Environment Canada
Inland Waters Directorate
Water Planning and Management Branch

ASSESSING THE EFFECT OF CLIMATE CHANGE ON THE OPERATION OF A WATER-SUPPLY RESERVOIR

VOLUME I - REPORT

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ABSTRACT

This study defines a framework for assessing the impact of climate change on the operation of a water-supply reservoir. The evaporation/evapotranspiration component of this framework is studied in detail using the so-called complementary relationship models developed by Morton. The relative influence of several hydrological and climatological parameters on evaporation and evapotranspiration is assessed. Two methods of estimating runoff under 2 X CO_2 conditions of climate change are tested and evaluated. Finally, the problem of reservoir operation under 2 X CO_2-induced hydrological changes is analysed and recommendations considered necessary for further work on this subject are provided.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

The concensus of the scientific community predicts that human-induced global warming will become significant before the middle of the next century. The warming effect is likely to cause changes in precipitation and evaporation, two principal elements of the hydrologic cycle. The time scale of the expected climate change is similar to that required for planning large-scale water management activities. Planning and management of water systems has traditionally been based on the assumption of unchanging climate. Therefore, there exists an urgent need to assess the effect of the climate change factor on water management systems, particularly in regions of marginal water supply.

1.1 Study Objectives

The recognized need to assess the possible impacts of climate change in terms of water planning and management provided the impetus for this study. Another incentive is the fact that as a research discipline, the assessment of climate change impacts on physical and human systems is currently at a very rudimentary level. Considerable basic developmental effort is required to establish appropriate research methods and to amass relevent information. Accordingly, the objectives of this study are: 1) to design a research framework; 2) to develop an appropriate database; and 3) to apply the results to assessing the possible impacts of climate change scenarios on the operation of a water-supply reservoir. The location chosen as the test case for the study is the Lake Diefenbaker reservoir in the South Saskatchewan River drainage basin.

1.2 Study Approach

The subject of climate change and its impact on water resources can be evaluated at two levels:

- general characteristics of climate change, and

- specific water supply implications at a regional scale.

The general level includes: 1) observations and evidence of climate change and a review of this evidence; 2) an explanation of the causes of climate change, natural and artificial, including an evaluation of their relative importance; and 3) description through modelling of climate change. The specific water supply, or water resources, level: 1) works with quantitative inputs from the general level (i.e. with estimates of changes of major climatic variables); 2) attempts to simulate the hydrological regime change corresponding to the expected change in climatic variables; and 3) evaluates the performance of water resource systems for the simulated post-climate-change regime (Klemes, 1984a).

This study deals with the general level of investigation only to the degree of briefly describing the evidence of human-induced climate change. It concentrates on several selected questions belonging to topics 1 and 2 of the water supply level of the climate change problem, with only a very brief excursion into topic 3, as described above. In other words, it works mostly with estimates of changes in climatic variables and with directly related changes of the hydrological regime.

Topic 1 of the water resources level of climate change, changes of climatic variables, necessarily includes all major climatic characteristics such as air temperature, precipitation, evaporation and evapotranspiration, humidity and others. Since these parameters interact and their variation in nature involves complicated interrelated physical processes, it is extremely difficult to study them together in all their complexity. The approach adopted in this study is to investigate one climatic variable in depth and to include others only in simplified form or, if necessary, to the degree needed to assess their impact on that one selected variable.

The variable selected for special study should satisfy two basic conditions. First, the selected variable should be one of the primary climatological parameters which causes direct and measurable impacts on water resources. Second, a modelling tool which enables adequate description of this variable should be available. This tool should be sufficiently tested and geographically transferable. It should at least show promise of climatological transferability. A model is geographically transferable when, after being developed and tested for one geographical area, yields good results in a different location, and requires changes only of spatially-specific parameters such as longitude, latitude and altitude. Similarly, a model is climatologically transferable when, after being developed for present-day climate situations and proven to be geographically transferable, functions satisfactorily with new data and thus requires minimal to no adjustments for new situations, such as climate change scenarios. Finally, data preparation and use of the model should preferably be simple.

The climatic variable selected as the main focus of this study is evaporation/evapotranspiration. (Hereinafter, the term evapotranspiration will also mean evaporation, unless otherwise specified.) The importance of the ability to describe changes in evapotranspiration caused by eventual climate change is self-evident. This modelling capability is especially desirable for application to arid and semi-arid areas with high levels of evapotranspiration and marginal availability of water. From among the several modelling tools that are readily available, the models developed at National Hydrology Research Institute by Dr. F.I. Morton were selected. Development of the Complementary Relationship Areal Evapotranspiration (CRAE) and the Complementary Relationship Lake Evaporation (CRLE) models by Morton over the past twenty or so years is considered by some experts as one of the corner stones of modern hydrology. The models are physically based, extensively tested and deal very well with system aspects of the problem; namely, with the interrelation of variables, feedbacks, and the hierarchy of the natural system. The models are fully geographically transferable and show promise, especially the CRLE model, of climatological transferability (Morton, personal communication). Data preparation and application of the models are quite simple. Literature related to these and other evaporation/evapotranspiration models is disucssed in Chapter 2.

On the other hand, existing models describing the greenhouse warming effect on primary climatological variables such as precipitation and temperature are rather new and problematic, particularly when applying climate change scenarios to regional impacts studies. The main problem with these climatological models, which are usually called General Circulation Models (GCMs), is the relatively coarse spatial resolution of the results. Typically, the outputs of GCM climate change scenarios are produced for a global scale. GCM data points of the so-called grid point networks are defined geographically by longitude and latitude with no regard to functional and spatial characteristics of hydrological, agricultural or other specific systems. Results of these models are used in this study only as one type of input, without discussion or evaluation. Other types of simulated data describing precipitation and temperature changes could serve the same purpose, without risk of being considered valid, definitive answers.

The above considerations are not meant to suggest that the results of GCMs are substandard, but to simply clarify that they are not tested or assessed in this study and are handled merely as one possible type of simulated data. Other related variables such as humidity, solar radiation and lake depth are evaluated only in the sense of their interaction with the selected basic variable, evapotranspiration. Runoff is estimated in this study using the basic water balance equation $R = P - E$ (runoff equals precipitation minus (actual) evapotranspiration).

1.3 Study Area

The methodology developed in this study was applied to the Lake Diefenbaker reservoir in Saskatchewan and on the contributing portion of the South Saskatchewan River Basin (Figure 1.1). The reservoir is located in the semi-arid region of the Prairies. One could assume that climate change has or will have more pronounced impact on a marginal semi-arid basin than on a more stable humid-region basin. Furthermore, Lake Diefenbaker has clearly defined, dominant input, consisting of the South Saskatchewan River inflows. Local inflows due to surface runoff range from negligible to practically non-existent. Such a water resource system is easier to analyse than other, more complicated systems. Also, the Lake Diefenbaker reservoir is extremely important for the development of intensive agriculture in the area as well as other significant activities, such as hydroelectricity and recreation. Last, but not least, recent droughts in the Prairies have confirmed both the sensitivity of water resources to climatic factors and the importance of water management to socio-economic well-being in this area.

