Chapter 4

Hydrology and water resources

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1 Introduction

Changes in climatic conditions due to increasing atmospheric concentrations of radiatively active trace gases will probably alter land and water resources, their distribution in space and time, the hydrologic cycle of water bodies, water quality, and water supply systems and requirements for water resources in different regions. Quantitative estimates of the hydrologic effects of climate change are essential for understanding and solving potential water resource problems associated with domestic water use, industry, power generation, agriculture, transportation, future water resources systems planning and management, and protection of the natural environment.

Climate change can be expected to lead to changes in soil moisture and water resources. The most important climate variable that may change is regional precipitation, which cannot be predicted well. Water supply and use in semi-arid lands are very sensitive to small changes in precipitation and evapotranspiration by vegetation, because the fraction of precipitation that runs off or percolates to groundwater is small. Increased heat will lead to more evapotranspiration, but the increase is expected to be partly offset by reduced plant water use in a COj-enriched atmosphere.

Higher temperatures may also have an impact in the transitional winter snow zones. More winter precipitation would be in the form of rain instead of snow, thereby increasing winter season runoff and decreasing spring and summer snowmelt flows. Where the additional winter runoff cannot be stored because of flood control considerations or lack of adequate storage, a loss in usable supply would be the result.

This chapter presents estimates of the influence of climatic change on hydrologic and water resource conditions in various countries and regions.

2 Climate scenarios

Forecasts of changes in climatic conditions for different regions and periods of time are required to estimate the hydrologic effects of increasing trace gas concentrations in the atmosphere. Air temperature, precipitation, cloud cover or insolation, wind speed and humidity are the most important conditions. However, reliable forecasts of regional climate change are unavailable. In their absence, various approaches to the development of scenarios of future climatic conditions are used, including (1) hypothetical (or prescribed) scenarios, **(2)** scenarios obtained from atmospheric general circulation models (GCM), and (3) scenarios based on historical and palaeoclimatic reconstructions.

The first approach is to prescribe climatic changes for various regions or river basins in a simplified manner. As a rule, such scenarios specify air temperature increases from 0.5 °C to 4.0 °C and precipitation changes (increase or decrease) in the range of 10% to 25%. Some authors also prescribe hypothetical changes in evaporation.

The second approach is to obtain scenarios directly from GCMs in which the atmospheric concentration of CO_2 is doubled (2 x CO_2). A problem with using GCMs is that the simulations for the same regions by different climate models may yield different and sometimes opposite results, especially for precipitation changes (Gleick, 1988).The third approach is to develop future climate analogs based on climatic reconstructions of past warm epochs, when atmospheric CO_2 was above the present value. For instance, Soviet climatologists show in their studies (Budyko and Izrael, 1987) that the so-called Holocene optimum (about 5-6 KA) can be considered as a 1°C global warming analog (about in the year 2000-2005); the last interglacial epoch (the Mikulino, 125 KA) can serve as an analog of the climatic conditions with a 2°C warming in the year 2020-2025; and the Pliocene climatic optimum that took place a few million years ago, with mean air temperatures 3°C-4°C above present, can be an analog of climatic conditions for the more distant future years 2040-2050.

There are difficulties and limitations in the application of palaeoclimatic reconstructions owing to the uncertainty of the climatic conditions of the remote past and to the lack of reliable palaeoclimatic data for many regions and countries. There is also a continuing discussion of the relative merits of the three approaches. In the absence of reliable predictions, the question of which scenario is best remains unanswered.

3 Some physical aspects of hydrology and water resources

3.1 Methodological approaches

During the past 10 years hydrologists from many countries have extensively studied hydrologic consequences of future anthropogenic climate change.

These studies are based on various methods that can be united into the following groups:

(i) Analysis of long-term variations in runoff and meteorological elements over past periods. This method can be approached in two ways. The first consists of statistical analyses of the relations between runoff, air temperature, and precipitation. This approach has been used by Stockton and Boggess (1979) and Revelle and Waggoner (1983) for western regions of the US and the Colorado River basin, and by Polyak and Speranskaya (1987) for annual river runoff in the USSR. The second way is to study the hydrologic consequences of past periods of very warm or cold, wet or dry conditions. Such analyses have been carried out by Schwarz (1977) and Glantz (1988) for the US, by Liu (1989) for northern China, and by Demaree and Nicolis (1990) for the Sahelian region.

In the US, the first major assessment of climate-runoff relations was conducted by Langbein et al. (1949), who produced a set of rainfall-runoff curves widely used in crude impact studies. These relations were tested and updated by Karl and Riebsame (1989), based on an analysis of actual climate fluctuations over 90 undisturbed drainages. They found that runoff was less sensitive to temperature changes than suggested by Langbein and his colleagues.

(ii) Use of water balance methods over a long period of time. In this approach the main task is to estimate future total evaporation. These methods have been used by Glantz and Wigley (1987) for the US, Babkin (Shiklomanov, 1988), Vinnikov et al. (1989) for the USSR, Griffiths (1989) for New Zealand.

(iii) Use of atmospheric GCMs. In this approach, GCMs with prescribed increases in the concentrations of trace gases in the atmosphere (usually $2 \times CO_2$) are used to obtain direct estimates of changes in the climatic and hydrologic characteristics for large regions. For example, possible changes in runoff, soil moisture, and evaporation have been estimated for the US and Canada using GCMs (USEPA, 1984; Sanderson and Wong, 1987; and Singh, 1987).

(iv) Use of deterministic hydrologic models. In this approach, rainfall-runoff models for river basins are employed with climatological data sets, including GCM outputs, to determine changes in hydrologic conditions. This approach was used by many authors for the basins located in various hydroclimatic environments (Nemec and Schaake, 1982; Gleick, 1986, 1987; Mather and Feddema, 1986; Cohen, 1986; Flashka et al, 1987; Bultot et al, 1988; Kuchment et al, 1989; Shiklomanov, 1989a; and Croley, in press).

The first and second methods have been widely applied to estimate changes in water resources over large areas because a relatively small amount of initial data is required, usually annual runoff, precipitation, and air temperature. Caution should be exercised in extrapolating regression relationships over past years to future periods. One cannot assume that a past interannual pattern of meteorological factors will be repeated in the future. It is also true that for the same annual precipitation and temperature, annual runoff can widely vary, depending on the distribution of the meteorological variables within months and seasons.

The results obtained in hydrologic simulations based on different GCMs are inconsistent for certain important hydrologic conditions and regions. This can be attributed to the low resolution of the current generation of GCMs, and to their simplified description of hydrologic processes. Nevertheless, the approach is very promising and studies of this type should be continued.

Deterministic hydrologic models have some desirable properties. They allow explicit study of causal relations in the climate-water resources system for estimating the sensitivity of river basins to changing climatic conditions. In addition, when regional climatic forecasts are available, possible runoff changes in different hydroclimatic environments may be simulated for water planning and management.

Perhaps the most comprehensive assessment of the effect of climate change on water resources was a recent report that focused on the US by the American Association for the Advancement of Science Panel on Climatic Variability, Climate Change and the Planning and Management of US Water Resources (Waggoner, 1990). This document includes 18 papers by more than two dozen authors and encompasses methods and issues ranging from climate forecasting, the translation of climatic change information into hydrologic consequences, vulnerability of water systems, impacts and responses, to future water use and decision making under climate uncertainty. Its contents cut across most of the above stated methods.

3.2 Changes in annual and seasonal conditions

Since the late 1970s, changes in annual and seasonal runoff have been extensively investigated and described in many publications. This is because annual and seasonal river runoff are very important for providing adequate water supplies to meet the demands of most regions. Quantitative estimates have been obtained for many regions of the US, for the USSR and New Zealand, for some regions of Canada, river basins in England, Wales, Belgium and other specific regions (see Sections 4 and 5).

Investigations highlight the great sensitivity of river watersheds to even small changes in climatic conditions. Watersheds located in arid and semi-arid regions are especially sensitive because annual runoff is highly variable. For watersheds where snowmelt is an important source of runoff, annual runoff and its seasonal distribution is vulnerable both to changing air temperature and to changing precipitation. In middle latitudes of the Northern Hemisphere with a 1°C or 2°C warming, the winter runoff is expected to increase drastically and spring high water to be lower owing to earlier snowmelt (see Section 4).

Many estimates of runoff change due to global climate warming, including those given in Sections 4 and 5 do not consider the possible direct influence of increased CO_2 on évapotranspiration (with increased CO_2 concentration évapotranspiration usually decreases). This phenomenon is considered in Idso and Brazel (1984) for five US river basins as well as in Aston (1987) for river basins in Australia. In these studies, the results were opposite to those obtained by other researchers, namely, a doubling of CO_2 concentration brought about a 40% to 60% increase in annual runoff for US rivers in question, and that for Australian rivers by 60% to 80%. Wigley and Jones (1985) and Palutikof (1987) pointed out to the great role of taking into account the direct CO_2 effects on évapotranspiration and total evaporation, which is ignored by many researchers. These findings are controversial and need further investigation as total evaporation from land is thought to be determined primarily by energy factors.

An important hydrologie consequence of global warming is potential changes in runoff extremes, both high and low. Changing high flow extremes raise the problems of runoff control, development of flood control works, and design of hydrologie structures. Changing low flow extremes may require a reassessment of water storage requirements and of water allocation schedules, in particular in the limiting periods of the year.

Estimation of extreme river runoff conditions in conjunction with anthropogenic climate change is a very important problem in hydrologie engineering calculations, since the design of hydrologie structures is based on the concept of stationarity of hydrometeorological conditions. It is assumed that the observational data over past decades reflect hydrometeorological conditions during the design life of the project. Changes in extremes will modify statistical calculations to estimate sizes of constructions and their conveying capacity and to maintain stability during disastrous natural events.

Since extreme meteorological events cannot be explicitly forecast by GCM simulations, nor by using palaeoclimatic analogs, in practice the quantitative regional estimates of possible changes in runoff extremes are as yet unavailable. Nevertheless, there are plenty of qualitative estimates, based usually on an assumption about the proportionality of changes in runoff extremes to those in annual, seasonal or monthly runoff (see Section 5). More reliable conclusions about the runoff extremes in various regions of the world could be drawn if detailed quantitative estimates of changes in meteorological characteristics over shorter periods of time were available.

3.3 Water demand

Under global climate wanning, changes in demand for water resources should be expected in many regions of the world. Considerable transformation in the structure and the character of water consumption by different branches of industry and agriculture, and deepening conflicts and contradictions between individual water users, are possible. With the same level of economic activities in a region, the water requirements and even actual consumption are determined by the extent of total moisture delivery to the region.

The relation between water consumption and available water is illustrated in Figure 4.1 which shows per capita water consumption in the year 2000 and a dryness index R_D/LP (where R_D is the radiation balance of a wet surface, P is the precipitation, and L is the latent heat of condensation). The greater the dryness index, the higher the specific water consumption. The relations depicted in Figure 4.1 are derived for large natural-economic regions of the world by estimating future water consumption in various countries up to the end of the century under stable climatic conditions (Shiklomanov and Markova, 1986; Shiklomanov, 1988, 1989b). Using these graphs and knowing possible changes in climatic parameters with global warming, it is easy to estimate approximate changes in total water demands in different world regions. GCM simulations with 2 x CO_2 in the atmosphere allow direct estimations to be made for regional changes in the dryness index; such estimates have been made for the US (Stakhiv and Lins, 1989).

The actual values of water consumption in various regions will depend on climatic factors, the extent of development of water-consuming sectors of national economies (primarily on irrigated lands), and on the limitations in water resources. With significant future climate change there will probably be problems in planning and locating future irrigated areas, industries with high water consumption, reservoirs, and problems of water supply for current water users. These changes may exacerbate problems in arid and semi-arid regions, where at present there are difficulties with water supply and where conflicts take place between various water consumers and managers.

Much is known about how water resource systems operate under climatic stress, and extrapolations of this knowledge will help us anticipate impacts on management and demand for water, and on protection afforded from floods and droughts in a changing climate (Fiering and Rogers, 1989; Stakhiv and Hanchey, 1989).

A useful literature has developed on water system sensitivity and adaptability to climate fluctuations. Fiering (1982) and Hashimoto et al. (1982) laid out criteria for assessing system sensitivity, including reliability, resiliency and vulnerability. Matalas and Fiering (1977) described an optimising approach to designing water systems with climate fluctuations in mind, and Novaky et al. (1985) offered a conceptual model of water system impact and response and created a matrix for assessing system sensitivity to climate change. Klemes (1985) synthesised the water system sensitivity literature, suggesting that the key concept is reliability - the long-term ability of a system to meet demand despite fluctuations in climate.

Peterson and Keller (1990) have evaluated the influence of temperature and precipitation changes on the irrigation requirements and the possibilities of developing future irrigated areas in arid regions of the western US. They came to the conclusion that a warming could exert an enormous effect on irrigation development in the region. By increasing temperature by 3°C and decreasing precipitation by 10%, cultivated areas in the western US could decrease by 30% and efforts would be required to improve efficiency of water use and to develop new freshwater supplies (Gleick, 1989).

Studies on the effects of effects of anthropogenic climatic changes on irrigation water consumption have been conducted by the Food and Agriculture Organization (FAO) along with the UK's Institute of Hydrology for the 3240 km^2 Malibamatsama Basin in Lesotho (South Africa) (Nemec, 1989; Institute of Hydrology, 1988). Future climate change simulations for this region have been accomplished using a GCM with doubling CO_2. The GCM data indicated a 6°C increase in mean monthly temperature, a 4-23% decrease in monthly precipitation from December to May, and a 10-15% increase in monthly precipitation from June to November. Estimates of changing evaporation and river runoff were based on a water-balance model with a 10-day time increment. The research showed that with a doubling of CO_2, changes in meteorological conditions in the Basin led to a 65% increase in water demands for irrigation; this could bring about the shrinkage of irrigated areas from 37,500 ha at present to 20,000 ha.

Regional estimates of potential changes in water demand with global warming are presented below in Sections 4 and 5. The cases indicate that estimating future water requirements and arrangements should be made by taking into account the peculiarities of each region. Then the reliability of such estimates will be primarily dependent on the accuracy and comprehensiveness of predicting the changes in climatic characteristics and hydrology with global warming.

3.4 Water balance and lake levels

The hydrologic cycle of large lakes, in particular of enclosed lakes, integrates climatic variability over vast areas, including the lake basins and adjacent regions. Future global warming due to increasing CO_2 in the atmosphere would lead to changes in the lake water balance components (precipitation, evaporation, inflow and outflow), their levels and heat budget. These changes are different for the drainage basins and the enclosed lakes. Given below in Section 5, as an example, are some approximate estimates of possible changes in the water balance and hydrologic cycle of the North American Great Lakes and of the Caspian Sea, the largest enclosed lake in the world.

3.5 Other hydrologic characteristics

The hydrologic consequences of anthropogenic global warming are not limited to changes in river runoff and water balance values. Other consequences include changes in total water amount and levels, erosion in river basins and riverbeds, and modifications of turbidity and sediment load. Water quality in many water bodies could deteriorate. Decreasing river runoff and lake level declines could decrease the possibility of dissolving pollutants and flushing processes.

Sea-level rise and runoff changes could lead to increased flooding of low-lying coastal regions, increased shoreline erosion, changes in deltaic processes, salinity changes in estuaries and rivers, and contamination of aquifers through saltwater intrusion (see Chapter 6). Answers to questions associated with the hydrologic consequences of global warming can be found only through innovative and geographically diverse studies that take into account forecasts of both changing regional climatic conditions and water use.

4 Hydrologic and water resource changes in large regions and countries

4.1 North America

4.1.1 United States

In the US, in the 1970s and 1980s, on the basis of hypothetical climate scenarios and river runoff dependence on meteorological factors, future annual runoff changes were determined for the northeast (Schwarz, 1977) and western regions of the US (Stockton and Boggess, 1979), and the Colorado River basin (Revelle and Waggoner, 1983). A similar study, using an annual water-balance model was conducted by Flaschka (1984) for the Great Basin rivers. A deterministic hydrological model was used by Nemec and Schaake (1982) to study two idealised basins in arid and humid regions. The research demonstrated a strong sensitivity of river basins (in particular, in arid and semi-arid regions) even to small changes in climatic conditions.

For example, increasing the annual air temperature by 1°C or 2°C and decreasing precipitation by 10% decreases the annual river runoff in regions with relatively low precipitation by 40% to 70%. Subsequently, these results were supported by calculations made by Stockton et al. (1989) who used more advanced models simulating runoff formation in river basins. These authors predict changes in water resources for diverse water supply regions of the country using two hypothetical scenarios: warm and dry (temperature change of +2°C, precipitation change of -10%) and cold and wet (-2°C and + 10%). The results are given in Figure 4.2. They show that for many regions of the US, water resources are expected to decrease by 1.5 to 2 times under the warm and dry scenario.

Schaake (1990) investigated how the sensitivity of runoff to given scenarios of climatic change would vary spatially with different climate conditions over the southeastern US. A simple, monthly, non-linear water-balance model was developed using a basin in China and another in Oklahoma, US. Constant values were assumed for the five parameters of the model over the entire region. The model and parameter values were tested using more than 2000 station-years of data from 52 basins in the region. None of the test data were used to develop or calibrate the model. Simulated mean annual runoff for 49 of the 52 basins fell within error bounds of 100%. The climate scenarios were for changes of 10% in potential évapotranspiration and 10% in precipitation. The study concluded that the hydrologic processes amplify the effects of such changes on runoff.

