate of confidence limits on model results and would be of value in the application of these results in risk and policy analyses.
4. Improved methodologies to develop climate change scenarios are needed. Removing the uncertainties in current scenarios is dependent on improvements in both GCMs and scenario generation procedure. Scenarios must provide the spatial and temporal resolution required by assessment models and they must incorporate the simulated changes in mean and variability of the climate variables.
5. Simulation capabilities have generally exceeded available data bases. Detailed data sets in a variety of climatic and physiographic regions collected at a range of spatial and temporal scales are critical to improving our understanding of hydrologic processes and to testing and validating the more physically based models that are being developed.

6. Modular modeling systems need to be developed to facilitate interdisciplinary research on the full range of modeling problems and to provide a framework in which to apply solutions to the range of assessment questions. Maximum use of current and future advances in the fields of expert systems, geographical information systems, remote sensing, information management, and computer science should be made in the development of such systems.

7. References:

(1) Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, R E., and Rasmussen, J.: 1986, 'An Introduction to the European Hydrological System - System Hydrologique Europeen, SHE, 1. History and Philosophy of a Physically-Based, Distributed Modeling System', J. Hydrol. 87, 45-59.

(2) Anderson, E. A.: 1973, 'National Weather Service River Forecast System - Snow Accumulation and Ablation Model', NOAA Technical Memorandum NWS Hydro-17, U.S. Department of Commerce, Silver Springs, MD.

(3) Kaspar, F., 2003: Entwicklung und Unsicherhe its analyseseines globulin hydrologischen (Model Development and Uncertainty Analysis of 150 References a Global Hydrological Model). University of Kassel, Kassel, PhD thesis.