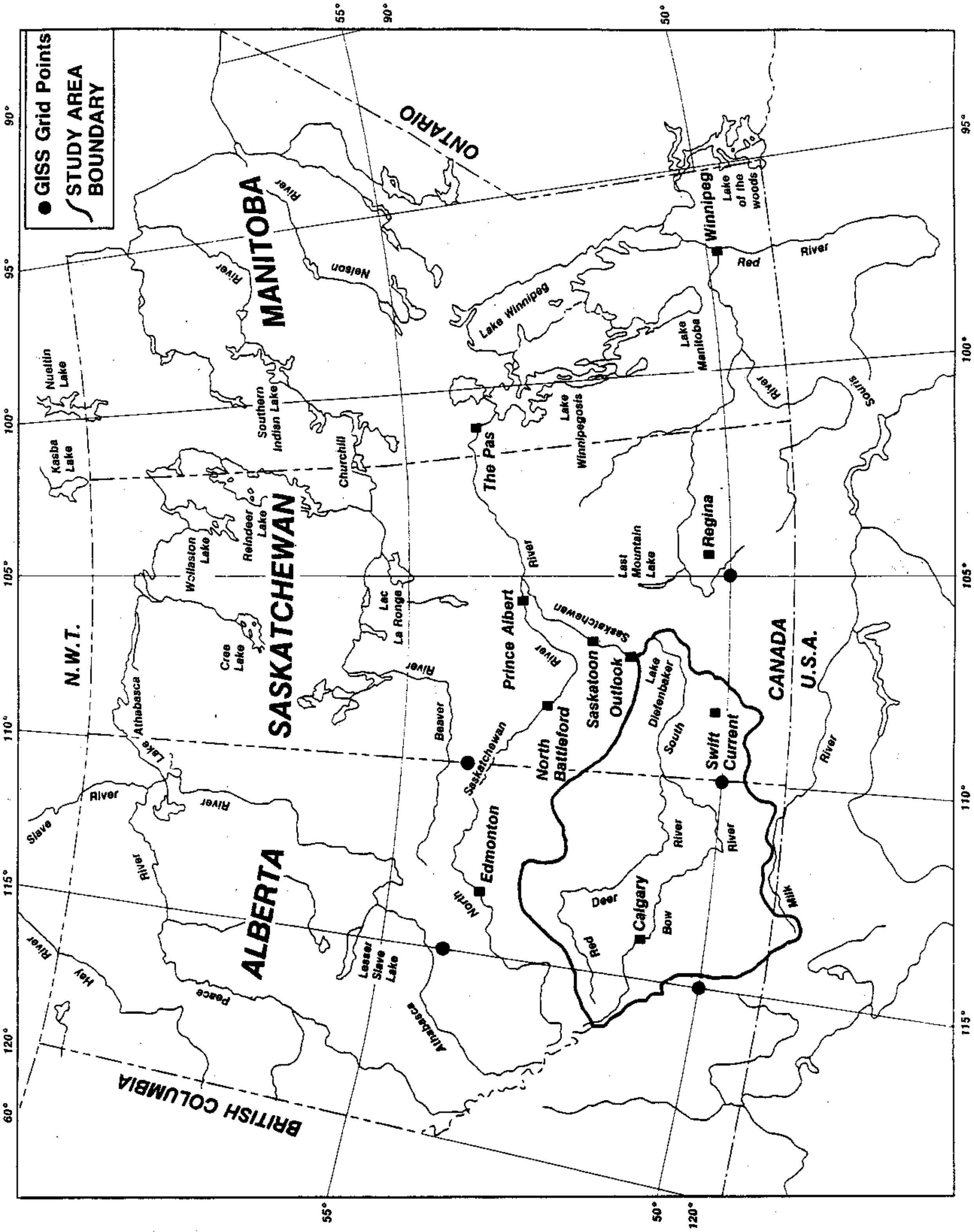

Figure 1.1 South Saskatchewan River to Lake Diefenbaker Study Area

1.4 Report Presentation

Following the Introduction, the necessary basics of assessing climate change at the general level are presented in Chapter 2 and then synthesized in Chapter 3, as part of a detailed description of the overall structure of the study. Data requirements, database organization and basic characteristics of GCM data are discussed in Chapter 4. Chapters 5 and 6 represent the bulk of the study, with Chapter 5 assessing evapotranspiration and its possible changes, and Chapter 6 working with the runoff aspect of the problem. Chapter 7 evaluates the options for assessing the influence of climate change related hydrological shifts on the Lake Diefenbaker reservoir. This reservoir is part of the South Saskatchewan River system and a more detailed evaluation of changes in reservoir operation would require an assessment of the whole system, a task which exceeds the scope of this study. Chapter 8 contains conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

Five areas of literature were reviewed. Selected literature dealing with a possibility of an unprecidented climate change in the near future (within the next 50 to 80 years) was examined. Topics of interest were: existence or nonexistence of evidence of climate change occurrence; natural and human-induced climate change; and different possible causes of human-induced climate changes. The impact of increasing carbon dioxide concentration in the atmosphere, the ability to describe and model this phenomenon, and trends in its development were studied in more detail.

Literature assessing the impact of climate change on water resource management was also reviewed. The problem of realistic simulation of streamflow series for a changed climate consists of two separate components: simulation of a time series of the primary climatic variables, such as precipitation, radiation, humidity, evaporation and evapotranspiration, and then transformation of this time series into streamflow series. Regarding time series simulation, only literature dealing with evaporation and evapotranspiration was studied. Simulation of precipitation and temperature time series was not attempted and instead, the results of two General Circulation Models were used as inputs. The very limited time scope of this study did not enable time series data simulation; however, consideration of inclusion in future work would be worthwhile. Regarding time series transformation, most of the studied literature dealt with a simulation of the hydrological regime created by hypothetical climate change scenarios and with an evaluation of performance characteristics of water resource systems for simulated post-climate-change hydrological regimes.

Also reviewed were papers on water supply implications at a regional scale. Relevant literature addressing evaporation and evapotranspiration was studied in more detail, because of the importance of these parameters for this study. Finally, hydrological characteristics of the South Saskatchewan River at Lake Diefenbaker and operational rules for Lake Diefenbaker were reviewed. The results of the literature review are presented in the sections that follow.

2.1 Climate Change in General

Basic questions of climate change are discussed by Rosenberg (1987). He provides a definition and the basic characteristics of climate, reviews evidence of global climate change and describes workings of the climate systems including radiation and energy balance. The article also addresses the effects of human activity on climate, especially regarding the "greenhouse effect" as caused by certain atmospheric trace gases, in particular, the concentration of atmospheric carbon dioxide (CO_2). Figure 2.1 illustrates apparently conclusive evidence of the increase of global temperature which is at least partially attributable to an enhanced greenhouse warming effect.