A measure of this amplification is elasticity; the ratio of the relative change in a runoff variable to the relative change in a climate variable. To illustrate this point, maps showing the percentage change in mean annual runoff to a 10% change in precipitation and potential évapotranspiration are presented in Figure 4.3. Elasticities as high as 5 were found in the southeastern US. The study concluded that: dry climates are more sensitive to change than humid climates; elasticity to precipitation change is greater than to évapotranspiration change; low flows will be more affected than high flows; reservoir yields will be affected, but the elasticity of reservoir yield is less than the elasticity of the mean flow; and, because water quality problems tend to be coupled with low flow conditions, water quality effects may prove to be among the most significant, especially in arid areas.In 1984, the US Environmental Protection Agency (USEPA, 1984) used output from GCMs directly for analysing changing precipitation, soil moisture, and runoff under doubled atmospheric CO_2 conditions. The results indicated a significant increase (20%-60%) in river runoff in the northwestern US, and a decrease (26%) in the central region. Manabe and Wetherald (1986) obtained similar results using a GCM to estimate soil moisture changes in the mid-continent region of the US. In contrast, however, simulations with other GCMs produced opposite results for the same region (Schlesinger and Mitchell, 1987; Mitchell and Warrilow, 1987).

Developing reliable scenarios of potential climatic changes for regional impact assessment is a major problem. The use of output from the current generation of GCMs to estimate regional hydrologic impacts of climatic change is highly suspect because of the coarse resolution of the models and the gross simplifications used in the parameterisations of the terrestrial hydrology (Gleick, 1989; WMO, 1987). Since soil moisture and river runoff processes are not well specified in GCMs, a more fruitful approach for estimating hydrologic impacts is the coupling of GCMs and deterministic hydrologic models. In this case, the GCM output (typically temperature and precipitation) becomes the input data for more comprehensive regional hydrologic models.

Gleick (1986,1987) was one of the first to apply this approach for estimating global warming effects on the seasonal runoff of the Sacramento River (California). As the basis, Gleick used climate change scenarios (monthly air temperature and precipitation) developed from three GCMs with 2 x CO_2 in the atmosphere. Simulation of hydrologic impacts was carried out with a water-balance basin model with a monthly time increment. These simulations showed increased winter runoff from 16% to 81% and decreased summer runoff from 30% to 68%. These results can be explained by a drastic change in snowfall and snowmelt conditions associated with a rising air temperature. A similar approach has been used by other authors. With doubling atmospheric CO_2, Great Lakes basin runoff decreased by 12-13% (Sanderson and Wong, 1987), Great Lakes net basin supplies decreased by 2-113% (Croley, in press), and the flow of large rivers in the Province of Quebec, Canada, increased by 7-20% (Singh, 1987).

Of the four GCMs most widely used in the United States, none is capable of simulating observed annual or seasonal precipitation with accuracy on a regional basis. The models also differ in the values of forecasted warming for US regions, particularly for the summer months. Nevertheless, in analysing the conclusions drawn by different researchers, the following regional tendencies are presented as potential hydrologic effects of global warming:

Pacific Northwest: some increase in annual runoff and floods;

California: a considerable increase in winter and decrease in summer runoff with insignificant rise in annual runoff;

Colorado and Rio Grande River Basins, the Great Basin: decreasing runoff;

Great Lakes Basin: decreasing runoff and increasing evaporation;

Great Plains, northern and southeastern states: uncertain changes in water resources.

The above inferences were also obtained by Soviet climatologists (Budyko and Izrael, 1987) using palaeoclimatic analogs. These results show a considerable decrease in moisture south of 55°N and a noticeable increase in precipitation in northern regions of North America.

4.1.2 Canada

In recent years a number of studies have investigated the potential hydrologic and water resources effects of a climatic warming for Canada over the coming decades. Most of these studies have based their impacts on climatic simulations produced by the GISS, GFDL, and UKMO GCMs (Marta, 1989). A summary of the results of these studies is presented in Table 4.1. Most of the investigations focused on one of three distinct areas in the south-central part of the nation: the Great Lakes, James Bay, and the Saskatchewan River sub-basin. A nationwide study of broad Canadian regions has also been completed. In the Great Lakes region, GCM-simulated temperatures range from +3.1°C - +4.8°C. The simulations for precipitation are much more variable, ranging from -3% to +8%. Generally speaking, the mix of this range of conditions could portend a decline in the hydrologic and water resource base or the region. Under these temperature and precipitation conditions, runoff to the lakes is estimated to decrease between 8% and 11%, lake levels could drop between 21 cm and 59 cm, and water supplies could fall from 18% to 21%.

Farther north, in the James Bay region, the water resource picture appears more favourable. Model-simulated temperature increases for this area fall in the range of 3.5°C to 4.7°C, with precipitation estimated more narrowly to increase from between 15% to 17.5%. This range of climatic conditions favours increases in runoff ranging from 8% to 16% with concomitant increases in water supply of 9% to 22%. Moving west onto the Canadian Prairie, impacts on the hydrology of the Saskatchewan River sub-basin appear to be strongly model-dependent. Both the GISS and GFDL simulations indicate impacts of fairly large magnitude, especially in terms of changes in the timing, location, duration and extent of runoff as well as soil moisture. However, the GISS simulations indicate increasing streamflows and water supplies for the region while the GFDL simulations indicate decreases. In terms of net basin supply, incorporating projected consumptive use, the GISS simulation produced a range of increases varying from 29% to 40%. On the other hand, the GFDL simulation produced declines in net basin supply ranging from 27% to 70% (Cohen et al, 1989).

Water in the Saskatchewan River sub-basin is utilised for agriculture, hydroelectric power production, cooling at thermal power plants, recreation and industrial processing. Agriculture is a major con

Table 4.1 Estimated hydrologic impacts of varying climatic change scenarios for Canada (Marta, 1989).

Author	Region	Drainage area ($km^2 \times 10^4$)	Est. climatic changes (T°C)	(P%)	(GCM)	Est. hydrological changes (Runoff - %)	Other
Southam and Dumont (1985)	Great Lakes	76.0 (32% is lake surface)	+4.5	-3 to +8	GISS/84		Levels (cm) -21 to -59 Flows (%) +2 to -13
Cohen (1986; 1987)	Great Lakes	76.0	+3.1 to 3.7 +4.3 to 4.8	+0.8 +6.5	GFDL/80 GISS/84	-8.2 -10.9	Supply (%) -18.4 Supply (%) -20.8
Singh (1988)	James Bay	17.5 (18% is lake and reservoir surface)	+3.5 +4.7	+17.5 +15	GFDL/80 GISS/84	+10.9 +15.7	Supply (%) +13.9 Supply (%) +16.1
Cohen et al. (1989)	Saskatchewan River	36.4	+2.5 +4.4	+18 +19	GFDL/80 GISS/84	-58 +37	Supply (%) -65 Supply (%) +38
Haas and Marta (1988)	S. Saskatchewan River (to Lake Diefenbaker)	15.7	+2.5 +4.4	+18 +19	GFDL/80 GISS/84	-20 +28	
Ripley (1987)	Arctic	331.0	+2 to 3.5	+54	UKMO/83	+95	
	Atlantic	151.0	+2 to 3.5	+11	UKMO/83	+10	
	Gulf	3.0	+2.5 to 3	+23	UKMO/83	+235	
	Hudson	356.0	+2 to 4.5	+17	UKMO/83	+20	
	Pacific	94.0	+2 to 3	+23	UKMO/83	+20	
	Canada	935.0	+2 to 3	+23	UKMO/83	+32	

sumer of water, in which return flows are considerably less than withdrawals from surface supplies.

Certain others, such as hydroelectric production and recreation, are in-stream users that do not 'consume' water, that is, their use of water does not result in a 'loss' from surface supplies. If the status quo is to be maintained, results from the study of this watershed indicate that for the GISS scenarios, an increase in agricultural demand for water would not significantly affect the availability of water for other users, since the net basin supply is estimated to be relatively high. For the GFDL scenarios, however, the low estimated net basin supply could seriously compromise all users. Such a situation would necessitate a major policy response, such as the establishment of a regional water allocation scheme for the sub-basin, involving government agencies, user groups and the public. Should there be increases in population, reservoir storage, industrial or agricultural development, such a scheme might not be required to cope with the conditions estimated under the GISS scenario, but any increases in water demand would only make the situation more critical given the conditions estimated by the GFDL GCM.

Looking very broadly at the impact of climatic warming on the water resources of Canada in the aggregate, the general outlook may be somewhat favourable. With temperature rises generally in the 2°C to 4°C range and precipitation generally increasing across the country from 11% to 54%, runoff could be expected to increase in all major regions by 10% to 235% (Ripley, 1987).

4.2 Brazil

The Brazilian government and scientific community only recently became concerned over the prospect of a greenhouse-gas-induced climate warming and its associated consequences on the water resources of South America. Attention has been given to the possible effects of deforestation of Amazonia on regional hydrology and atmospheric carbon dioxide. Very recently, the Brazilian government began to exert some control over the deforestation process.

Although this is a positive step toward decreasing the atmospheric build-up of CO_2, it is also necessary to point out that fossil fuel combustion is about 3 to 5 times more important than deforestation as a net contributor to global warming (Moore and Bohn, 1987).

As yet, there are no indications of a large scale anthropogenically-induced change on precipitation in the Brazilian Amazon (Sternberg, 1987). This stability is probably due to the relatively small percentage of the total rainforest area that has been deforested (7%). Nobre et al. (1989) simulated the climatic effects of total deforestation using a model developed by Sellers et al. (1986). This model incorporates the interactions between vegetation and the general circulation of the atmosphere. The model results indicated that the ground temperature in the Amazon region would increase between 1°-3°C, évapotranspiration would decrease 20-40%, and precipitation would decrease 20-30%.

Such a temperature increase, whether from deforestation, fossil fuel emissions, or both, will probably intensify and concentrate tropical convective rainfall and, as a result, promote increased flooding and erosion, and decreased soil moisture. This suggests that the firm yield from existing reservoirs could decrease and that the probability of dam overtopping owing to extreme floods may increase.

4.3 Western Europe and Scandinavia

Effects of climate change on water resources have been estimated for Western Europe (primarily for the northern regions) by using various scenarios and approaches. Western Europe was similar to North America in that river basins were very sensitive to small variations in climatic conditions, especially precipitation (Palutikof, 1987; Novaky, 1985; Beran, 1986; and Verhoog, 1987).

Studies by Schnell (1984) and Beran (1986) are significant for forecasting future water resources. Schnell estimated the consequences of CO_2 doubling for river runoff in the countries of the European Economic Community (EEC) using temperature and precipitation derived from the UK Meteorological Office (UKMO) GCM. The runoff values obtained by Schnell using waterbalance methods show possible significant increases in the north of Europe (the UK, The Netherlands, and Belgium) and decreases of similar significance in central and southern Europe.

A very comprehensive assessment of the potential water resources response to climate change for over 12 countries within the EEC has been conducted by da Cunha (1989). Detailed information about water resources and water availability for each country, coupled with the scenarios of climatic change simulated by GCMs for the EEC region, indicate that man-induced climatic change is likely to influence water resources differentially in different parts of the region. If the simulated GCM results turn out to be correct, then average precipitation values in the southern part of Spain, Portugal, and Greece can be expected to decrease, while increases can be expected throughout the rest of the EEC region. The model results also indicate a tendency for reduced precipitation variability in some of the northern parts of the region during the entire year, and for increased variability in Greece and southern Italy during the summer. Such changes in variability could mean that higher flood peaks are possible in parts of the UK, Germany, Denmark, and The Netherlands, while more severe droughts are possible in Greece and southern Italy. Thus, it is implied that a large part of the EEC region would benefit from what appear to be potentially favourable changes in climate, while a smaller part in the south would suffer unfavourable impacts.

The impacts of climate change on water resources have been classified by da Cunha into three groups: economic, social, and environmental. Economic impacts are often the most relevant. The changes in the global amount of water resources available and in the space and time distribution of these resources may lead to water shortages and cause water price increases. Changes in water quality are also likely as a result of climatic change. Temperature increases would also induce an increase in the demand for water, thus contributing to a worsening situation resulting from a decrease in water availability. The negative impacts are expected to be particularly serious on cultivated land areas. Examples of these negative impacts include crop losses or shortages, replacement of present agricultural species by other species more resistant to water shortage but less useful, increased activity of insects and predators, and the abandonment of agricultural land. Such impacts may also affect livestock by reducing herd sizes and increasing disease and problems of vector control. Other economic impacts relate to losses in timber production, fisheries, and recreational businesses. Important indirect impacts include sedimentation processes, ie erosion, transport and deposition of sediments, as well as agriculture, hydraulic work operations, and estuarine and coastal areas.

The social impacts of climatic change on water resources are also important, since it is essential that decision makers provide guidelines on the strategies to be adopted by water users to enable them to cope with climate change. In fact, the various types of water users (farmers, industrialists or domestic consumers) are not, by themselves, able to assume individually the most positive attitudes in order to reduce the negative impacts of climate change on water resources. The possible climatic impacts on water resources will force society to modify its relation with the environment by introducing a number of adjustments in its behaviour. Emigration from the southern parts of the EEC unfavourably affected by climatic change would be one immediate form of social adjustment. Other possible social consequences include unemployment, deterioration of conditions of hygiene and public health in the affected regions, as well as public safety from forest fires.

Environmental impacts may also be relevant, ranging from serious ecological disruption to less serious and more localised effects. Examples of serious disruptions are desertification, which is a possibility in the southern region, and sea-level rise with possible effects on flooding in coastal areas, destruction of engineering works and structures, and modification of coastal and estuarine environments. Examples of more localised effects include damage to wildlife habitat owing to water shortages, degradation of visual landscape quality, increased salinity of soil and groundwater, soil, erosion, forest fires, plant diseases, and insect and predator plagues.

Bultot et al. (1988, 1989) made the most detailed estimations of river runoff changes for Belgium with a doubling of the CO_2 concentration. The authors used the monthly values of climatic conditions obtained from GCMs predicting a 2.9 °C annual air temperature increase and a 55 cm precipitation rise. To assess the hydrologic consequences for the three river basins with different conditions of runoff formation, a conceptual hydrologic model with diurnal time increments was used. The calculations showed increasing annual runoff (3-10%) and changes in the seasonal runoff pattern. The winter and spring runoff increased by 10-14%, while the summer runoff remained unchanged of decreased from 1% to 15%).

To date there have been no studies in the UK using hydrologic models to estimate the effect of climatic change on annual runoff. Beran and Arnell suggest, however, that it may be possible to make some generalised statements using a simple water-balance approach where changes in mean annual runoff are determined from changes in mean annual rainfall and mean annual evaporation (Beran and Arnell, 1989). Evaporation, however, is dependent on several climatic attributes which vary together in a complex manner. Thus, a simple empirical formula developed by Turc (1954), which operates on an annual time scale, was utilised by the British.

Mean annual runoff is estimated by subtracting evaporation from precipitation, for three combinations of mean annual temperature and precipitation found in different parts of the UK (Table 4.2). Parts a and b in the table represent catchments with similar rainfall, but different mean annual temperature and, for a given change in precipitation, there is relatively little difference in effect on runoff between the 'cool Scottish' and 'mild English' sites. The data in the table imply that if temperatures were to increase by 3°C, an increase in annual precipitation of 10% or more would lead to an increase in annual runoff. For comparative purposes, the current scenario implies an increase in annual rainfall of 140 mm (14% on an initial value of 1000 mm) if summers are wetter (as in Scotland and the north of England), but only 80 mm (8%) if summers are drier. The estimated conditions depicted in part c of Table 4.2 are more representative of the drier climates of southern and eastern England. Here annual precipitation would have to increase by over 10% before annual runoff would increase. The scenario increase in precipitation of 80 mm (10% of 800 mm) is just at this threshold value.

These estimates imply that mean annual runoff would probably increase over most of the UK in a warmer world, with the greatest increase in the north. The actual increase in runoff is very sensitive to the estimated increase in precipitation (more so than to changes in évapotranspiration). It is important to note that alterations in annual runoff due to climatic change may approach changes in runoff due to major land use change. Gross et al. (1989) used a conceptual rainfall-runoff model to show, for example, that clearing the forest in a small basin in upland Wales could produce an increase in annual runoff of nearly 30%.

Although the evidence is limited, it is possible that the model-simulated increased seasonality in rainfall will be reflected in a stronger seasonal variation in streamflow throughout the UK. Note, even under the 'wet summer' scenario, increases in summer precipitation are less than increases in winter precipitation. However, the effect will depend strongly on catchment geology, and it is possible that summer flows in catchments with high groundwater levels will be maintained or even increased by higher winter and spring rainfalls.