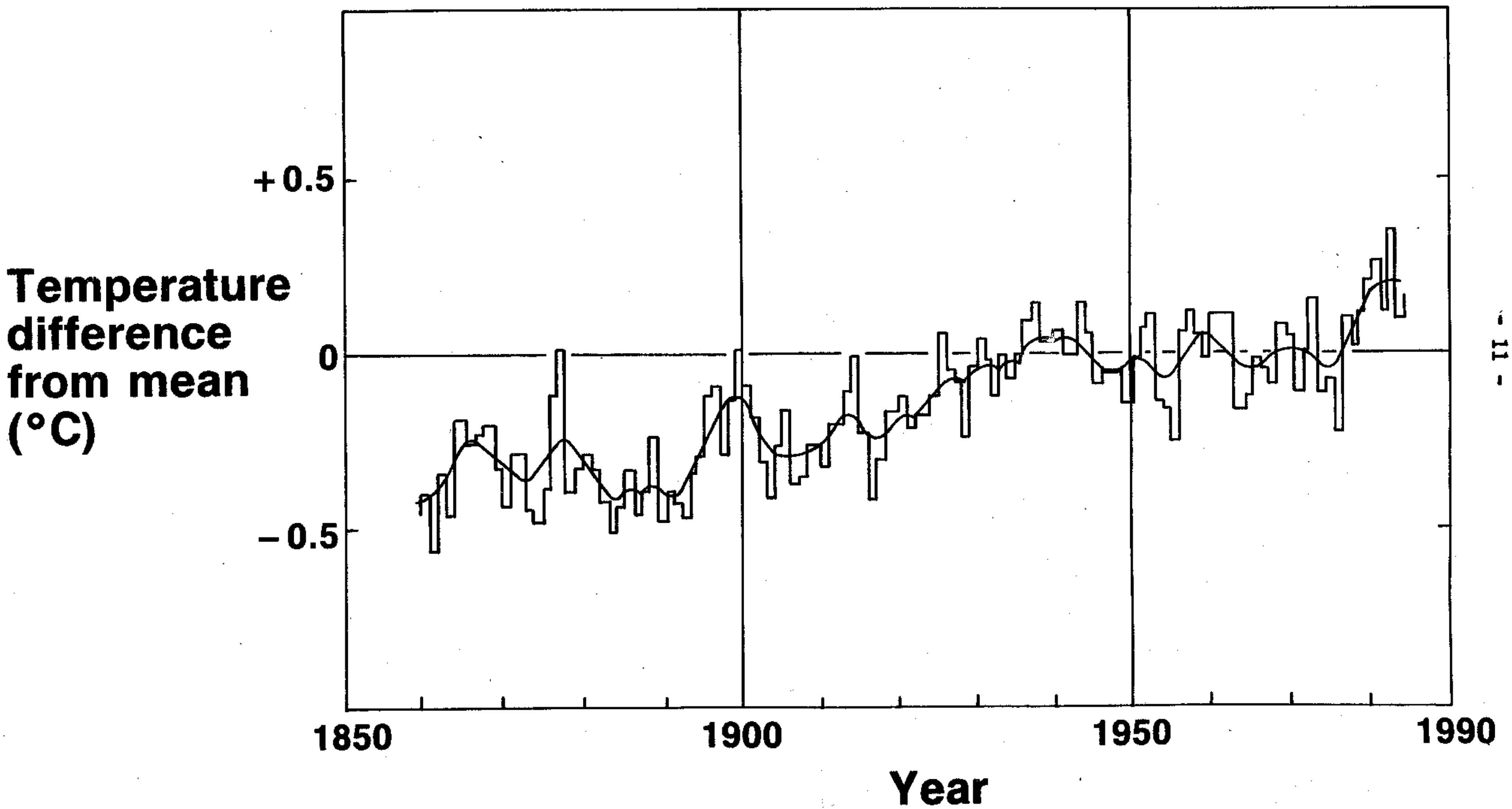

Figure 2.1 Global Annual Mean Temperature Variations Since 1861, based on Land and Marine Data.

Source: Based on figure in P.D. Jones et al., 1986.

The most important human contribution to climate change is the rapid increase of atmospheric CO_2 over the last 120 or so years. The problem is described in detail by MacCracken and Luther (1985). The document contains state-of-the-art articles that synthesize an extensive volume of research and thus represents a summary of current knowledge. In one key article, Schlesinger and Mitchell assess simplified climate models and more complex GCMs, including climate change results for zonal mean air temperature, precipitation, soil moisture and cloud cover. They also describe and compare in detail four independently developed GCMs, including the two whose results are used in this study. Three appendices of the document were reviewed as well. Appendix A by Schlesinger deals with energy balance models and radiative-corrective models. Appendix B by Luther and Cess discussed the carbon dioxide and climate change controversy. Finally, Hall in Appendix C reviews the reliability of climate model projections, in particular the problem of model validation and sensitivity analysis.

2.2 Climate Change Impacts on Water Resources

An important contribution to this area of study is the research carried out under Project IV.1 within the World Climate Program (Water) of the World Meteorological Organization. A summary of this project is provided by Klemes (1985). The report recommends that the assessment of the possible impacts of climate change on water resources be divided into three distinct steps:

1) a quantitative estimate of changes in the long-term indices of the major climatic variables such as air temperature, precipitation, evapotranspiration, snow cover, runoff;

2) a simulation of the hydrological regime corresponding to these changes; and

3) an evaluation of performance characteristics and design parameters of water resources systems for the simulated post-climate-change hydrological regime.

In a paper appended to the WMO report, Klemes and Nemec (1983) summarize the main difficulties connected with obtaining an accurate assessment of climate change impacts on water resource development:

1) uncertainty in quantitative estimates of change of primary climate variables which is mainly due to our imperfect understanding of climate dynamics;

2) the limited capability of current hydrological models which is a consequence of our imperfect understanding of hydrological mechanisms;

3) shortness of historic records which hinders the identification of the correct structure (and parameters) of the streamflow stochastic process which constitutes the basis of any assessment of a statistical significance of climate change impact;

4) inadequacy of current statistical methods for making useful inferences on the basis of small samples;

5) difficulties with information transfer form proxy variables in the absence of solid understanding of dynamic relationships between them and the primary variables, namely streamflow.

The authors call for advancement and refinement of the present state of knowledge and available analytical tools with regard to climate change modelling and impact assessment in order to provide a useful contribution to future-focused water resource planning and development.

The proceedings of an international symposium on "The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources" (Solomon et al., 1987) contain several papers of basic importance. Askew places the consideration of the impact of climate on water resources in a broad context. He investigates interrelations between climate, hydrology, water-resource systems and society. Clark discusses the effects of climate change on hydrologic design criteria for flood events. Henderson-Sellers describes in a very interesting way the impact of increasing atmospheric carbon dioxide concentrations upon reservoir water quality.

Probst and Tardy (1987) investigated long range streamflow and runoff fluctuations at the regional, continental and world scales using the records since the beginning of this century for fifty major rivers. The authors identified the so-called "great hydroclimatic periods" that have affected the various drainage basins. They found good correspondence between the global temperature fluctuation curves and the world runoff fluctuation curve, with the basic relationships being "hot and wet" and "cold and dry". Global runoff increased about 3% as an average between 1910 and 1975, resulting from above average continental runoff increases in the Americas and Africa. The authors concluded that since the beginning of this century, the world climate has been getting hotter and wetter, which corresponds with the global climate simulations of general circulation models.