Saelthun et al. (1990) have produced an initial assessment of the consequences of climatic change for water resources in Norway. Using a climate

Table 4.2 Extimated percentage changes in mean annual runoff at three sites in Great Britain in response to changes in temperature and precipitation*

a) Initial mean annual precipitation: 1000 mm
Initial mean annual temperature: 8 °C
Initial estimated mean annual runoff: 530 mm

Temp. change (°C)	Change in annual precipitation					
	-10%	0%	10%	20%	30%	40%
1	-21.3	-4.8	12.3	29.7	47.4	65.3
2	-25.8	-9.6	7.1	24.2	41.7	59.4
3	-30.4	-14.7	1.7	18.5	35.8	53.3
4	-35.1	-19.8	-3.8	12.7	29.6	46.8
5	-39.8	-25.0	-9.5	6.6	23.2	40.1

b) Initial mean annual precipitation: 1000 mm
Initial mean annual temperature: 10 °C
Initial estimated mean annual runoff: 479 mm

Temp. change (°C)	Change in annual precipitation					
	-10%	0%	10%	20%	30%	40%
1	-23.0	-5.6	12.6	31.2	50.2	69.6
2	-28.1	-11.2	6.4	24.7	43.4	62.5
3	-33.3	-17.0	0.2	18.0	36.3	55.1
4	-38.5	-22.8	-6.2	11.1	29.0	47.4
5	-43.7	-28.7	-12.7	4.1	21.5	39.5

c) Initial mean annual precipitation: 800 mm
Initial mean annual temperature: 10 °C
Initial estimated mean annual runoff: 311 mm

Temp. change (°C)	Change in annual precipitation					
	-10%	0%	10%	20%	30%	40%
1	-26.1	-7.0	13.3	34.4	56.3	78.8
2	-32.2	-14.0	5.5	26.0	47.3	69.3
3	-38.3	-20.9	-2.3	17.4	38.1	59.5
4	-44.2	-27.8	-10.1	8.9	28.8	49.5
5	-49.9	-34.6	-17.8	0.3	19.4	39.4

* Based on the Turc formula (Beran and Arnell, 1989)

change scenario of a temperature increase of 1.5°-3.5°C (with the higher temperatures prevailing during winter and in upland areas) and a precipitation increase of 7-8%, the following hydrologic consequences were posited. Annual runoff in mountainous areas and regions of high annual precipitation will likely experience a moderate increase. In lowland and forest inland basins, annual runoff may decrease in response to increased evapotranspiration. The intensity of the spring flood could decrease in most basins, while winter runoff may increase substantially and summer runoff may decrease. Floods are likely to occur more frequently in autumn and winter. The period of snow cover will probably be shortened by one to three months. The scenarios indicate that glaciers will decrease, particularly those in inland areas. The net melt could be lower on glaciers near the west coast, while the glaciers on the coast of northern Norway will most likely remain unchanged. The duration of ice cover may decrease and it is possible that many of the larger lakes in southern Norway may not develop ice covers in most winters.

Erosion and sediment transport is likely to increase significantly during winter unless the agricultural practice of leaving soils bare during winter is changed. Soil loss could become a very serious problem.

Finally, a positive potential outcome of global warming is that the hydroelectric power production of Norway could increase by 2-3% under the assumed climate change scenario. This is due in part to an increase in reservoir inflows, and in part to reductions in reservoirs spillovers. The seasonal distribution of runoff may more closely match that of energy consumption, thereby increasing firm power yield.

4.4 Union of Soviet Socialist Republics

Quantitative estimates of potential climate change effects on rivers in the USSR have generally been based on palaeoclimatic analogs of the past. The proxy-based estimates were first obtained at the State Hydrological Institute in 1978 under the guidance of M.I. Budyko (Budyko et al, 1978). Subsequently, as the climatic predictions were refined, estimates were made for changes in annual runoff of rivers in the USSR for the years 1990, 2000, and 2020. This procedure was repeated for other regions of the Northern Hemisphere. The results of these simulations are presented in the report Anthropogenic Climatic Changes (Budyko and Izrael, 1987) and by Shiklomanov (1988). The simulations were based on meteorological-runoff relationships, or on water-balance equations, developed over long time periods. The results of the simulations were presented in the form of runoff change isoclines and also as averages for the main basins for the years 2000-2005. These average changes were in the range of +/-12% (Shiklomanov, 1988). The values are only rough approximations due to the uncertainty associated with the initial air temperature and precipitation data for certain river basins.

The mean annual runoff changes over the USSR for a 1°C global warming (expected to occur between 2000-2010) have been estimated. This work was based on refined predictions of changes in summer and winter temperature and annual precipitation for the USSR (Budyko, 1988) developed at the State Hydrological Institute under the guidance of K.Ya. Vinnikov. The comprehensive data presented in Figure 4.4 suggest the following conclusions. The most detrimental effect on resources can be expected in the south of the forest zones of the European USSR and west Siberia. Annual runoff could fall to 10-20% of normal (20-25 mm). This effect is due to an increase in air temperature accompanied by no change or even a slight decrease in precipitation.

In the southernmost steppe regions, owing to a marked increase in precipitation, the annual runoff is most likely to increase by 10-20%. In the northern regions of the European USSR and Siberia, runoff may increase by 280-320 km^3/yr or 7%, which may compensate for future water consumption. Estimates for the more distant future are less certain; nevertheless, there is evidence to suggest that with a 2°C global warming the annual runoff will increase by 10-20% on all the large rivers of the USSR. This increase will provide an additional 700-800 km^3/yr of water for the whole country. Although these values are very approximate, they cannot be ignored in the long-range planning and management of water resources and protection of the natural environment.

Additional effects may be caused by global warming on seasonal and inter-annual runoff patterns. For a number of river basins in the European USSR, the influence of climatic change on the hydrologic cycle has been simulated using a specially developed water-balance model with a 10-day time increment. The model was calibrated and checked by observational data over long-term periods. The simulations were carried out for four river basins: one small and two middle-sized basins located in the forest-steppe and steppe zones, and the Volga River Basin, the largest in Europe. The climatic scenarios used included changes in summer and winter air temperature and annual precipitation in the years 2000-2005, taken from the palaeoclimatic maps for each river basin (increasing summer temperatures by 0.5°-1.5°C and winter temperatures by 1.5°-2.5°C and changing annual precipitation by -3% to +12%).

The model calculations show that even small changes in climatic conditions can lead to considerable alterations in the runoff regime. The primary manifestation of such an alteration is a dramatic increase in winter runoff, owing to more intense snowmelt during the winter season and a corresponding decrease in spring runoff. The seasonal runoff changes averaged over a long-term period for the indicated river basins are presented in Table 4.3. This table indicates that winter runoff for the relatively dry zone (steppe) increases many-fold and considerably rises even for the vast Volga River basin. Observational data show, on the rivers of the European USSR since the second half of the 1980s, that winter runoff has tended to increase noticeably, possibly as a consequence of global climate warming.

4.5 Northern China

The analysis of hydrometeorological observational data for northern China (Chunzhen, 1989) shows that the warmest period over the last 250 years began in 1981. The mean air temperature over the period 1981-87 was 0.5°C above the normal, while for the same period precipitation was somewhat lower than normal (for Beijing by 4%). Studies of natural climate variations for the past 100 years suggest that the warming in northern China will continue up to the next century. Estimates of the potential influence of increasing atmospheric CO_2 on northern China arc not available. At the same time, it is possible that small climate changes can have considerable hydrologic consequences. Simulations using the Hinangchzang hydrological model show that in semi-arid regions, with a 10% increase in precipitation and a 4% decrease in evaporation,

Table 4.3 Potential changes in seasonal runoff in response to a temperature warming of 1°C for selected rivers in the USSR

River	Basin area (km^2)	Zone	Runoff (mm)			
			Annual	Winter	Spring	Summer-Fall
Volga-Volgograd	1,360,000	Forest/Forest-steppe	187	22	107	58
			165	35	94	36
Sonsa-Yeletz	16,300	Forest-steppe	144	30	102	12
			129	53	63	13
Chir-Oblivskoye	8,470	Steppe	47	3	43	1
			70	22	45	3
Devitza-Nizhnedeyitsk	76	Forest-steppe	127	26	60	41
			112	36	41	35

Note: For each river the top set of runoff values refers to the long-term mean under natural conditions. The bottom set of values is the estimated runoff for an assumed warming of 1°C.

the runoff will increase by 27%. Increasing precipitation by 10% and evaporation by 4% results in an 18% increase in runoff. If these climatic changes take place in semi-arid regions, runoff increases by 30%-50% (Chunzhen, 1989).

4.6 Japan

A number of agencies and institutes within Japan have begun to focus on how climate warming would affect the water resources and related environment systems of that country. To date, the studies have emphasised the empirical description and characterisation of effects and problem areas with the aim of identifying how to derive quantitative estimates of likely impacts. To estimate the potential hydrologic consequences of global warming, long-term series of meteorological observations in different regions of the country have been analysed. In particular, precipitation and runoff characteristics have been compared over the coldest and the warmest 10-year periods with the mean temperature difference of 0.074°C. Precipitation over the warmest period turned out to increase by 10%, the incidence of heavy rains (more than 300 mm for two days) becoming much more frequent. At the same time, precipitation sums for 60- to 90-day periods with minimum rains during the warm decade have been noticeably smaller than in the cold decade (Yamada, 1989). This empirical data analysis makes it possible to assume that with global warming in most regions of Japan, maximum precipitation and river runoff volume are expected to somewhat grow, especially over the periods of rain storms. At the same time, in dry seasons the runoff can decrease thus exacerbating the problems of water supply. Because of the lack of data, it is impossible to estimate quantitatively the corresponding values. The use of GCM output is particularly troublesome in Japan since a large percentage of precipitation is generated by typhoons and convective storms, which are not resolved by the GCMs, as well as by frontal storms, which are. Accurate accounting of water resource impacts would, therefore, need to consider, for example, how typhoon frequency, magnitude, and intensity would be affected.

Given the critical concern with which the government of Japan views the potential threat imposed by a greenhouse-gas-induced climatic warming, a preliminary study was undertaken with the support of the Japanese Environment Agency (Matsuo et al., 1989). It assessed effects on a number of environmental systems, including water resources, associated with a potential severe change in climatic conditions. The specific water resources issues addressed included flood control, water use, and water quality.

Looking first at flood control, the report notes that current reservoir storage capacity is limited, so much so that the multipurpose use of reservoirs for flood control and water use could become increasingly difficult. An increase in rainfall intensity brought by typhoons or fronts would give rise to serious flooding. Prolonged periods of drought, punctuated by short bursts of intense precipitation, could lead to increased frequency of mudslides. Since many Japanese cities are situated in coastal areas and lowlands, any flood could produce heavy damages. Rising atmospheric temperatures could be expected to alter the timing and volume of snowmelt generated runoff, thereby producing the potential for increases in flood peaks and associated damages.

In terms of water use, a number of effects were identified. In general, water demand is expected to increase, while water supply decreases, spreading localised water shortages to broader regions or to the nation as a whole. Reduced precipitation and the associated reduction in discharge can be expected to reduce both the amount and regularity of hydroelectric power generation. In the particular case of rivers dependent upon snowmelt, the impact could be quite significant. Moreover, contamination due to salt-water intrusion could lead to acute agricultural and municipal water supply problems. Reduced water levels in rivers and lakes could also produce deleterious effects on navigation and recreational activities. Finally, with respect to water quality, the expectation is that river water quality will decline with decreases in minimum flow. Lake quality could be threatened by a prolonged state of thermal stratification, and increasing temperatures may lead to increased eutrophication. It is also thought that declines in the water level and storage capacity of lakes and dams could adversely affect water quality, although the precise mechanism behind such deterioration remains unclear.

4.7 New Zealand

In June, 1988, the New Zealand government instituted a national climate change program under the coordination of the Ministry for the Environment. Three working groups were formed, considering respectively facts, impacts, and responses, consistent with the three working groups of the IPCC. The Facts Working Group was formed to produce a report on the scientific basis for the predictions of climate change. An abridged version of this report has been published which contains the following conclusions (Salinger and Hicks, 1989). Annual average warming in New Zealand under a doubled CO_2 climatic regime range from 1.4°C to 3.5°C. There is some possibility that winter temperatures will rise faster than summer temperatures in more southerly parts of the country. It is possible that the snowline could retreat between 100 m and 150 m for every 1°C rise in temperature. However, even though New Zealand temperatures have increased by 0.5 °C since the 1940s, no retreat of snowline or advance of tree line has yet been measured.

The Impacts Working Group was formed to produce a series of reports addressing the broad range of physical, biological, economic, and social issues likely to be affected by the climatic change estimates provided by the Facts Working Group. One of these impact reports deals with water resources (Griffiths, 1989). All the impact assessments considered two scenarios of climate change, one based on a temporal analog (referred to as SI) and the other on the limiting conditions simulated by GCMs (S2). The analog scenario is based on the period of maximum warmth 8,000 to 10,000 years ago, when westerlies were weaker and there was more airflow from the northwest. New Zealand temperatures were 1.5°C warmer than at present and westerly winds were lighter, especially in winter. There was a reduced frequency of frontal storms, and global sea-level was 20 cm to 40 cm higher than at present.

The second scenario is based on the model-simulated upper limit to greenhouse warming in the New Zealand area of 3°C. It is accompanied by positive mode Southern Oscillation conditions (La Nina) on average. Frequent incursions of tropical air from the north are expected and, although the intensity of the westerlies may decrease, they will still prevail. Moreover, global sea-level may be 30 cm to 60 cm higher than at present.

Regionally, the principal likely impacts of climate change on runoff are depicted in Figure 4.5, and more broadly on water resources as follows. In Northland, flooding could become more frequent and more severe. Baseflows in rivers and streams may be enhanced, while lake levels may rise. There could be greater groundwater recharge and less demand for irrigation. Wetlands may not drain as easily, especially in the Ruawai flats south of Dargaville. Earthflow and other erosion in weathered greywackes, Tangihia volcanics and podsolised sand hill country may precipitate increased suspended sediment loadings in rivers and streams.

A number of similar effects could probably occur in the region around Auckland. These include more frequent and severe flooding, enhanced baseflows in rivers and streams and increased lake levels, and greater recharge of groundwater and less demand for irrigation. There could also be changes in lake stratification patterns and a rise in the number of dune lakes. Moreover, a number of urban-related problems are possible. It may be that more care will be needed in siting urban developments to protect them from increased flooding. High intensity rainfalls may overload stormwater/sewerage systems leading to frequent discharges of contaminated water. Finally, the possibility of increased erosion may result in higher suspended sediment concentrations in estuarine and harbour receiving waters.

The region encompassing Waikato Bay of Plenty-Taupo also is likely to be more prone to frequent and sever flooding, especially in the Hauraki Plains, Bay of Plenty coastal plains, and Lower Waikato River valley. Enhanced baseflows in rivers and streams and lake levels on the volcanic plateau will rise. Lakes may stratify more often and a reduction in lake carrying capacity could possibly occur, although this may be offset to some extent by increased flushing rates and higher water levels. Anoxic conditions are likely in some lakes, while those already anoxic will probably have the period extended. This area, too, may experience greater groundwater recharge and reduced demand for irrigation. The increased frequency of subtropical cyclones may be compensated for by the lower frequency of southeasterly storms under climate scenario SI, but not under scenario S2. A number of other unique impacts are also likely. For example, geothermal systems may receive greater groundwater recharge; Waitomo Glow Worm Cave may be closed more frequently because of flooding, and siltation in the cave may increase; a significant increase in water yield from *Pinus* rodiafa-forested basins can be expected with more yield in summer than in winter; the operation of the Huntley thermal power station may be affected by increased river temperatures (discharges are already limited by temperature restrictions in the summer), although increased river flows may compensate to some degree; and sever gullying could occur in highly erodible volcanic materials leading to increased infilling of hydro-dam reservoirs, thus reducing reservoir life and flood storage capacity.

In the Taranaki-Manawatu-Wellington region flooding is also likely to become more frequent and severe, especially around Ohura, along with enhanced baseflows in rivers and streams. This area may experience a slight increase in groundwater availability and less need for irrigation under scenario SI and greater irrigation demand under S2. An increase in high intensity rainfalls will probably have significant effects on agricultural productivity in Taranaki, as well as overloading storm water/sewerage systems that could produce frequent discharges of contaminated waters. Increased erosion here will also probably result in higher suspended sediment concentrations in rivers and streams.

The southeast part of the North Island, the Gisborne-Hawkes Bay-Wairarapa region may exhibit a number of unique water resources effects. For example, greater incidence of drought and the more frequent drying-up of long reaches of river may accompany climatic warming, as well as diminished baseflows in rivers and streams in Hawkes Bay and eastern Wairarapa. Lake levels will be low more often and anoxic conditions could result at times, especially in Lake Tutira, while impedance of drainage at river mouths will occur in Hawkes Bay requiring increased pumping capacity. Although little change in groundwater recharge is likely, the increased use of groundwater for irrigation is. Also, under scenario S2, it is possible that devastating impacts could be produced by the more frequent passage of large tropical cyclones.

On the South Island, in the Nelson-Marlborough Region, the likely impacts include more frequent and severe flooding along with a small increase in the pumping of drains; urban flooding of east coast catchments; flooding in Tikaki Valley; enhanced baseflows; more droughts in the drier eastern hill country of Marlborough; and more frequent erosion episodes in the Marlborough Sounds. In addition, there may be a small beneficial effect in the availability of groundwater resources, and the Takaka River may run dry less often. However, salinity increases in the Waikoropupu Springs are possible, along with a slight increase in mean discharge, and highly erodible basins in eastern Marlborough could supply more suspended sediment to the Wairau River. This may affect irrigation regimes and produce an increased demand for groundwater.

Potential impacts in the Westland-Fiordland region include several that are more related to mountainous conditions. For example, the meltdown of the snowpack could significantly increase the size of flood peaks, while the drying out of regolith could promote slope failure during high intensity rainfalls giving increased suspended sediment loading in streams. Moreover, under scenario S2, there maybe an overall tendency toward a more stable, less extreme environment, but periods of water deficit are likely to occur.

In Canterbury, little change in groundwater recharge is likely under either scenario SI or S2, but an increase in the number of days of soil moisture being below the wilting point suggests that there may be greater demands for groundwater-supplied irrigation. There may also be a greater incidence of drought and of river reaches drying up, along with major aridity problems on non-irrigated downland areas. Canterbury will also probably experience greatly increased competition for water between instream and out-of-stream uses. Another potential problem relates to snowmelt. It is probable that there will be less water in rivers in late spring and early summer in those regions where snowmelt is now important. Moreover, very little snow storage is likely in South Canterbury resulting in significant changes in the temporal pattern of runoff. Snowmelt contributions will probably move forward about a month in time.

Finally, in the Otago-Southland region, a significant reduction in the long-term availability of groundwater is likely in the eastern parts of the regions. Droughts are likely to increase and major aridity problems may prevail in downland areas particularly in central and eastern regions. Eastern areas may also experience a greater and an earlier demand for irrigation water, while forested areas there will supply a reduced water surplus to stream flows and groundwater recharge. There is also likely to be increased water use by permanent grassland and a shortening of the period of soil water recharge.

5 Case studies of effects in critical or sensitive environments

5.1 Large water bodies

5.1.1 The Great Lakes Basin (US/Canada)

A detailed examination of available water supply and users for the Great Lakes basin reveals a number of commonly encountered conflicts among competing water uses, even under present climatic conditions. First, it should be recognised that there are two major and different hydrologic regions: the Great Lakes proper and the tributary watersheds. Most of the salient conflicting water uses for which the regulation and stabilisation of the Great Lakes is important is navigation and hydroelectric power production, which favour high lake levels versus recreation, reduction of flooding and shoreline erosion which favours low lake levels. The former (hydroelectric power and navigation) affects the basis of an extensive industrial economy in the region, while the latter affects millions of residents who wish to recreate on the shores of the Great Lakes and whose houses and property are affected by storm damage. Since the lakes themselves are a vast reservoir of water, the projected typical consumptive uses of water (municipal and industrial water supply, thermal cooling) are not expected to impose a significant incremental adverse impact. Tributary watersheds, on the other hand, experience highly variable flows, with significant present constraints on in-stream and off-stream water uses.

Over 8,000 km^3, storing 20% of the world's fresh surface water and 95% of the fresh surface water of the US, the Great Lakes have a surface area of 246,000 km^2. The drainage area, including the surface area of the Great Lakes encompasses nearly 766,000 km^2. Eight states of the US and two provinces of Canada (Ontario and Quebec) border the Great Lakes (Figure 4.6). Two of the Great Lakes are regulated: Lake Superior and Lake Ontario; ie their outflows are controlled. Lakes Michigan and Huron are connected by the Straits of Mackinac and their surface water elevations respond synchronously to changes in water supply.

The Great Lakes Basin encompasses a population of 29 million Americans (12% of the US population) and 8 million Canadians (27% of the Canadian population) (Cohen et al, 1989). Millions of people benefit directly from the water-resources related-services of the Great Lakes in the form of hydroelectric power, navigation/transportation of mineral resources including coal and iron and food. In 1975 economic activity in the US portion amounted to $155 billion (1971) while that of Canada was estimated to $27 billion (1971) (International Joint Commission, 1985). By 1985, the Great Lakes Basin accounted for 37% of the US manufacturing output, consisting of transportation equipment, machinery, primary metals, fabricated metals and food and beverage products.

The Great Lakes water levels have fluctuated over a range of 2 m during the past 150 years. Seasonal lake level variations average 0.3 m in Lake Erie and 0.5 m in Lake Ontario. Also, the Great Lakes region has experienced twelve serious droughts in the past 60 years and six periods of extensive flooding. A high precipitation regime during the past 20 years resulted in 1986 in record high lake levels for this century.

The GCMs used to predict temperature and precipitation differ substantially in their prediction for each of the regions under consideration. Figure 4.7 shows, for example, that the GISS model predicts a net increase in summer precipitation in the Great Lakes of about 0.4 mm/day, whereas the GFDL model shows a decrease of over 0.6 mm/day and the OSU model shows no change. Precipitation is important for non-irrigated agriculture (dryland farming). However, water availability in the streams (runoff) and in the soil is a function of évapotranspiration, which is a non-linear function of temperature. Hence, runoff computation based on GCM model outputs will also vary widely depending on the temperature and precipitation conditions predicted by each model. A comparison of the runoff computations for the doubled-$C0_2$ scenario based on the outputs of three GCMs (GISS, GFDL and OSU) was conducted by Croley (in press). The analysis used daily models to simulate moisture storage and runoff for 121 watersheds draining into the Great Lakes, over-lake precipitation into each lake, and the heat storage and evaporation for each lake. Table 4.4 shows that there is a 23% to 51% reduction in net basin supplies to all the Great Lakes for the three models. The largest changes in net basin supply would occur in Lake Erie, a feature that was uniform in all three models, with the GISS model showing the greatest percentage change. Sanderson (1989) simulated the effects that the reduction of net basin supply would have on the historical levels of Lake Erie from 1900-1980 (Figure 4.8).

Table 4.4 Estimated percentage changes in Great Lakes net basin supplies between current climatic conditions* and doubled CO_2 conditions**

Basin	1xCO_2 Net basin supply and 2xCO_2 relative changes BASE (mm)	GISS (%)	GDFL (%)	OSU (%)
Superior	847	-2	-57	-19
Michigan	698	-45	-65	-32
Huron	1052	-46	-41	-19
St.Clair	4395	-50	-28	-25
Erie	592	-113	-91	-56
Ontario	1941	-43	-29	-11

* (1 x CO_2 or the BASE case)

** as simulated by the GISS, GFDL and OSU GCMs (Croley, undated)

Thermoelectric power cooling is projected to increase significantly, accounting also for much of the increase in consumptive water use. Consumptive uses of water, largely through evaporation, represent a net loss of water to the hydrologic system. This fairly large loss was estimated by the USGS to be 85 cm in 1985, rising to 170 cm in 2000. This loss, however, would only account for a reduction of a few centimetres in lake levels in comparison to a one-half metre drop in lake levels projected from a reduction of net basin supplies due to increased natural evapotranspiration. If the dramatic climate change scenario were to materialise, the large socioeconomic impacts would stem from water use conflicts and shortages that are currently encountered primarily during naturally fluctuating low lake level stands. That is, hydroelectric power production would be significantly affected, particularly in the Lake Ontario and Lake Erie drainage areas. There are substitutes for the loss of hydroelectric power, but most will add to the emission of greenhouse gases (GHG) and consumption of thermoelectric cooling water.

Commercial navigation is a very important component of the Great Lakes economy that would be seriously affected by lower lake levels. Either cargoes would have to decrease to get through the locks, imposing increased transportation costs, or the locks on the Great Lakes would have to be rebuilt. In either case, the economic cost would be high.

The water resources impacts are also likely to be of great socioeconomic consequence in the streams of the watersheds that drain into the Great Lakes. These watersheds are largely unregulated and the municipalities and industries depend on natural streamflow and groundwater. Although the variability of weather and associated shifts in the frequency and magnitude of climate events were not available from the outputs of the GCMs, there is reason to believe that the increased precipitation regime predicted by some of the GCMs will result in greater and more frequent flooding in the tributary watersheds. Along with this trend, it is possible that the frequency, duration and magnitude of droughts might also increase as a consequence of the warming trend. In other words, the cycles of floods and droughts experienced in the current hydrologic record could become worse, exacerbating future conditions of higher water demands.

5.1.2 The Caspian Sea

The Caspian Sea is the world's largest enclosed lake with a surface area of 371,000 km^2. Lake-level variations have a very large amplitude and depend mainly on the river inflow-water surface evaporation ratio (precipitation on the lake surface is small). Over the last 2000 years the amplitude of lake-level variation has been about 10 m. Instrumental observations (since 1837) indicate that lake-level variations ranged between -25.5 m and -26.5 m abs during the period 1837 to 1932. The lake then began to fall and reached a low of -29.10 m abs in 1977. From 1978 to present the lake level has increased, reaching a level of -27.7 m in 1989 (Shiklomanov, 1988).

Future lake levels depend on natural inflow variation (80% of the inflow is contributed by runoff from the Volga River). Other controlling factors are man's activities in the river basin, anthropogenic climate changes, and changes in precipitation and evaporation. To assess future levels of the Caspian Sea, methods for probabilistic prediction have been developed which take into account potential effects of natural and anthropogenic factors, including global warming. The methods are based on a complex water balance model which uses Monte Carlo procedures to simulate an annual inflow series.

The scenarios were based on empirical data for all the water-balance components obtained since 1880. The mean decrease in river water inflow due to present and projected man's activities are, according to SHI estimates (in km^3 yr^{-1}): in 1989, -40; 2000, -55; 2010, -60; 2020, -65. For every year the values of river runoff were taken separately for all the main rivers. In the case of non-stable climatic conditions, possible climate changes for the years 2000 and 2020 have been estimated for the basin and the Sea according to predictions by Soviet climatologists on the basis of palaeoclimatic reconstructions (see Section 4.4). Possible changes in river water inflow to the Sea have been obtained independently by two extreme estimates derived from the river runoff change maps for 2000 (Figure 4.9) and by the water balance model over decades (Section 4.4). Changing evaporation has been calculated from air temperature and precipitation data.

Table 4.5 shows calculated changes in the water-balance elements for the Caspian Sea with global warming. According to these estimates a considerable decrease (relative to the normal) in river water inflow to the Sea would occur by the end of the century, mainly due to decreased Volga River Runoff. This would be followed by a marked increase in inflow. Precipitation increases over the Sea would be particularly significant (up to 60% in the year 2020, from the current annual mean precipitation of 240 mm); evaporation would change insignificantly (up to 3%).

Table 4.5 Changes in components of the water balance of the Caspian Sea in response to global warming

Water balance component	Year 1989	2000	2020
Total inflow (km^3 yr^{-1})			
From map analysis	0	-20	+40
From model analysis	0	-30	+10
Precipitation (mm)	0	+100	+150
Evaporation (mm)	0	+15	+30

A simulation of water-balance components under varying climate conditions has been carried out by the same technique, taking into account, however, the data in Table 4.5 with interpolation for each year of the period under consideration. In this case, the shape of distribution curves, variability of water-balance components, coefficients of their autoregression and intercorrelation are accepted according to observational records. The results are presented in Figure 4.9. By the end of the century some lake-level lowering is expected to take place due to increasing human activities in the basin. After the year 2000, some stabilisation may occur followed by a significant rise in the Sea's level owing to predicted increases in inflow and precipitation over its surface (Shiklomanov, 1988; 1989a). These results, though preliminary, show the importance and necessity of taking into account anthropogenic climate change forecasts to estimate the fate of continental reservoirs and to plan future management.

5.2 The arid and semi-arid zones of North Africa, including the Sahel

North Africa and the Sahelian zone are both subject to frequent and disastrous droughts, progressive aridisation, and encroaching desertification. The Sahel, a vast though narrow, belt stretching from West Africa to the Horn of Africa, is the transition zone from the Saharan desert to the hot and semi-arid African savannahs. Analysis of annual precipitation data from stations in the Sahelian zone for the period 1968-88 indicate that this period was exceptionally dry. Although the current Sahelian drought appears to many scientists and policy makers to be a persistent and unprecedented phenomenon, this drought is far from unique. During the current century, the Sahelian region experienced several dry periods of varying duration, magnitude, and spatial extent (Grove, 1973; Sircoulon, 1976). During the last five centuries, historical accounts and palaeoclimatic evidence indicate that there have been rainfall fluctuations of extremely variable duration (from years to several decades) (Nicholson, 1978; 1989). Demarée and Nicolis (1990) viewed the Sahelian drought as a fluctuation-induced abrupt transition between a stable state of 'high' rainfall and a stable state of 'low' rainfall.

The major reason for Sahelian droughts is a decrease in annual precipitation. Ojo (1987) analysed precipitation data for 1901-85 using 60 stations in western Africa. He found that during 1970-79 average precipitation there was 62% of normal and, during 1981-84, about 50% of normal (Figure 4.10). The Sahelian zone is characterised by a strong sensitivity to hydrometeorological conditions, especially precipitation. This is confirmed by analysis of precipitation and runoff over the most dry and wet five year periods of time in the Senegal, Niger and Shari Rivers basins, as well as by Lake Chad levels and areas indicated in Sircoulon (1987). According to these data, with precipitation increasing by 20-30% the runoff rises by 30-50% in the river basins; with precipitation decreasing by 9-24% the runoff is reduced by 15-59%. In addition, between the early 1960s and 1985, the area of Lake Chad shrank by more than 11 times, ie from 23,500 km^2 to 2000 km^2.

The analysis of the series of total annual precipitation amounts from the stations situated in arid zones of Northern Africa for the period 1972-87 shows a trend toward decreasing total annual precipitation. The total annual precipitation amounts are much below normal (during the period in question). Likewise for Sahel, it is a succession of dry years that has created a critical situation in the region. This succession of dry years has led to decreasing water resources in region. An analysis of the number of rainy days during which a considerable amount of precipitation was observed showed a decrease toward days with small amounts of precipitation. From the decrease in the number of rainy days, the coefficient of runoff decreases too, which is manifest in a general decrease in runoff. A change in the distribution of precipitation toward a decrease in the number of rain days, as well as a significant shortening in the length of the rainy season, have been mentioned by many authors who have analysed Sudano-Sahelian precipitation data for the last 20 years (see, eg Demar6e and Chadilly, 1988 and Erpicum et al, 1989).

In view of its recurrent but aperiodic character, this tendency may represent a potential risk of drought possibly contributing to the process of desertification and extension of deserts. It seems obvious that the future water resources, ecology and economies of countries in the Sahelian and arid and semi-arid zones will depend upon changing precipitation in the region due to the growth of radiatively active trace gas concentrations in the atmosphere.

An optimistic forecast has been proposed by Soviet climatologists for Northern Africa on the basis of palaeoclimatic reconstructions (Anthropogenic climatic changes, 1987). According to these data, in the next several decades annual precipitation may increase considerably as may total moisture and river runoff. The estimates obtained are very approximate and need thorough checking and improvement, based on more detailed information and different methods. The quality of the data, however, should not deter attempts to solve the problem of considering climate variability in water resources management. In this regard two issues should be considered: water resources management problems and water quality problems.

The first issue is directly related to the sensitivity of hydrologjc systems to climate changes and, in particular, to droughts and floods. This necessitates taking into account risks while developing water resource projects. The second issue is related to water quality, ie the problem of pollution in relation to both human activities and natural processes. From the standpoint of anthropogenic climate change, there is no evidence to suggest that the drought problem for Northern Africa and the Sahelian zone will be reduced. Finally, taking into account the importance of climatic and hydrologic data for use in economic analyses of the African continent, there is a clear need to establish (i) systematic networks for meteorological data monitoring, and (ii) improved and expanded surface hydrologic data collection networks.

5.3 Water conditions in critical agricultural regions

5.3.1 The South Platte River

Next to the direct impact on water resources, perhaps the most critical social and economic concern associated with climatic change is the impact on agriculture. This is especially true in marginal farming regions of dryland farming or those that are heavily dependent upon irrigation for the maintenance of agricultural productivity. An example of such a region is the South Platte River basin in the west-central part of the US. The basin is primarily in the State of Colorado, but the river also drains parts of southwestern Nebraska and southeastern Wyoming (Figure 4.11). It is watershed number 1019 which drains into Water Resources Region 10, the Missouri River basin. The basin comprises 62,210 km^2 of mountains, plains foothills and alluvial fans. The western part is dominated by the rugged mountains of the Front Range, which is part of the Southern Rocky Mountains in Colorado. Of the 49,250 km^2 of the basin in Colorado, about 20% is above 2700 m in altitude, and more than half is above 1800 m. A few peaks rise above 4000 m.

Land use is diverse in the South Platte River basin. Most of the mountain area remains as near-natural National Forest land, with coniferous trees as the dominant vegetation. These forest lands are not extensively logged, and are now used mainly for recreation. Some of the lower slopes of the mountains are used for grazing. The transition area between the mountains and the plains includes most of the urban and suburban development. The plains are used principally for pasture and rangeland, dry cropland, and irrigated cropland.