A general overview of possible climate change impacts on water resources, from a Canadian perspective, is provided by Ripley (Healey and Wallace, eds., 1987). He describes climates of the past, discusses in more detail the natural and artificial factors related to climate change, and provides a description of the current approach to climatic modelling. The author also presents a rough estimate of impacts of climate change on runoff in the major drainage basins of Canada. His water balance calculations project increases in mean annual runoff for all major drainage regions in Canada. Ripley concludes by encouraging continued climate change research, despite lingering uncertainties, so as to better understand the likely impacts on water resource systems and to identify sufficiently in advance options for effective societal response.

2.3 Climate Change Implications for Water Supplies at a Regional Scale

The amount of available literature in this area is still very limited. The material reviewed indicates that alterations in regional hydrologic cycles and changes in regional water availability are poorly understood consequences of global climate changes. Beran (1986) summarises the impact of a future climate change on water resources on both general and regional scale levels. He describes methods and models that have already been used to forecast the effect of climatic change on the availability of water for human consumption, irrigation, power production, effluent dilution and navigation. Beran divides the assessment of the climate change impact on water resources into two steps: the first one concerns impact on hydrological variables only, while the second deals with changes of the exploitable fraction of the runoff.

An important article by Gleick (1986) provides a conceptual framework, an empirical overview and more detailed information on the subject. Gleick suggests that the basic water balance model is one of the more useful tools for identifying the regional hydrologic consequences of climate change. The application of future global climate scenarios to regional impact studies is addressed in Cohen (1988). The author discusses methodological concerns, such as mismatch of scales and interpolation problems, and uses Canadian research experiences, including a Saskatchewan River study, as coping examples. In the same volume, Lawford (1988) reviews some of the main knowledge gaps present in the analysis of climate change and its impact on water resources. The areas requiring enhanced research effort include modelling climatic change and assessing the impacts of climate change and variability on water resources. Specific opportunities for climate-water research are discussed with reference to western Canada.

2.4 Evaporation and Evapotranspiration

There exists a large volume of literature on the subject of evaporation and evapotranspiration. The report for a Canadian workshop on "Evaporation and Evapotranspiration Processes" (Eley, 1988) recommends further development of practical modelling tools, emphasizing refinement of proven models. The results of a study that compares different methods for calculating potential evpotranspiration (Grace and Quick, 1988) are interesting since in practice these results are frequently used to estimate actual evapotranspiration. The tests, which were conducted in a Canadian, semi-arid prairie setting, revealed large discrepancies among the various results and indicated a need to develop and apply models that more correctly simulate real conditions of the study area.

The preceeding review suggests that the so-called "conventional conceptual" techniques used to estimate evaporation and evapotranspiration, particularly those used in current watershed models, are based on assumptions that do not reflect reality. From this perspective, papers by Morton (see References) represent the dominant contribution. The "complementary relationship" method of evaporation and evapotranspiration modelling is considered by some experts to be superior to the conventional methods. Indications are that the CRAE and CRLE models developed by Morton are experiencing increasing recognition. The Alberta Department of Environment has routinely used these models for several years (Holecek, 1982). Parts of the complementary theory were tested by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia (Byrne, Drenin and Diggle, 1988). The International Institute for Applied System Analysis (IIASA) proposed the modification of Morton's model to obtain estimates of average areal evapotranspiration (Kovacs, 1987).

2.5 Characteristics of the South Saskatchewan River and Lake Diefenbaker

Literature concerning the operation of the reservoir at Lake Diefenbaker and the role of the South Saskatchewan River was reviewed. A report prepared by the SNC Group (1987) for the Saskatchewan Water Corporation describes general characteristics of the lake, types of water use, expected development, water-use demands, and reservoir operation constraints. It also contains a simulation of the water resource system for the Saskatchewan River. The report published by Inland Waters Directorate of Environment Canada (1987) assesses four basic scenarios of development for a 'constant' climate using its Water Use Analysis Model. The results provide a detailed analysis of changes in rule curves and operating constraints for Lake Diefenbaker as a result of these hypothetical scenarios. The work by Cohen et al. (1988) deals with the same river basin chosen for this study, but uses a much larger part of it; namely, the Saskatchewan River at The Pas, Manitoba, with a total area of 364 000 km^2. The methodology used by Cohen et al. and the study results are evaluated in more detail in Chapter 6 of this report. Finally, Hopkinson (1985) provides measured surface temperature and estimated evaporation data for the years 1972 to 1986 for Lake Diefenbaker.

CHAPTER 3

RESEARCH FRAMEWORK

3.1 Basic Methodology

This study, as conceptualized in Chapter 1, includes five main methodological components:

1) description of the general situation, which is global climate change resulting from an enhanced greenhouse effect;

2) implications for selected aspects of the water cycle, that is, for water supply on a regional scale;

3) work with a selected part of the water cycle, which in this study is evapotranspiration (and using other parts of the water cycle only as input or to study the relative influence of other parts of the water cycle on the selected one);

4) assessment of the impact of evapotranspiration changes on the water balance equation; and finally,

5) implications of changes on the operation of a water-supply reservoir.

These five research aspects will be addressed in varying degrees of detail.

3.2 Framework Structure

Figure 3.1 illustrates the interaction between the five main components of the research framework. Figures 3.2 to 3.6 schematically show the logical structure of these main components. For this study it is relevant that the part of Component 1 that produces GCM forecasts of temperature and precipitation can be used as simulated input into Component 2. Component 2 deals mainly with the selection of a suitable water resources system and influences together with Component 3, evaporation and evapotranspiration change, Component 4, runoff change modelling. Components 3 and 4 are the main parts of the study and are described in full detail in Chapters 5 and 6, respectively. Component 5 takes into consideration characteristics of the Lake Diefenbaker reservoir and deals with the one selected aspect of climate change influence on reservoir operation.