By 1980, the basin had about 75 surface reservoirs with storage capacities of at least 6 million m^3, and about 300 other reservoirs with capacities of at least 0.6 million m^3. The total reservoir-storage capacity in the basin exceeds 2.5 billion m^3 (US Army Corps of Engineers, 1980). The reservoirs are operated primarily for irrigation, and public supplies, hydroelectric power generation, and flood control. However, recreation development has occurred on nearly all of the storage reservoirs in the basin (US Geological Survey, 1990). About 20 transbasin diversion structures have been used to import water into the South Platte River basin, including five tunnels and three pipelines US Army Corps of Engineers, 1977). The intensive development of water and lands in the South Platte basin has solved some problems while incurring others. There are still unmet demands for municipal and agricultural water supply. Groundwater overdrafting is occurring as a consequence. Over 200 communities have flooding problems and water quality has diminished, partly from irrigation return flows and partly from non-point source pollution.

The South Platte River basin is typical of the agriculturally based economy of the US Great Plains states, which includes a large livestock industry. Farmers in the Great Plains are particularly vulnerable to climate variability and the drought of the 1930s was so devastating, serving as the impetus for a large-scale social migration. The Great Plains has become a productive agricultural area in the US thanks to the large degree of water resources development. In its natural state, however, it is a marginal agricultural region and is very sensitive to climatic variability.This fact leads to considerable concern when current estimates of climate change are factored in. A comparison of the output of general circulation models, under doubled CO_2 conditions, show that both the GISS and GFDL models predict a net annual decrease in precipitation for the Great Plains region. The OSU models, on the other hand, shows a slight increase over present conditions, even during the critical summer period (Figure 4.12). The largest predicted summer season precipitation deficit is nearly 5 mm/day, according to the GFDL model, which is of the same order of deficit experienced during the devastating drought of the 1930s.The 2,301,000 people in the South Platte basin use 6894 litres per capita per day of fresh water for a total of 15,873 ML/day. Of this total, 4635 ML/day are withdrawn from groundwater sources and 11,237 ML/day from surface water sources. Irrigation is by far the largest user of fresh water (11,237 ML/day), of which 4271 ML/day if from groundwater sources and 6962 ML/day is from surface water resources. About 90% (9911 ML/day) of the water used for irrigation is lost by conveyance or consumption. Thermoelectric cooling uses account for 2247 ML/day and a consumptive loss of 53 ML/day. Publicly supplied water, largely for municipal uses, accounts for 2001 ML/day from surface water sources and 171 ML/day from groundwater sources.

Clearly, the doubled atmospheric CO_2 general circulation model simulations (except for those of the OSU model), if true, depict a potentially serious climate change scenario, particularly for the agricultural sector. Despite the large amount of irrigation, most of the farming in the South Platte River basin and the Great Plains is dryland. Only about 10% of the farmland is irrigated. The fact that 30-50% of all irrigation is from groundwater, which is already being rapidly depleted, does not bode well for any climate change scenario which greatly exacerbates current conditions.

In general, results of recent studies show a net reduction in crop (wheat and corn) yields, even with the compensating effects of CO_2 on plant photosynthesis (Smith and Tozan, 1988). Dryland farming would likely become increasingly risky and less economical. Moreover, the present water resources base (both surface and groundwater) could not compensate for the relatively large loss of marginal dryland acreage.

Navigation and hydroelectric power production on the mainstem reservoirs could be threatened as could surface water quality. Development of the basin's surface water potential is near capacity. Substantial changes in present water use technologies, particularly for irrigation, would have to be undertaken to meet the more stressful conditions postulated under the modelled climate change scenario. This encompasses increased water use efficiencies, conjunctive use of surface and ground waters, transfer of water rights and, lastly, major new imports of water from outside the basin.

5.3.2 The Murray-Darling Basin (Australia)

Another detailed look at the hydrologic and water resources impacts of a climatic change in a critical agricultural region has been completed for the Murray-Darling Basin in southeastern Australia (Stewart, 1989; Figure 4.13). In this basin, which has an area of 1.06 million km^2, about 10 million of the 12.4 million ML of water per annum available under present climatic conditions have already been developed and mean water usage already exceeds 8.6

million ML (Zillman, 1989). The region presently accounts for just under 60% of mean annual water use and includes 75% of the total irrigated area of the continent (1.7 million ha). The Murray-Darling Basin must be regarded as extremely vulnerable to the effects of climate variability or change and is of major socioeconomic importance to Australia.

The Australian analysis evaluated water resources impacts on the basis of output from five atmospheric general circulation models for both summer (DJF) and winter (JJA) seasons under equilibrium doubled CO_2 conditions. These included the GISS, GFDL, NCAR, OSU, and UKMO models. All of the models predict increases in surface air temperatures, ranging from 3°C to 7°C for the basin region. The models predict different changes in precipitation rates, including both increases and decreases, with a range 2.5 mm/day to 1.0 mm/day. The most widely used scenario of climate change in Australia is for a temperature rise of between 2°C and 4°C and precipitation increases up to 50% in summer (except in southern regions) and decreases of up to 10% in winter (Pittock, 1988).

Three distinct methods were used to estimate the estimate the potential impacts of these various model-generated climate scenarios; temporal analogs, spatial analogs, and hydrological models. Because the GCM models all predict increases in temperature of similar magnitude, and since global temperatures have undergone a modest increase over the past 100 years, temporal and spatial analogs operate on the assumption that the magnitude of the predicted global warming is correct. Although this assumption may or may not be valid, these procedures do provide one mechanism for understanding basin response to anomalous climatic conditions. Thus, periods of above average temperature in the historical record may provide indications of the potential impact of climatic change (temporal analogs). Areas with past climatic conditions similar to those expected in the future may also provide such indications (spatial analogs). Hydrological models can be used to determine the impacts of changes in precipitation and other factors defined by the scenarios or analogs.

Evaluation of the impacts of climatic change on a temporal basis can be studied in two ways. First, trends attributable to climatic change can be sought in recorded data and, if found, can be extrapolated into the future. Analysis of available temperature, precipitation, and runoff data from the Murray-Darling basin has not revealed any trend attributable to climatic change. This does not discount the possibility of climatic change but, rather, indicates that impacts are not yet discernible. The predictions of the general circulation models are for increasing temperatures across Australia of the order of 4°C to 5°C. If these changes are realised, the annual average temperatures in the southern part of the basin could rise to between 17°C or 18°C, while those in the northwestern region could increase to between 25°C and 26°C. Spatial analogs, that is using areas in Australia that currently have such temperature conditions to estimate future climatic patterns, would suggest that precipitation in both regions could decrease by 40% to 50%. Spatial analogs, however, can be misleading because not all characteristics are maintained in the analogous area. The differences can be in terms of vegetation types, topography, storm types and mechanisms, and moisture sources. Some of these characteristics may cause feedback mechanisms. It should be noted that the majority of the GCMs predict increases in precipitation, not decreases as suggested by the temporal and spatial analogs.

Close (1988) used computer models to examine how the River Murray system would have behaved if the current storages and current irrigation developments had existed for the last 94 years. By superimposing predictions of climatic changes assumed to be associated with the greenhouse effect, the impacts on water resources and system operation were estimated. Close concluded that:

(i) Tributary flows will increase over almost all of the Murray-Darling basin.

(ii) Flow increases will be more pronounced in the northern rivers of the basin than in those in the south.

(iii) Spring, autumn, and summer precipitation will increase while winter rainfall may decrease slightly.

(iv) Demand for irrigation water per hectare will decrease slightly.

(v) The water resources available for irrigation will increase, which will permit either the area of irrigation to be increased or the security of supply of the current irrigation areas to be improved.

(vi) Dilution flows will increase and hence salinity in the lower river will decrease.

It should be noted that these impacts are based on only one scenario, which does not agree with those provided by the majority of GCMs, or with the temporal and spatial analogs. The value of models is that they can be used to determine the impacts of a range of scenarios and to establish the most sensitive climatic parameters in a region, on which to then concentrate.

5.4 Water conditions in intensively urbanised areas - the Delaware River Basin (USA)

Estimating the water resources impacts of climatic change in dynamic and intensively urbanised areas has some unique problems. Perhaps the most significant of these is that such areas frequently undergo major population, commercial and industrial changes over time periods of several decades. The water resources effects of these changes are likely to be more significant than any that would be attributable to climatic change over the same time frame. Thus, estimates of changes in total population and its spatial distribution, as well as changes in industrial and land use conditions, are as essential to the determination of future water resources conditions as are estimates of climate change. Unfortunately, experience to date indicates that the estimation of future demographic, industrial, technological, and land use conditions, when available, is generally unreliable (Osborn, 1986).

In the US, a recent study investigated the sensitivity of hydrologic and water resource conditions in the Delaware River Basin, an intensively urbanised basin on the middle Atlantic coast, to potential changes in climate (Ayers et al., 1990). This work evaluated water resources impacts using estimates of climate change both with and without estimates of social and economic change.

The Delaware River Basin is an environmentally diverse region encompassing an area of approximately 33,000 km^2 and crossing five major physiographic provinces and three distinct ecosystem types. Runoff processes differ considerably over the basin; in addition, human activities influence the movement and storage of water in the basin, adding considerable complexity to the hydrologic response characteristics of the various physiographic provinces. Urbanisation in the lower portions of the basin has significantly altered the regional runoff response (Ayers and Leavesley, 1988).

With respect to climatic change, perhaps the most important issue is that the Delaware River provides water for an estimated 20 million people (Delaware River Basin Commission, 1986). Water availability is enhanced by complex systems of reservoirs for storage, and wells, pipes, tunnels, and canals for diversion and delivery. Moreover, the lower one-third of the river is tidal, and the freshwater part of the tidal river serves as a major source of groundwater recharge for aquifer systems supplying water to regions around the river and as an important water-supply source for the City of Philadelphia and many industries by direct diversion. It is critical, therefore, that the water in this stretch of the river remain potable, even during periods of prolonged low flow (droughts). This is the social and environmental context within which the Delaware Basin study was conducted.

Models of monthly streamflow (with and without reservoirs) and daily streamflow (without reservoirs) were developed to analyse the effects of climatic change on basin runoff. Analyses of the sensitivity of monthly streamflow to change in climate using a monthly water-balance model without reservoirs, and without changes in water use, indicate that warming could result in an increase in the proportion of winter precipitation that falls as rain in the northern part of the basin (McCabe and Ayers, 1989). The effect of such a change would be to reduce snow accumulation, increase winter runoff, and reduce spring and summer runoff. Basin-wide estimates of total annual runoff indicate that warming of 2°C-4°C, without corresponding precipitation increases, could produce a 9% to 25% decrease in total annual runoff as a result of increased evapotranspiration. The simulations suggest that an increase in precipitation of about 3% would be needed to counteract decreases in runoff that would result from each 1°C of warming. Annual runoff changes estimated from the water-balance model driven by climate change values generated using three GCMs ranged from -39% to +9%.

Similar sensitivity analyses using a stochastic monthly flow model with reservoirs indicate that the risk of drought is significantly greater in those climate change scenarios where precipitation does not increase sufficiently to offset the temperature increase. In one instance, water use was held constant at 1986 levels, that is, it was assumed that there would be no demographic, industrial, or technological changes occurring contemporaneously with climate change. The simulations indicated that the percentage of time that the basin would be under drought warning or emergency could increase. The probability of entering a drought condition in the Delaware River Basin currently is 9.5%, based on a 1000-year simulation (Table 4.6). Under assumed warmings of 2°C and 4°C, the probability of drought in the basin increases by 1.9 and 2.9 times respectively. When the two warming scenarios are accompanied by a 10% decrease in average precipitation, the probability of drought increases to 4.8 and 6.4 times the probability under current conditions respectively. A 10% increase in average precipitation in conjunction with a 2°C warming actually causes a decrease in the probability of drought. The simulated range in the amount of time the basin would experience drought, from a 60% decrease to a 540% increase, corresponds to the uncertainty associated with potential climatic change in the basin.

The simulation results presented in Table 4.6 indicate that virtually no change in the probability of drought will result from the projected growth in consumptive water use in the basin. Currently, however, a drought is defined only by the contents of the New York City reservoirs, and the magnitude of consumptive water use in the upper part of the basin is small relative to the diversions to New York City and to the increased evapotranspiration that could accompany a temperature increase.

Table 4.6 Simulated percentage of time in which the Delaware River Basin is in a drought warning or emergency condition*

Change in temperature	Change in precipitation -10%	None	+10%
For observed 1986 water use			
None		9.5	
+2°C	45.8	17.7	5.6
+4°C	61.1	27.2	10.3
For estimated 2040 water use			
None		9.6	
+2°C	46.0	17.8	5.7
+4°C	61.3	29.3	10.4

* For prescribed temperature and precipitation scenarios (Ayers et al., 1990)

A topographically based hydrologic model was developed and linked with a wet/dry climate model to assess the sensitivity of daily streamflow to climatic change in the Delaware River basin (Wolock et al., 1989). The sensitivity of streamflow in on-urban watersheds in the Delaware River basin to climatic change was evaluated using this daily flow model. The model stochastically generates time series of temperature and precipitation and uses estimates of parameters derived from watershed topography (Price et al., 1989) and soil hydraulic properties to generate a time series of streamflow.

A series of 60-year simulations, each representing a different possible future realisation of the same climatic change projection (a gradual warming of 3°C with current precipitation characteristics) was performed. Annual and monthly maximum daily streamflow and Kendall's tau statistics then were calculated for each of the 60-year streamflow time series to detect trends in streamflow.

These simulations illustrate two important characteristics about the sensitivity of basin watersheds to climatic change. First, seasonal differences in the expected effects of global warming on streamflow are observed. Maximum daily streamflows increase with time (more positive than negative trends) in mid winter months, decrease in spring and summer, and change little in fall and early winter. These seasonal differences in trend primarily reflect changes in snowfall accumulation and snowmelt. With warming, more winter precipitation falls as rain than as snow, and snowmelt occurs earlier. The warming effect is strongest in the northern part of the basin where snow accumulation currently is significant. Second, natural variability in precipitation masks the effects of increasing temperature. The percentage of simulations that do not show a significant increase or decrease is greater than 58% in any month and average 84%. Results of the simulations using the daily watershed model (without reservoirs) indicate that, overall, warming alone would cause a decrease in daily streamflow, specifically the maximum and average daily low and 7-day low flow. Most of this decrease would occur in the warmer months. Where snow accumulation currently is significant (in the northern part of the basin), however, the warming would result in an increase in the February average and maximum daily flow, regardless of precipitation changes. In general, watershed runoff was found to be more sensitive to changes in daily precipitation amounts than to changes in daily temperature or precipitation duration. Detectability of runoff changes was masked by the underlying variability in precipitation.

5.5 Regions of snowmelt-generated runoff: The Sacramento-San Joaquin River Basin (USA)

The Sacramento-San Joaquin Rivers comprise the drainage basin of the Central Valley of California, one of the most productive and diverse agricultural regions in the world (Figure 4.14). It encompasses several large metropolitan areas, and sustains many others. Over 40% of California's total surface water drains from the Central Valley Basin into the San Francisco Bay area, supplying water for irrigated agriculture, municipal and industrial uses and numerous other recreational and ecological purposes.

Elevations in the basin range from sea-level in the Sacramento-San Joaquin River Delta to mountain peaks of over 4,200 m in the Sierra Nevada range.

California's climate is characterised by wet winters and dry summers, with mean annual precipitation decreasing from 190 cm in the northern Sacramento River basin to 15 cm in the southern San Joaquin River basin. The key feature of the hydrologic characteristics of this basin is that a significant proportion of the basin's precipitation falls as snow in the high mountains. Consequently, storage of water in the snowpack controls the seasonal timing of runoff in the Central Valley rivers and has shaped the evolution of strategies for water management and flood protection (Smith and Tirpak, 1989).

California's rivers are highly regulated because its water resources are poorly distributed relative to its settlement patterns. Nearly 70% of the state's surface water supply originates north of Sacramento, while 70% of its population and 80% of the total demand for water lies to the south. About 85% of the Central Valley basin's total annual precipitation occurs between November and April, whereas peak water use occurs during the summer. About 826,000 ha are irrigated in the Sacramento River basin by groundwater and surface water sources. An additional 794,000 ha are irrigated in the San Joaquin River basin. Roughly 60% of the total population of California (26 million) is served by surface water sources, the remainder derived from groundwater.

Gleick (1989) reported that the drought of 1976-77 combined two of the driest years on record and resulted in a reconsideration of systemic water management procedures and their effects on the economic infrastructure of region. As an example of the severity of the drought, average annual precipitation in California is approximately 250 billion m^3. In the 1976 water year, precipitation decreased to 160 billion m^3, followed by even less precipitation in 1977, totalling 135 billion m^3, or 45% of average. Runoff in California's river dropped to 47% of normal in 1976 and to 22% in 1977.

Hydroelectricity is a major source of power in California, providing approximately 20% of the state's total electricity production. In 1976, total hydroelectric output dropped to just under 10%, while in 1977 it dropped to 7%. The reduction in relatively inexpensive hydroelectric energy production occurred as the need for groundwater pumping increased dramatically as a consequence of drastically reduced surface water deliveries. In 1977, 4.2 billion m^3 more water than normal were pumped from groundwater reservoirs (Gleick, 1988).

Droughts have a direct effect on salinity intrusion from San Francisco Bay into the Sacramento-San Joaquin Delta region. Upstream reservoirs changed their operating policies in the 1980s to prevent the worst effects of salinity intrusion during low flow years at the expense of increasing the vulnerability of the entire water management system. Flooding is a continuing major problem in the central basin and, as urbanisation increasingly spreads out onto the flat Central Valley, flood damages will increase proportionately.

Gleick also sees evidence of increased runoff variability in the long term record of the Sacramento River basin as expressed by the five-year moving average of the standard deviation of the Sacramento Basin unimpaired runoff record of 1906-86. This relatively recent increase in variability (since the 1970s) has resulted in a series of changes in standard planning and design assumptions about peak flood volumes, drought severity, recurrence intervals and reservoir operating rules. Thus, one of the likely future climatic states of global warming could be one in which there is a decrease in the mean runoff and an increase in variability, ie an increase in the frequency and magnitude of floods and droughts.

An assessment of the possible water resources impacts of a doubling of atmospheric CO_2 has been made using the output from three GCMs. It should be noted that conditions for the entire Central Valley drainage system are encompassed within one grid cell for each of the three GCMs. Again, there is considerable diversity among the three models, especially with regard to the seasonal prediction of precipitation changes. Nevertheless, based on a series of hydrologic impact studies conducted through the US Environmental Protection Agency and reported in Smith and Tirpak (1989), it was shown that total annual runoff in the Sacramento-San Joaquin River basin might be expected to remain near current levels or to increase somewhat under the scenarios simulated by each of the GCMs. However, major changes could probably occur in the seasonality of the runoff. In response to higher temperatures, less precipitation would be expected to fall as snow, and the snowpack that does accumulate could melt earlier in the year. Thus, there could be higher runoff in the winter months and considerably less in the traditional spring snowmelt-runoff season. Roos (1990) estimates that a 3°C temperature increase could shift about one-third of the present spring snowmelt into increased winter runoff. Also, the possibility exists for runoff variability to increase substantially during the winter season.

Change in the timing of runoff could have profound influences both on the aquatic and terrestrial ecology and on water resources management, despite the fact that total annual runoff could be slightly higher.

First, more liquid precipitation in the winters months could lead to reduced runoff in the late spring and summer, thereby reducing the carry-over soil moisture needed by the vegetation. Also, such a reduction in stream-flow in the late summer could lead to a degradation in the health of aquatic species.

An analysis of 1990 water use demands, in conjunction with instream flow constraints and delta outflow requirements and current reservoir operating policies, indicate a potential decrease in mean annual deliveries from 7% (OSU model) to 14% (GFDL model) to 15% (GISS model). This would occur because under current operating rules combined with earlier (ie winter) snowmelt, the reservoir would not have the capacity to store the early runoff for summer season irrigation withdrawals while simultaneously retaining springtime flood control capabilities.

Future demands for surface water from the Sacramento-San Joaquin system are expected to increase 30% by the year 2010. 'This demand could not be reliably supplied under the current climate and resource system, and the shortage might be exacerbated under either of the three GCM derived scenarios' (Smith and Tirpak, 1989). Furthermore, the potential magnitude of changes in the seasonality of runoff are such that operational changes alone would probably not significantly improve the systems performance.

Climate change impacts on agriculture are complicated by the fact that so much of it is dependent on irrigation, which accounts for 80% of California's water use. If there are substantial and persistent shortages as a result of the inability of current water management operating procedures to adapt to the change in seasonality, these deficits would clearly affect agricultural yields. However, two of the GCMs, the GISS and GFDL models, were used to predict changes in the yields of several different crops (sugar beets, corn, cotton, and tomatoes) under a doubling of CO_2 and the resultant potential changes in mean annual and seasonal temperature, precipitation and soil moisture. Under those direct conditions of climatic change, all the crops were simulated to suffer decreases in yield. When growth enhancing effects of a doubled $C0_2$ atmosphere were taken into account along with the primary climatic effects, all the crops (except corn) showed substantial increases in yield.

6 Conclusions

Relatively small climate changes can cause large water resource problems in many areas, especially arid and semi-arid regions and those humid areas where demand or pollution has led to water scarcity. Little is known about regional details of greenhouse-gas-induced hydrometeorological change. It appears that many areas may have increased precipitation, soil moisture and water storage, thus altering patterns of agriculture, ecosystems and other water uses. In other areas, however, water availability may decrease, an important consideration for existing marginal situations such as the Sahelian zone in Africa. This has significant implications for agriculture, water storage and distribution, and for hydro-electric power generation. In some comparatively small areas, assuming a 1°C-2°C temperature increase coupled with a 10%-20% reduction in precipitation, a 40%-70% decrease in annual or seasonal runoff could occur. Regions such as Southeast Asia, that are dependent on unregulated river systems, are particularly vulnerable to hydrometeorological change. On the other hand, regions such as the western USSR and western US that have large regulated water resource systems are less sensitive to the range of hydrometeorological changes in the assumed greenhouse scenario.

If meaningful estimates of water resources conditions, appropriate for planning and policy formulation, are to be produced, then studies must include estimates on the frequency, intensity and duration of potential future hydrologic events. This is especially critical for evaluating effects on agriculture, the design of water resource management systems, and for producing reasonably accurate water supply estimates.

In many instances, it can be expected that changes in hydrologic extremes in response to global warming will be more significant than changes in hydrologic mean conditions. Thus, attention must be focused on changes in the frequency and magnitude of floods and droughts in evaluating the societal ramifications of water resource changes.

Initial water resource planning and policy-making will continue to be implemented even in the face of uncertainty about global change. Clarification and specification of the useful information content of the various methods for estimating future change must be made available to the management community.

The most essential need is for more reliable and detailed (both in space and time) estimates of future climatic conditions. These estimates must be regionally specific and provide information on both the frequency and magnitude of events.

Increased understanding of relations between climatic variability and hydrologic response must be developed. Such work should include the developmenl of methods for translating climate model information into a form that provides meaningful data to watershed and water resource system models.

Areas particularly vulnerable to even small changes in climate must be identified worldwide. Vulnerabilities must be ascertained, considering both natural and anthropogenic conditions and potential changes.

Intensive assessments of water resource sensitivities are necessary in developing countries, especially those located in environmentally sensitive arid and semi-arid regions, where the potential for conflicts associated with low water resource system development and rapidly increasing water demands is high.

Studies are needed that produce improved procedures for operating water management systems in consideration of climate uncertainty. A related aspect of this work is the development of design criteria for engineered structures that specifically incorporate estimates of climatic variability and change.

Very little is currently known about the effects of climate change on water quality. Although water quality concerns are becoming increasingly important, the separation of human-induced versus climate-induced changes in water quality is a very difficult problem. Specifically, there is an immediate need to identify those aspects of this problem that hold the most promise for yielding credible evaluations of climatic effects on water quality.

Figure 4.1. Dependence of consumptive water losses, over large continental areas, on the aridity index. 1 - Africa, 2 - Europe and Australia, 3 - North and South America, and Asia

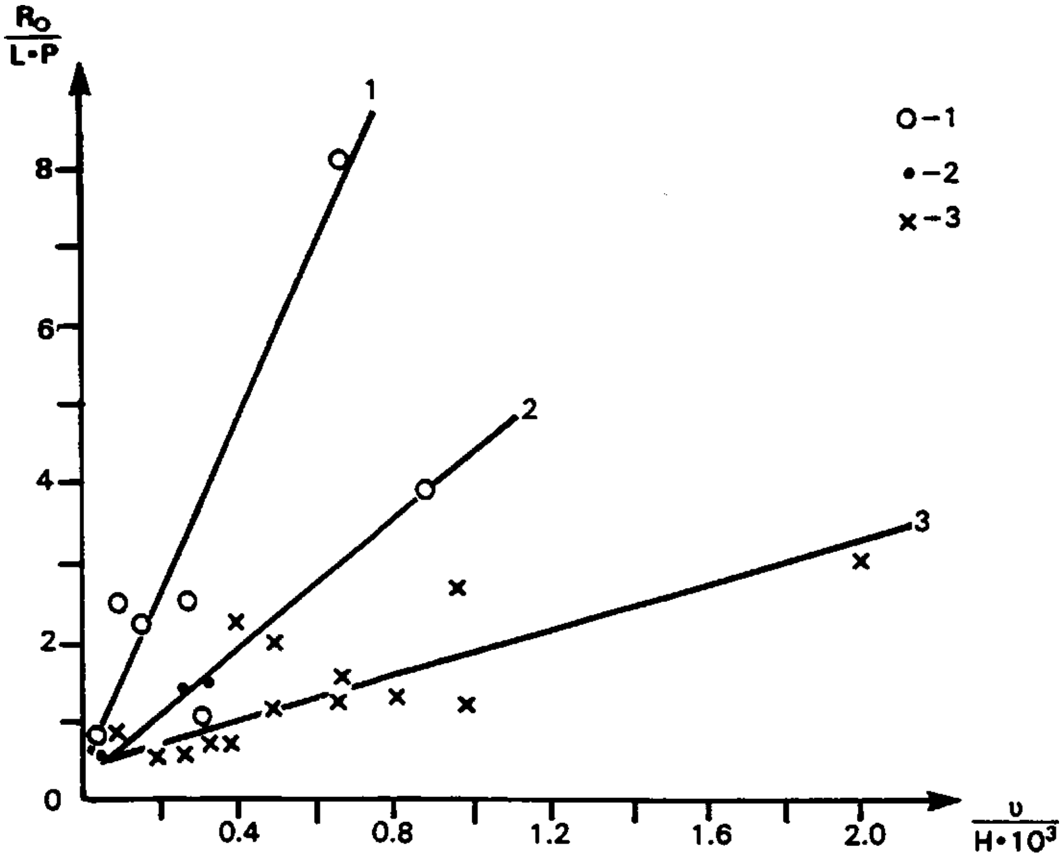


Figure **4.2.** Mean annual water supply (in billions of gallons per day) under current and hypothetical conditions for the major water resource regions of the US

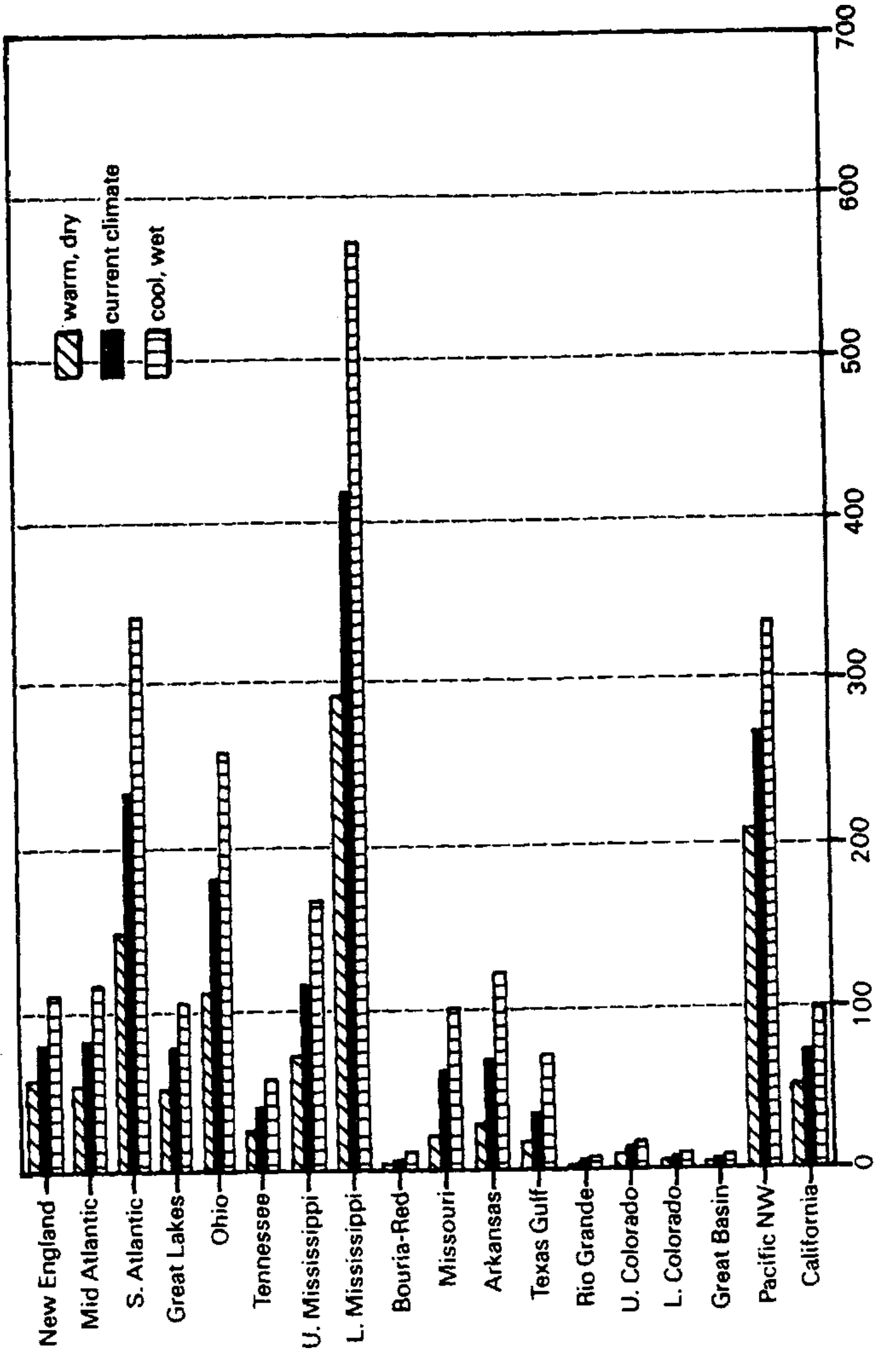
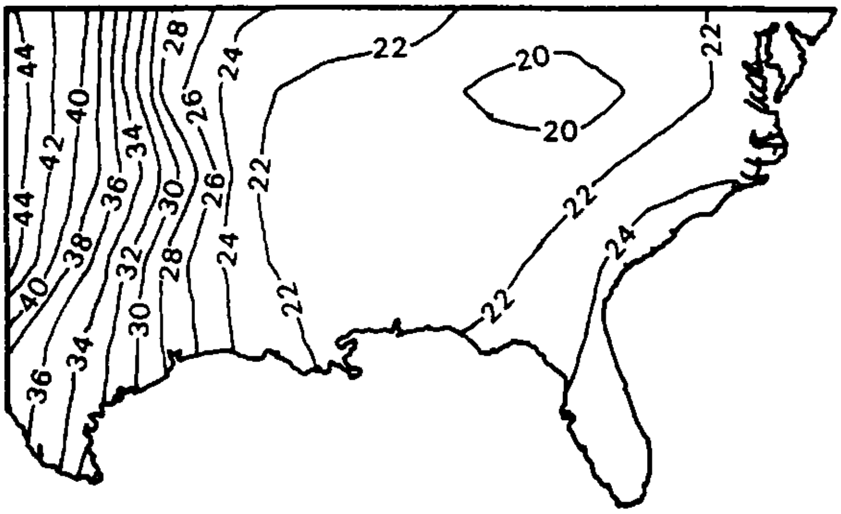
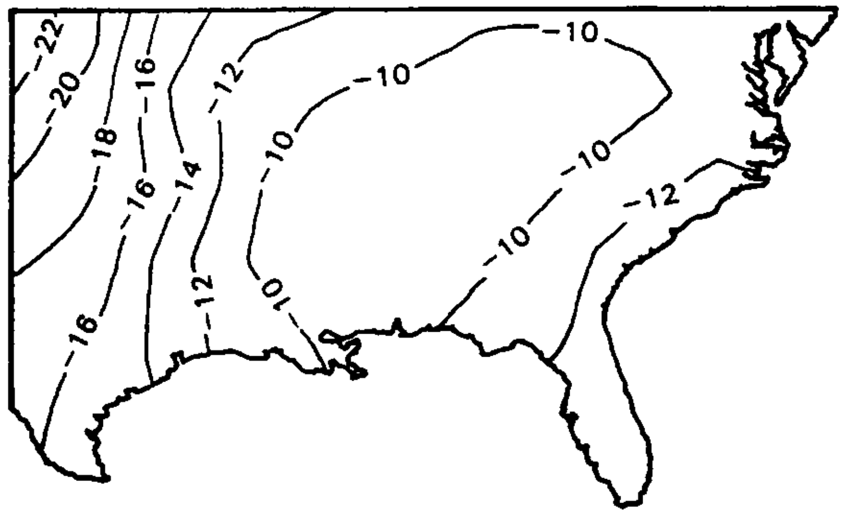


Figure 4.3. Percentage change in mean annual runoff by varying precipitation (upper) and potential évapotranspiration (lower) (Schaake, 1990)



PERCENTAGE CHANGE IN MEAN ANNUAL RUNOFF
PRECIPITATION +10%
POTENTIAL EVAPOTRANSPIRATION — NO CHANGE



PERCENTAGE CHANGE IN MEAN ANNUAL RUNOFF
PRECIPITATION — NO CHANGE
POTENTIAL EVAPOTRANSPIRATION +10%

Figure 4.4. Change in annual runoff (in centimetres) for the USSR as estimated for a warming of 1°