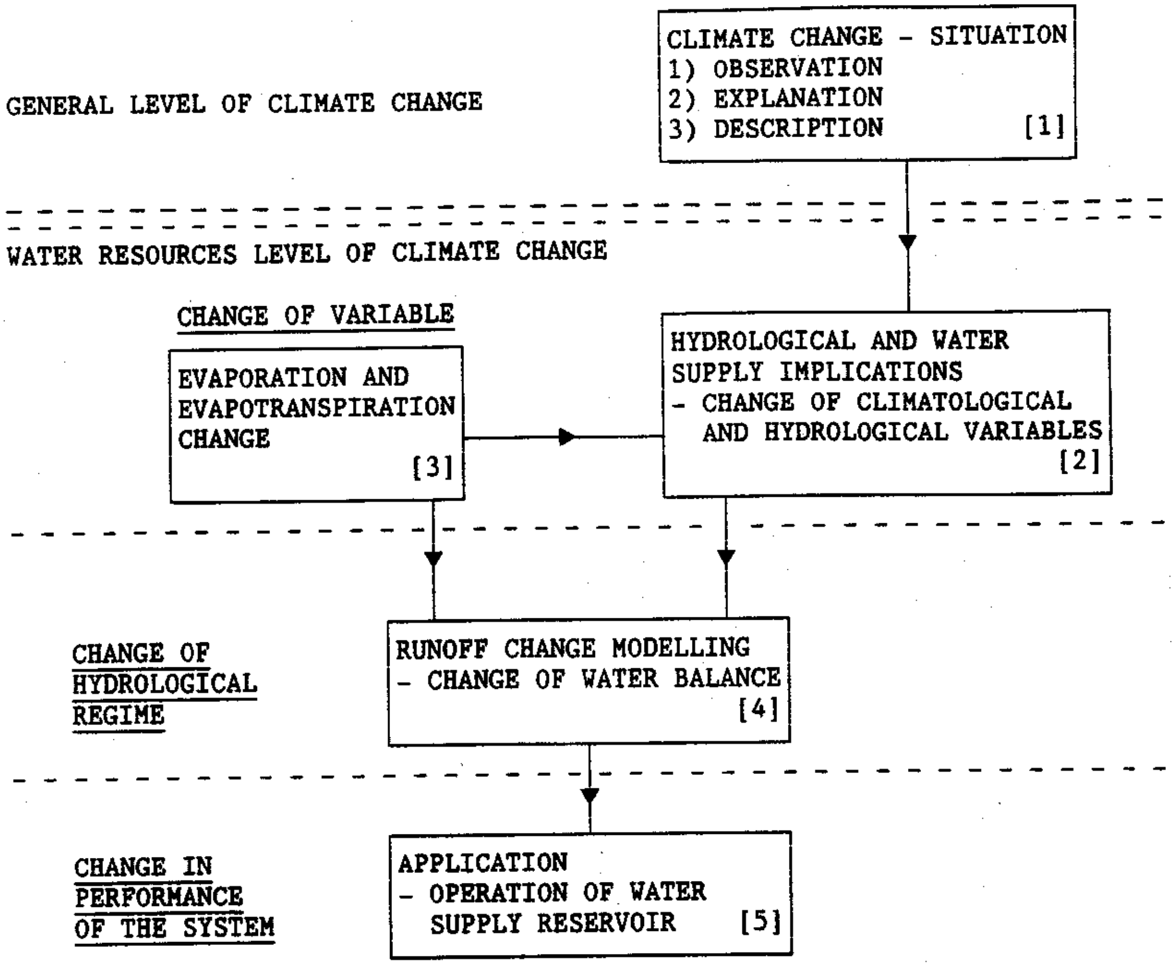

Figure 3.1 Five Main Components of the Research Framework.

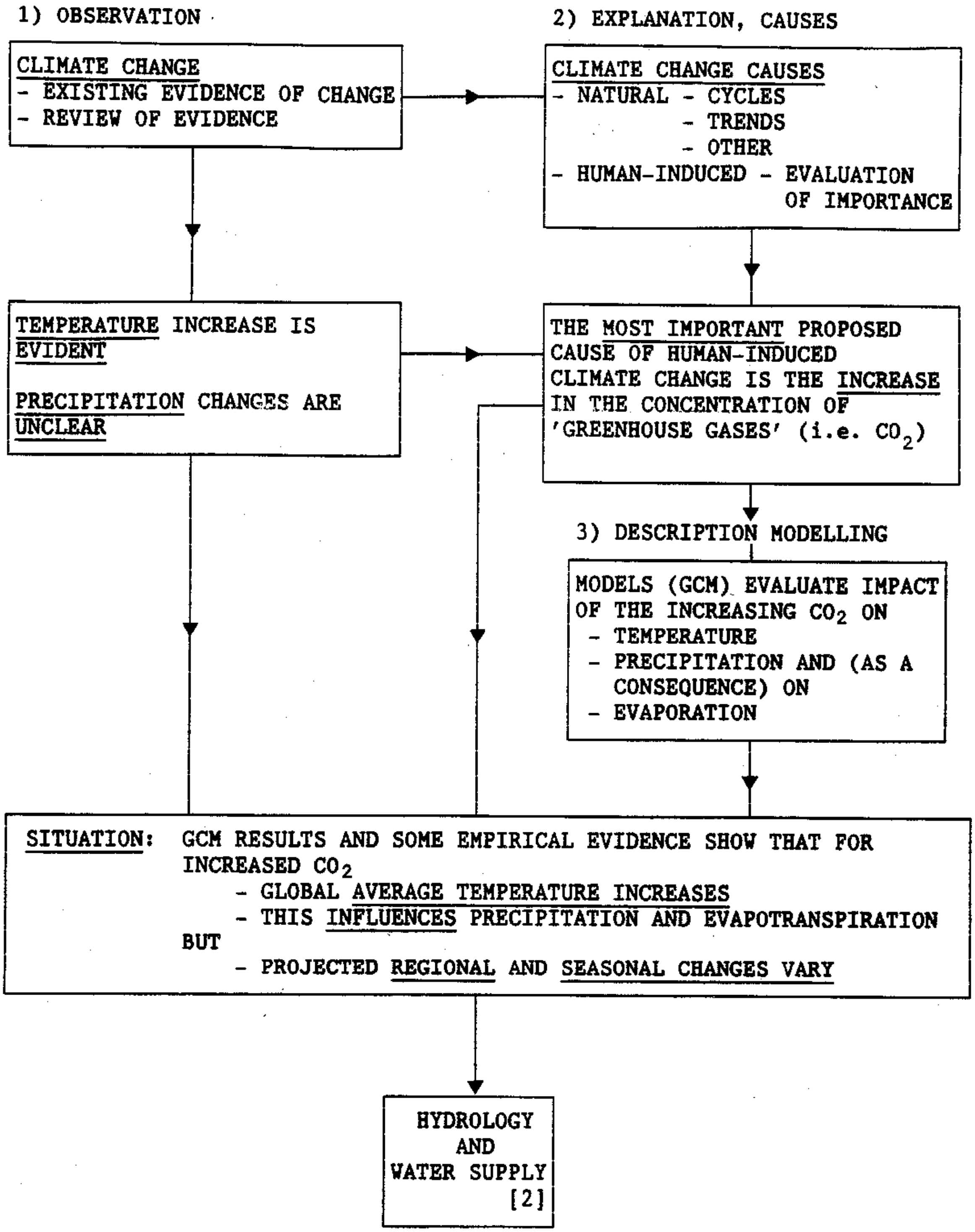

Figure 3.2 Situation Component of the Research Framework (Component [1])