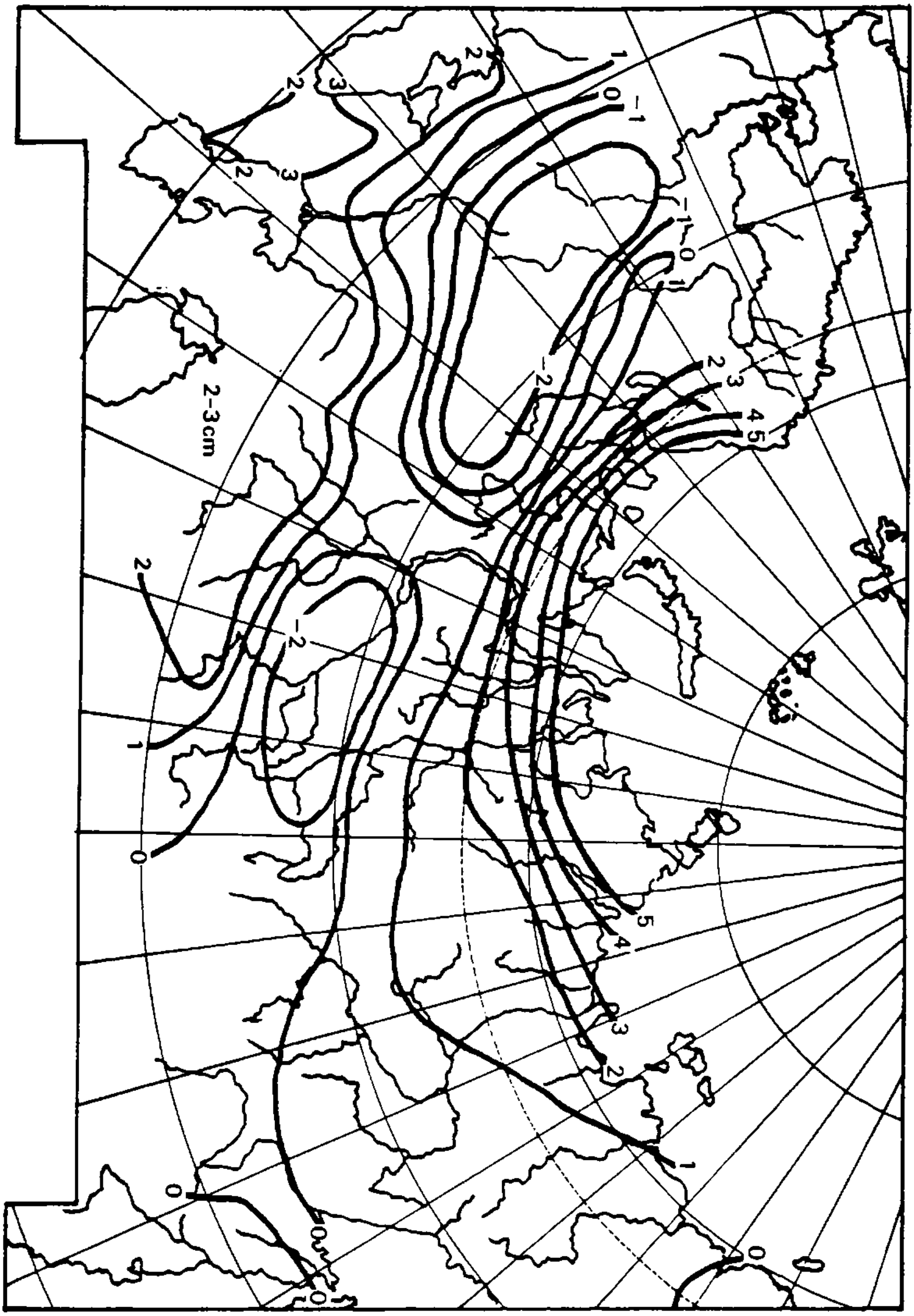


Figure 4.5. Estimated percentage change in annual runoff under climate change scenario SI (2030-2050) in New Zealand (Griffiths, 1988)

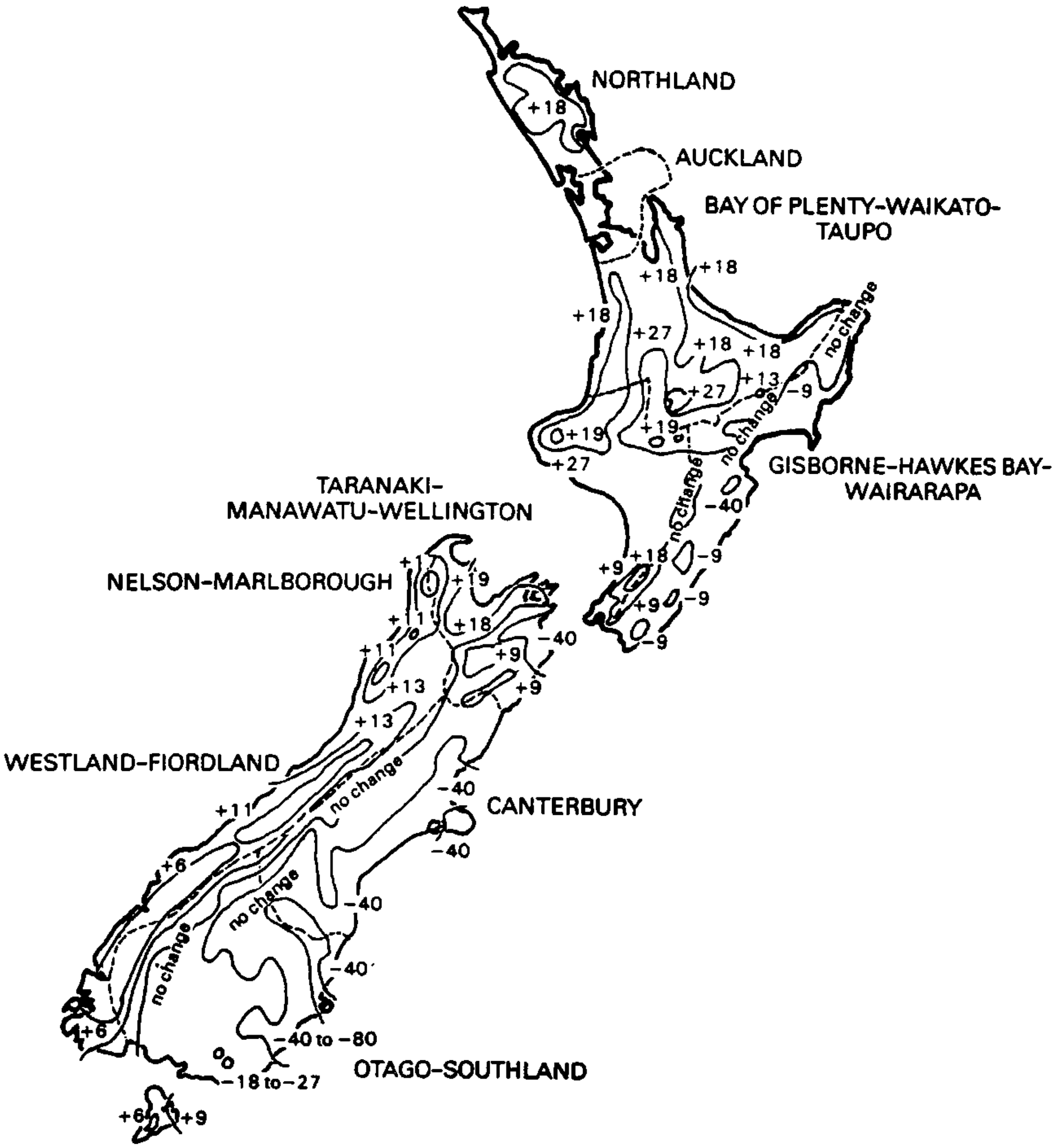


Figure 4.6. The Great Lakes drainage area (Smith and Tirpak, 1989)

Figure 4.7. GCM-estimated average seasonal and annual changes in temperature (upper) and precipitation (lower) for the grid cells encompassing the Great Lakes ($2 \times CO_2$ minus $1 \times CO_2$) (Smith and Tirpak, 1989)

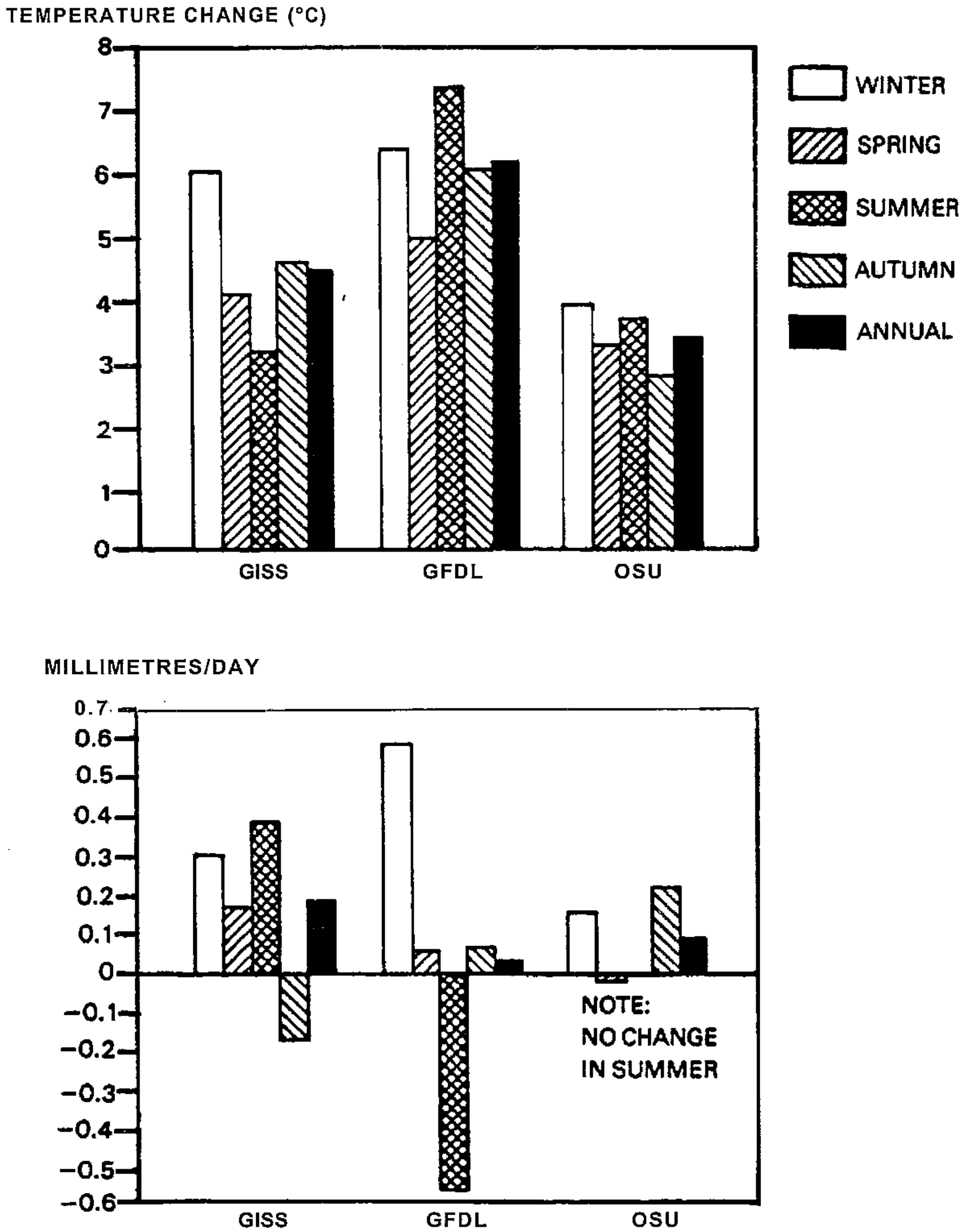


Figure 4.8. Comparison of actual levels of Lake Erie for the period 1900-80 with estimated levels for the same period generated by superimposing onto the actual conditions a warmer climate and a warmer climate with future levels of consumptive use (Sanderson, 1989)

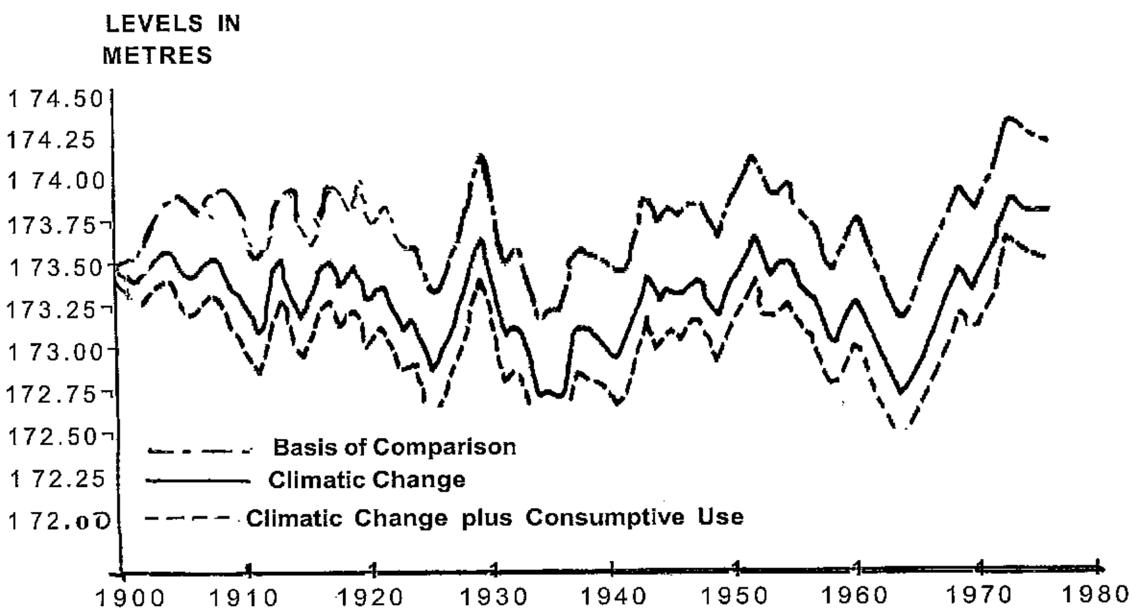


Figure 4.9. Estimated levels of the Caspian Sea, 1989-2020 under varying climate change scenarios: 1 - stationary climate with man's impact, 2 - model-based anthropogenic change in climate including man's impact, 3 - map-based anthropogenic change in climate including man's impact, 46 - observed lake level variations before 1988

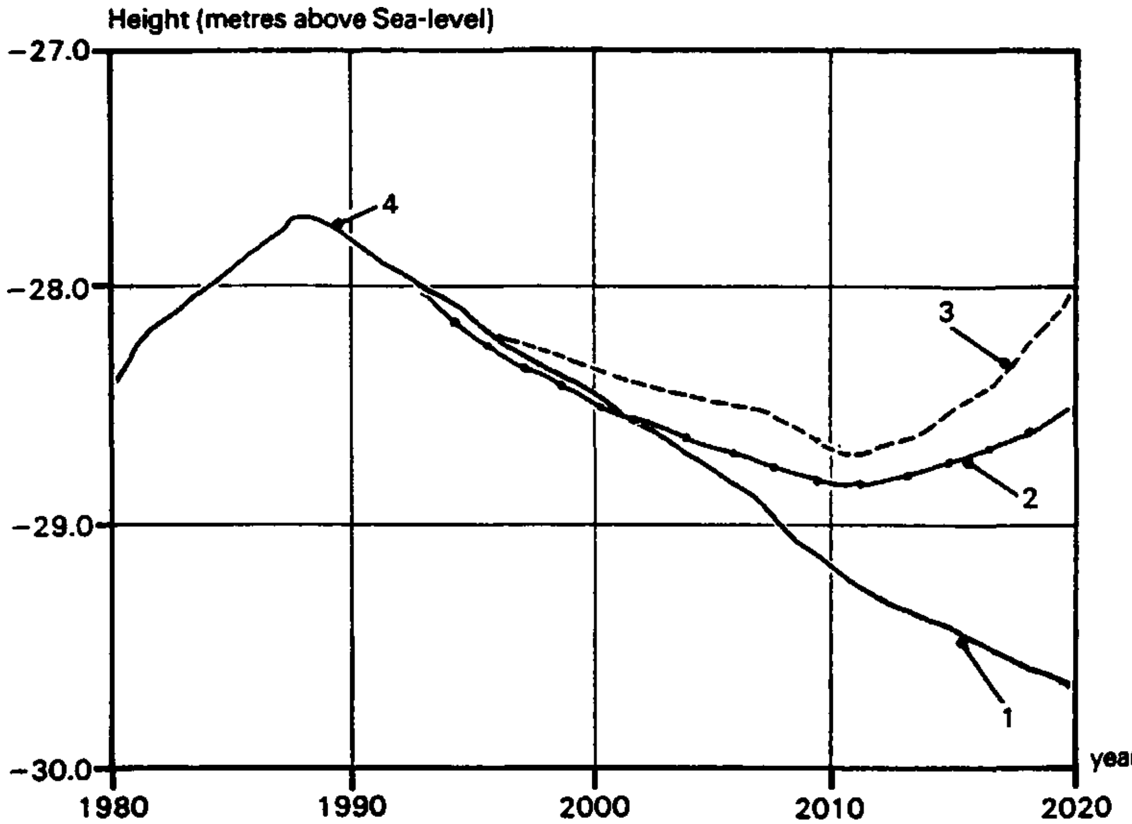


Figure 4.10. Plot of normalised annual average rainfall (solid line) and 3-year moving average (dashed line) for the town of Saint Louis, Senegal (upper, 1932-1982) and Oran es Senia, Algeria (lower, 1927-1987)

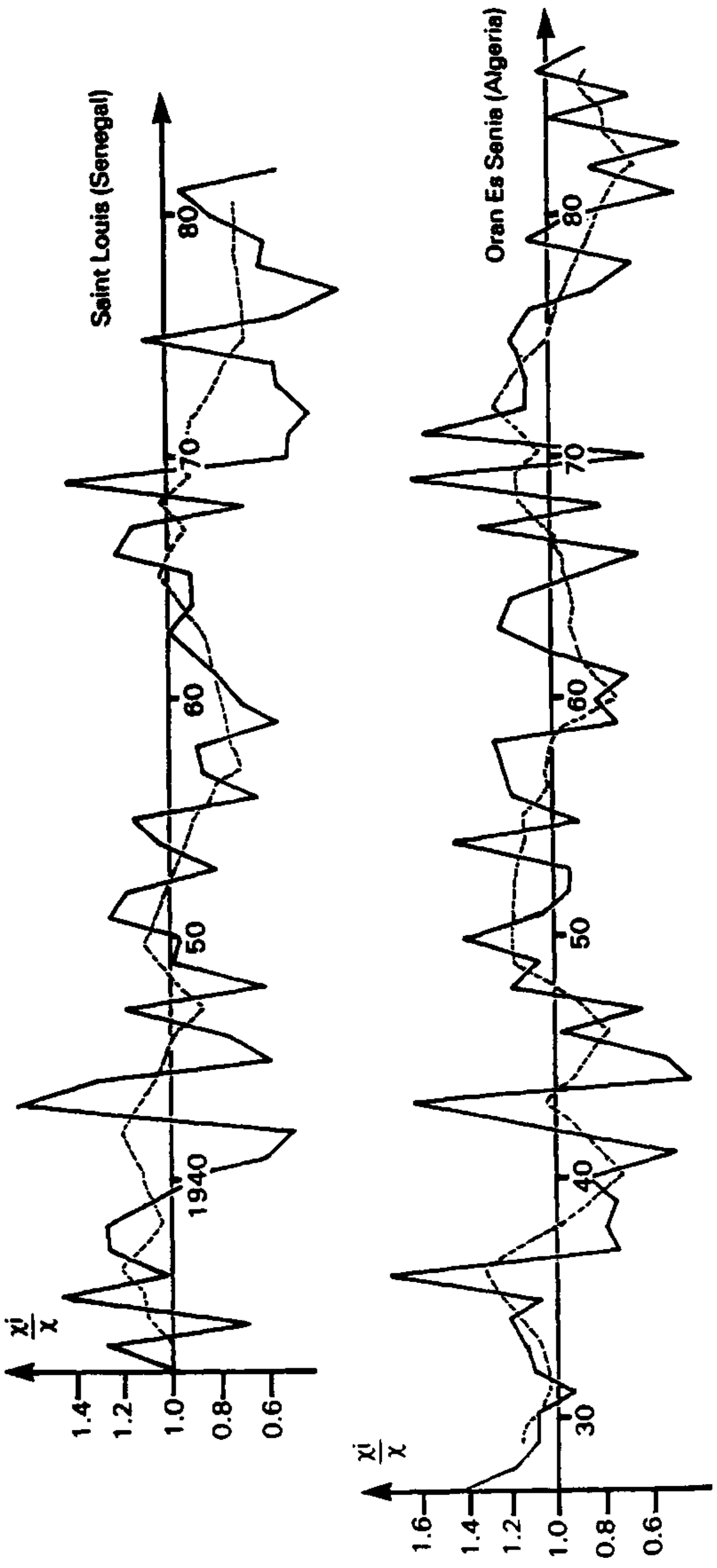


Figure 4.11. Drainage area of the South Platte River basin (US Army Corps of Engineers, 1977)

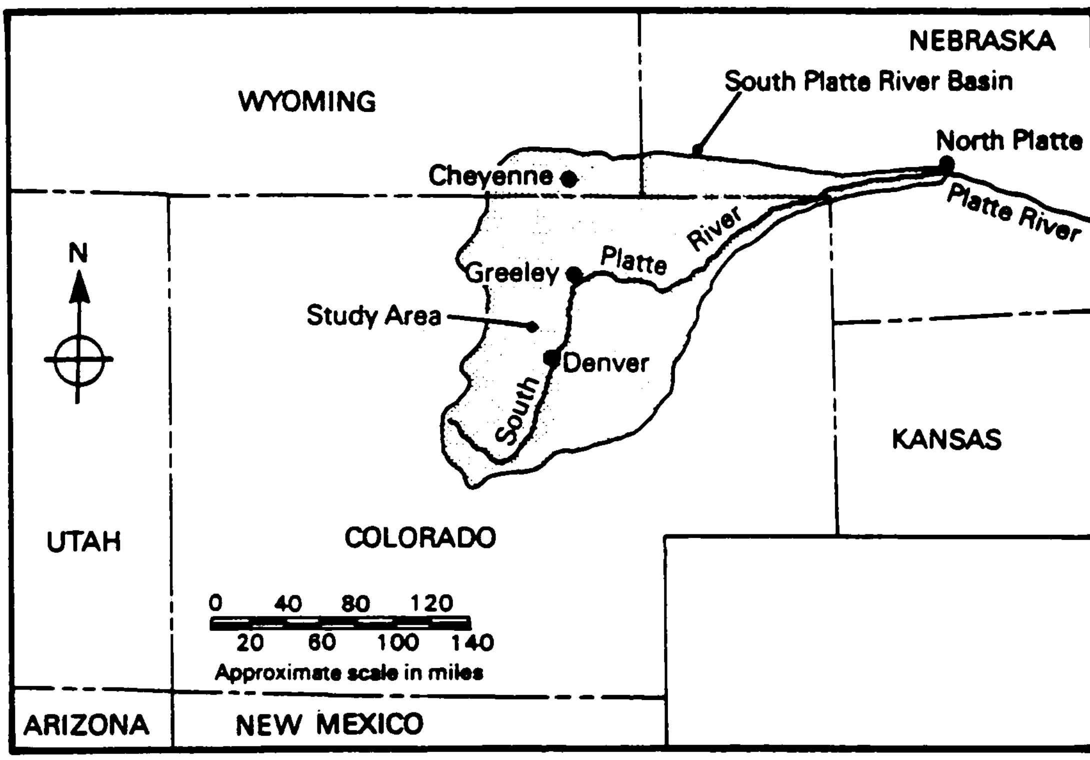


Figure 4.12. GCM-estimated average seasonal and annual changes **in** temperature (upper) and precipitation (lower) for the grid cells encompassing the Great Plains (2 x CO_2 minus **1** x CO_2) (Smith and Tirpak, 1989)

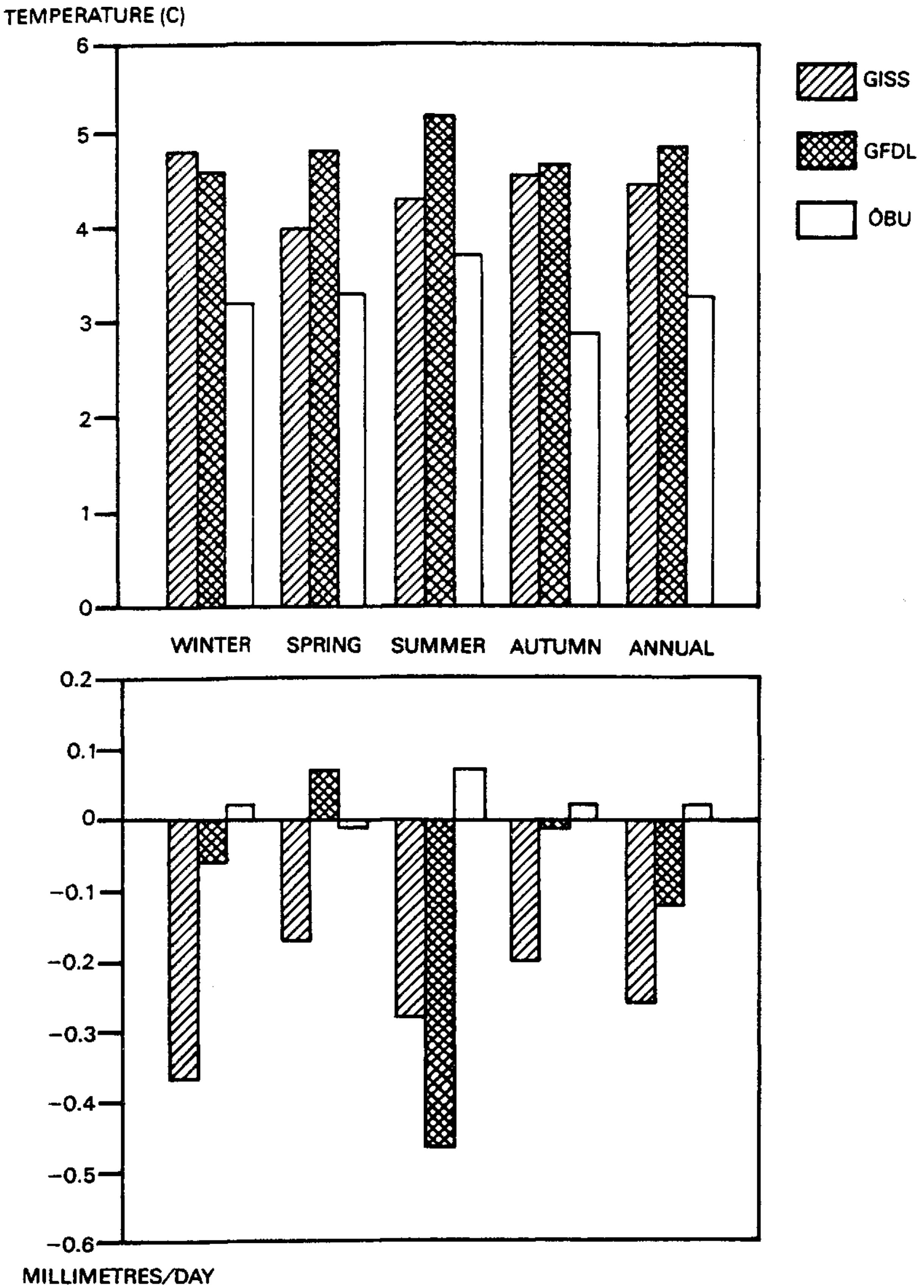


Figure 4.13. The drainage area of the Murray-Darling basin in southeastern Australia (Stewart, 1989)

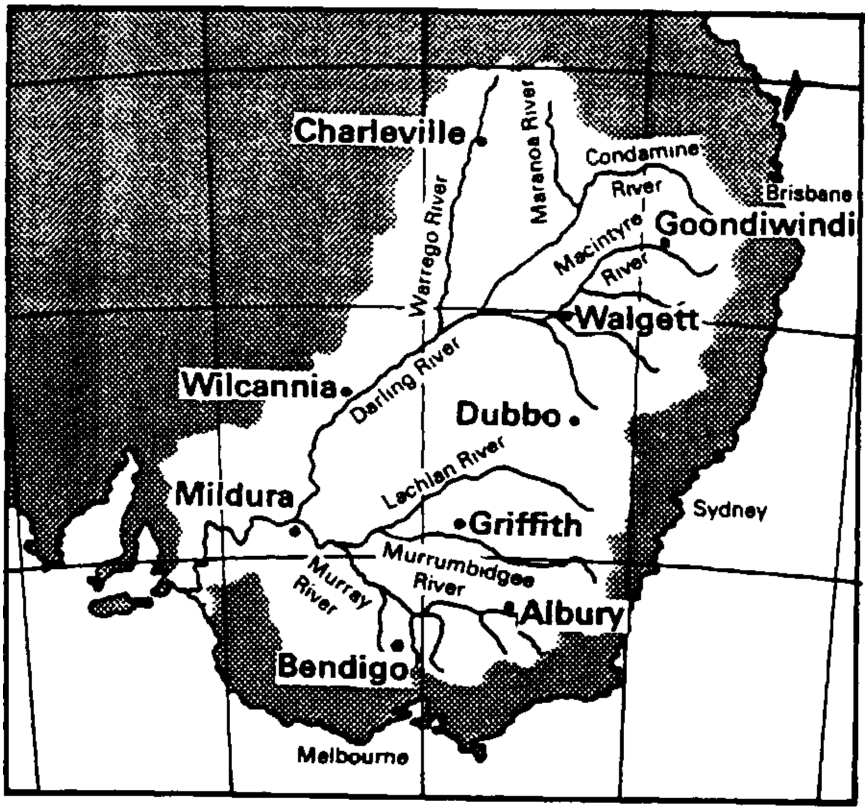
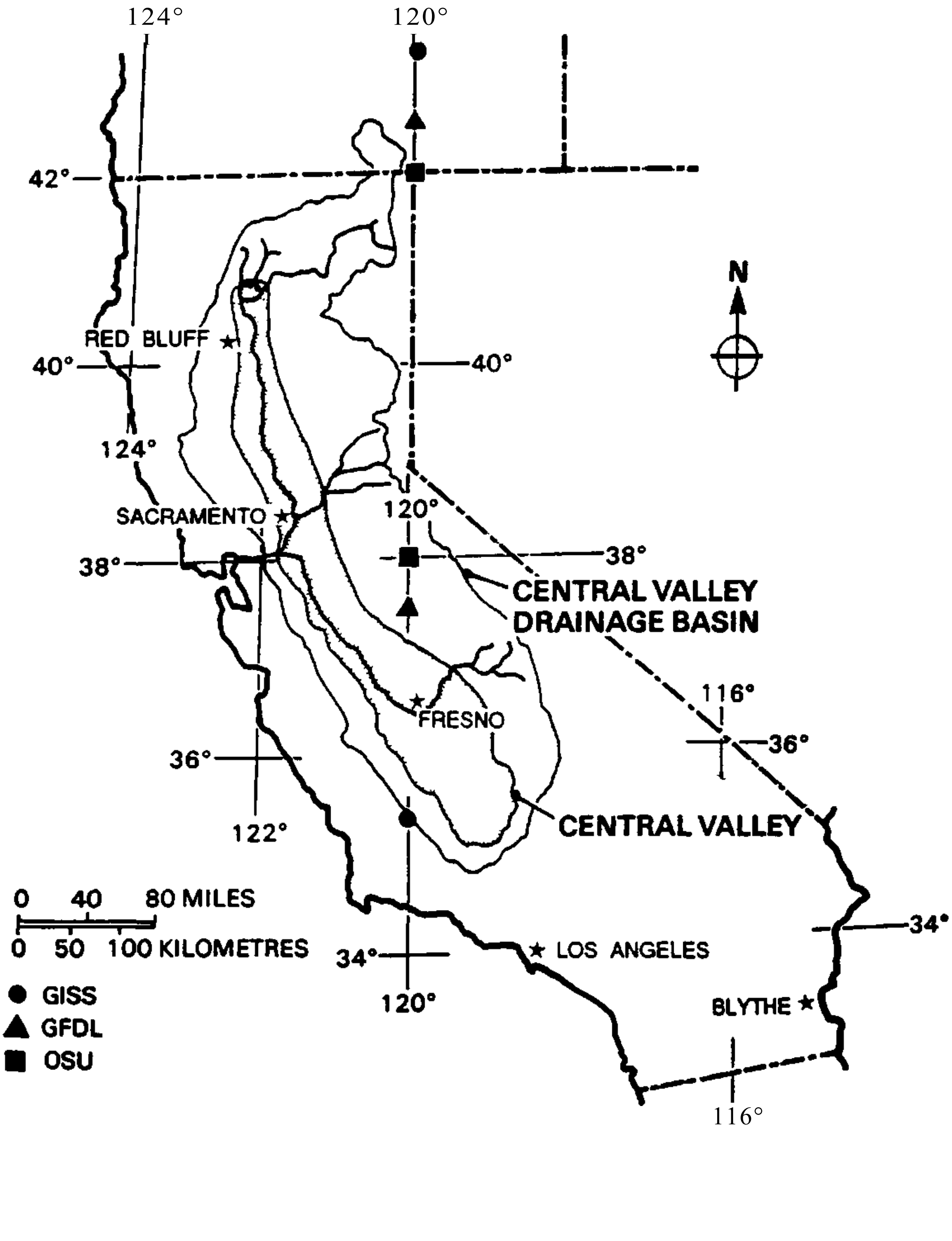


Figure 4.14. The Central Valley (shaded) and Central Valley Basin of California. Symbols refer to locations of the GISS, GFDL and OSU GCM gridpoints (Smith and Tirpak, 1989)



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