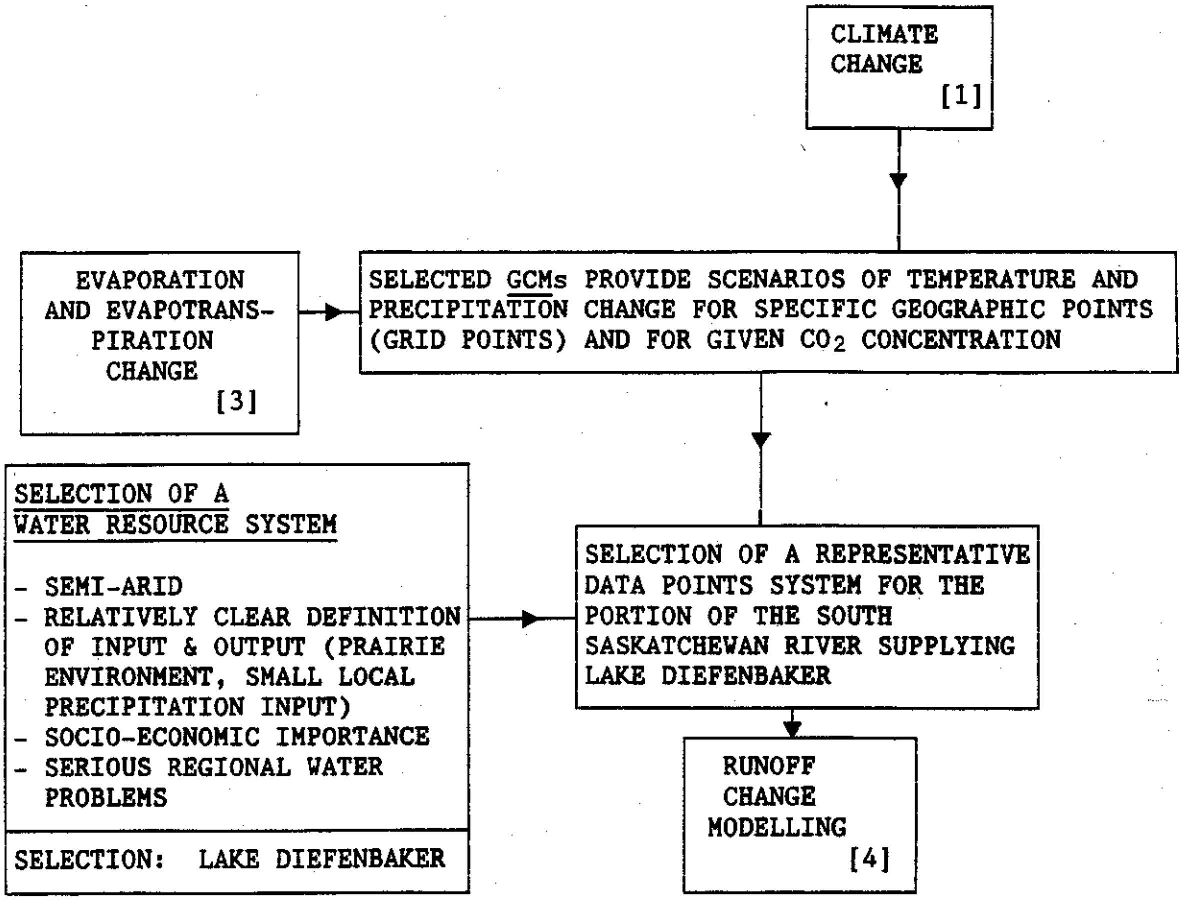

Figure 3.3. Hydrological and Water Supply Implications Component of the Research Framework (Component [2])

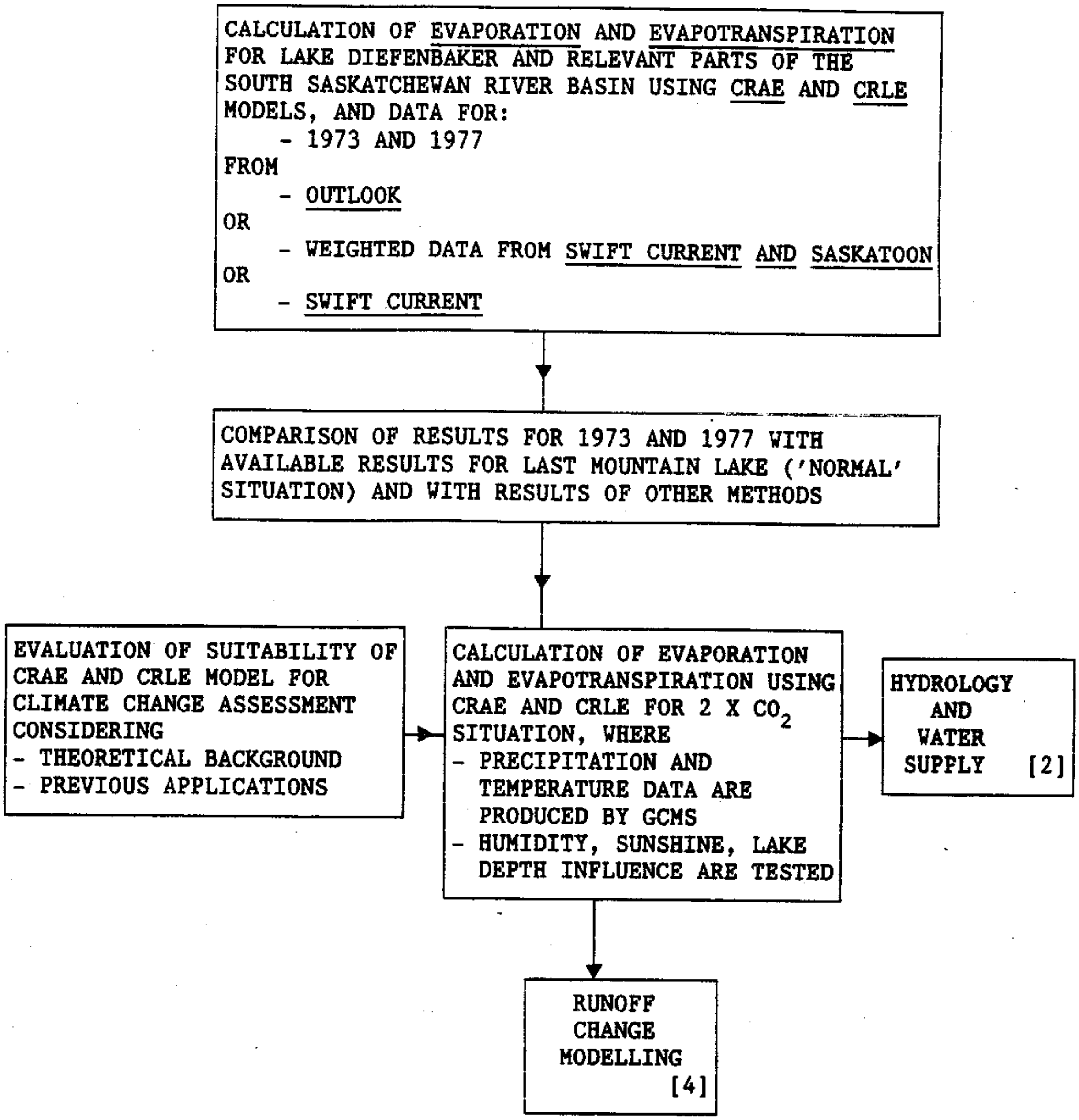

Figure 3.4. Evaporation and Evapotranspiration Change Component of the Research Framework (Component[3])

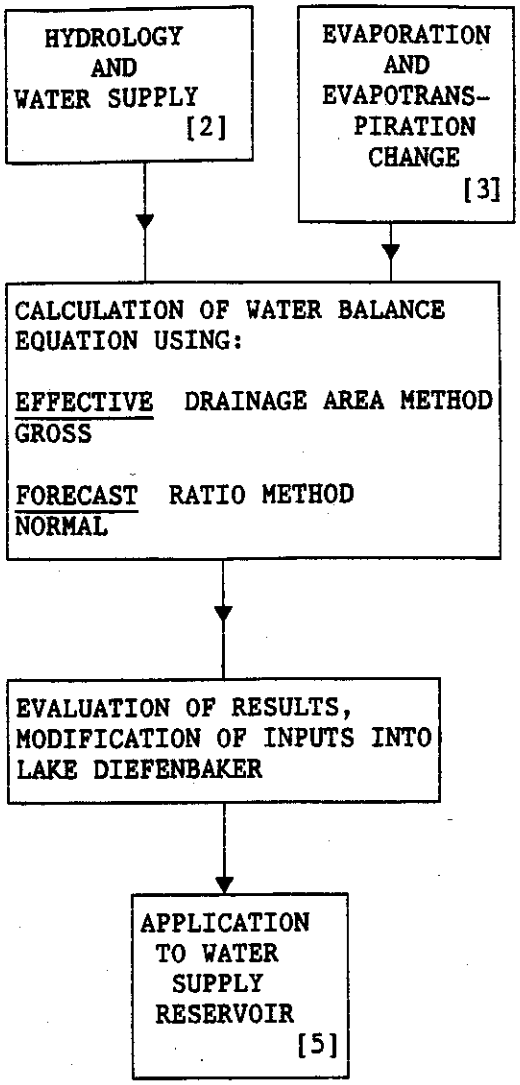

Figure 3.5. Runoff Change Modelling Component of the Research Framework (Component[4])

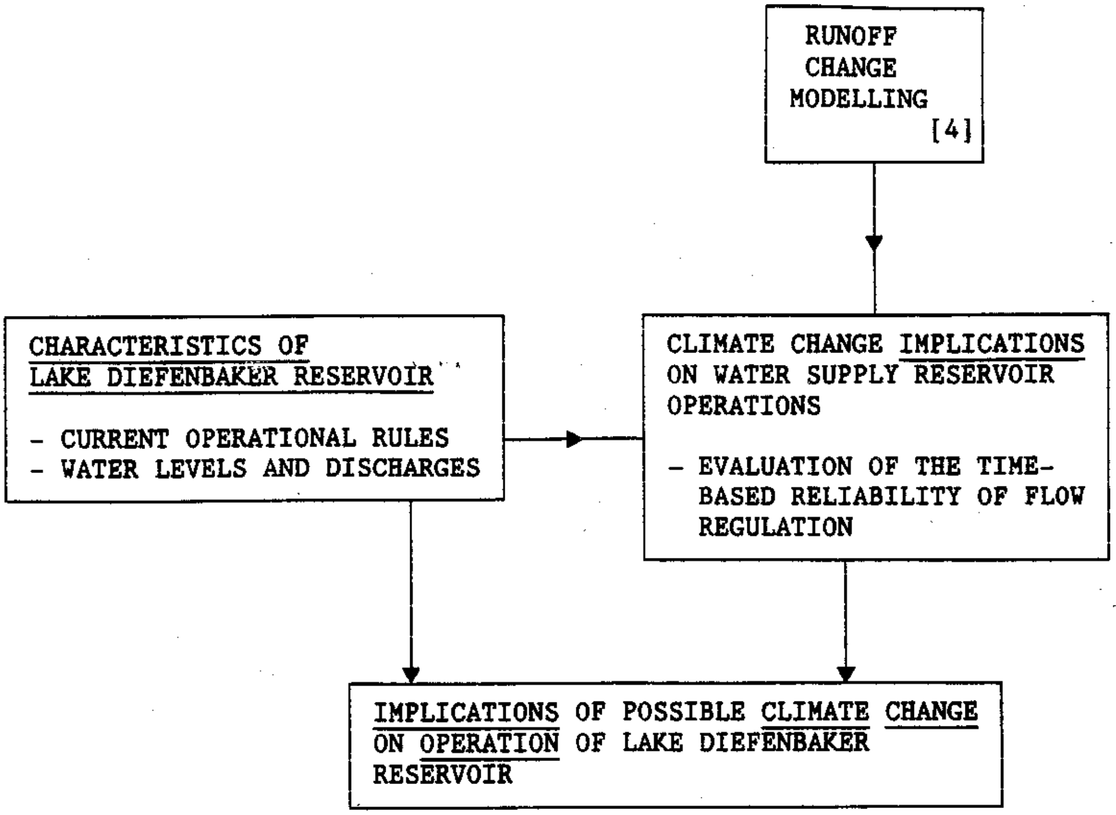

Figure 3.6. Application Component of the Research Framework (Component[5])

CHAPTER 4

DATABASE

4.1 Basic Structure

The database of this study has the following design characteristics. The database is stored on an IBM PC/XT computer with DOS 3.2. Programs handling parts of the database are written in MS FORTRAN 3.20. The functions of programs RELHUMID and DEWPOINT are discussed in Chapter 5. Program FLOWSTOR is described in Chapter 7. The database at this stage includes only monthly and annual data. Data are organized in parallel blocks or groups of blocks reflecting type of data, origin of data and their use in the study. The parallel block structure makes it easy to move data from one data file to another. Figure 4.1 shows the basic structure of the database while Figure 4.2 shows in more detail the structure of data for temperature, precipitation and the different types of evapotranspiration data used in this study.

4.2 Input from General Circulation Models

A general circulation model, or GCM, is a three-dimensional numerical climatic model of the atmosphere-land-ocean system that deals simultaneously with atmospheric motion, energy and mass transfer, and humidity. This study utilized outputs from two independently developed

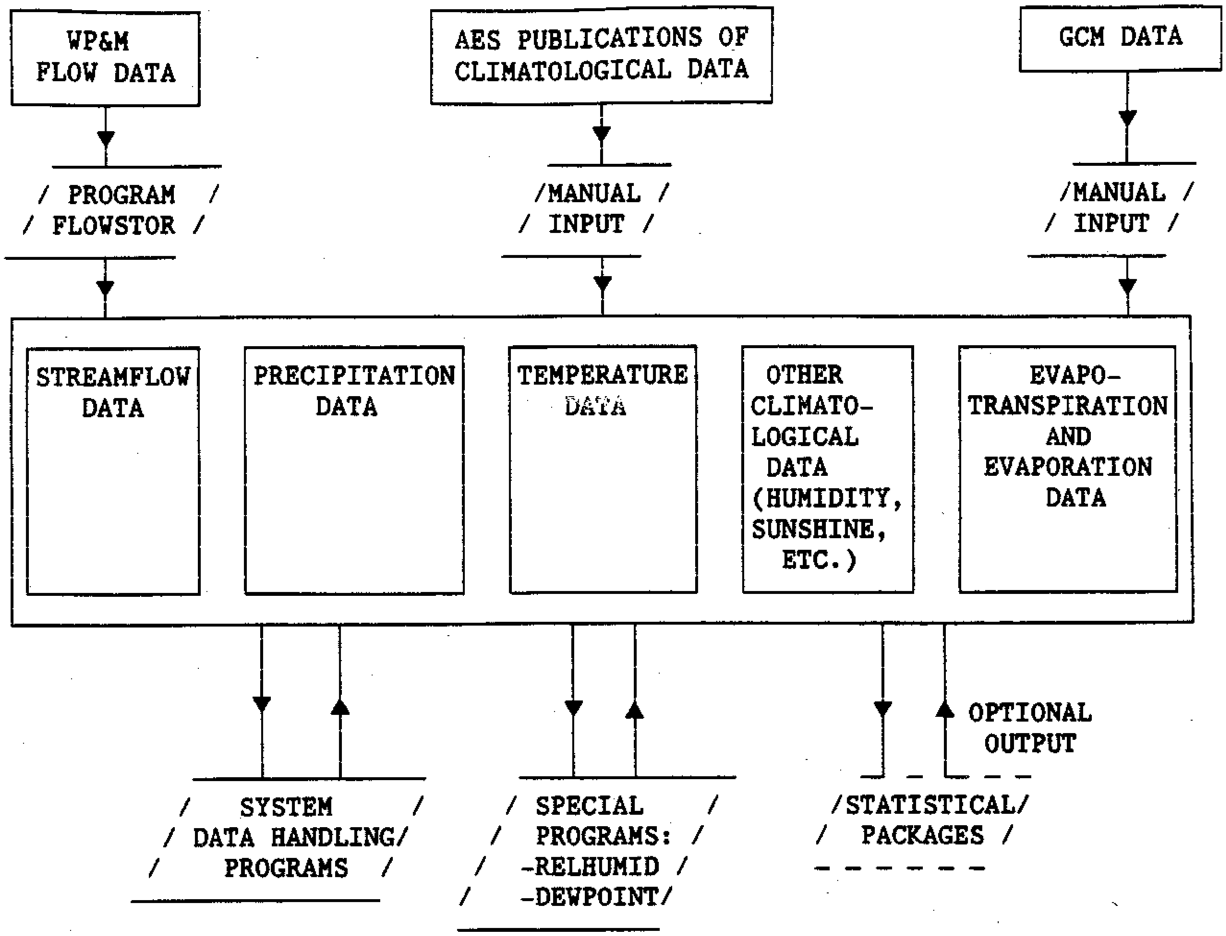

Figure 4.1 Basic Database Structure

(a) Temperature Data

GCM-DERIVED DATA		NORMALS FOR SELECTED TEMPERATURE STATIONS (1951-1980)	MONTHLY DATA FROM SELECTED METEOROLOGICAL STATIONS	MONTHLY VALUES USED AS INPUTS INTO CRAE AND CRLE MODELS
GISS GRID 1. NORMALS 2. 2 x CO SITUATION	GFDL (GISS GRID) 2 x CO SITUATION			

(b) Precipitation Data

GCM-DERIVED DATA		NORMALS FOR SELECTED PRECIPITATION STATIONS (1951-1980)	MONTHLY DATA FROM SELECTED METEOROLOGICAL STATIONS	ANNUAL VALUES USED AS INPUT INTO CRAE MODEL
GISS GRID 1. NORMALS 2. 2 x CO SITUATION	GFDL (GISS GRID) 2 X CO SITUATION			

c) Evaporation and Evapotranspiration Data

CRAE, CRLE RESULTS FOR 1. MEASURED DATA 2. SIMULATED DATA	GCM RESULTS FOR 1. NORMALS 2. GISS 3. GFDL (GISS GRID)	LAST MOUNTAIN LAKE RESULTS	HOPKINSON'S RESULTS FOR LAKE DIEFENBAKER
		COMPARATIVE RESULTS - CRLE	COMPARATIVE RESULTS - DIFFERENT METHOD

Figure 4.2 Detail of Selected Database Components

GCMs: the first from the Goddard Institute for Space Studies (GISS), and the second from the Geophysical Fluid Dynamics Laboratory (GFDL). In both cases, this study relied on output data summarized and adjusted by the Canadian Climate Centre (see Hengeveld and Street, 1986). These GCM outputs served simply as one possible type of numerical input for this study without being discussed or evaluated in detail. These data sets, however, are currently widely used in climate change impact assessment studies across Canada.

Both the GISS and GFDL models provide simulated data for temperature, precipitation and potential evapotranspiration for latitude-longitude grid points. GISS results were originally provided for an 8° latitude by 10° longitude grid, but were later interpolated to points at 4° latitude by 5° longitude intervals. Five GISS grid points were selected as representative of the part of the South Saskatchewan River Basin supplying Lake Diefenbaker. These grid points are located at 50°N115°W, 50°N110°W, 50°N105°W, 54°N115°W and 54°N110°W. Only the 50°N110°W point is located inside the basin, but the other four are relatively close (see Figure 1.1). The grid point at 50°N115°W seems to be the most important one for evaluating precipitation because it is located in the Rocky Mountains and should be able to describe the relatively high precipitation that occurs in this region.

The GFDL grid points are spaced at 4.5° longitude by 7.5° latitude intervals. Following preliminary attempts to simulate the regional hydrology of the Saskatchewan River drainage basin, Cohen et al. (1988)

concluded that the results from the GISS grid points described the conditions of the study area more adequately than those from the GFDL network. One reason for this discrepancy may be the higher density of the GISS network. The authors then adjusted the GFDL results for the GISS grid points, thus providing the two sets of data on the same grid point network. (The interpolation method is described in Cohen et al.) Since the adjustment also enhanced the comparability of the two GCM data sets, the GISS grid points version of the GFDL results was used for the purposes of this study.

Both GCMs provide simulated mean monthly and annual temperature, precipitation and potential evapotranspiration data for: 1) the time period 1951-1980 (this is the same time period used for calculating current climate "normals"); and 2) the situation with a 100% increase of CO_2 in the atmosphere (the so-called 2 x CO_2 situation or scenario). Complete sets of GCM-derived data are tabulated in Appendix A. It is important to note that hydrological changes predicted by GCMs are highly uncertain. The reason is that processes such as precipitation, evaporation and cloud formation occur naturally at finer spatial scales than those of GCM data networks. Consequently, parameterization of these processes is necessary, whereby they are predicted based on their statistical relationship with other, primary climatological variables (i.e. temperature). Hydrological changes are effectively treated by GCMs as secondary impact projections using assumptions that are greatly simplified compared to actual hydrological processes. This problem of accuracy and scale is addressed further in Chapter 5.

CHAPTER 5

EVAPORATION AND EVAPOTRANSPIRATION

Climate change that influences precipitation, humidity or solar radiation, and consequently temperature, will also influence evapotranspiration. Eventual change in evapotranspiration will have a profound effect on runoff and the availability of water, especially in arid and semi-arid areas.

As already discussed in previous chapters of this study, there are several tools available for evapotranspiration modelling (Eley, 1988, Grace and Quick, 1988). The models developed by Morton over the past twenty years were chosen for this study because they are physically based, extensively tested and fairly easy to use. Climate change suggests an uncertain future and it is obviously impossible to test now the validity of scenarios for precipitation, temperature and other climatic variables. However, given a tool that models evapotranspiration using generally valid physical processes and that was tested for geographical transfer reliability, one might expect some interesting results from climate change experiments.

The Morton models are considered by some experts to be closer to some ideal truth, about one segment of the problem, than anything else available right now. Existing measured data, as well as post-climate-change data (eventhough one cannot evaluate their quality), are used as the input into these models. Results of these experiments are useful because they can indicate the relative importance of climatic variables for modelling evapotranspiration change. One can also obtain some boundary estimates of evapotranspiration change. In addition, practical knowledge of the model will improve, including a better idea of whether or not the model is climatologically transferable.

Therefore, the purpose of this chapter is to briefly describe the evapotranspiration models selected for this study and to present the results of applying them to the Lake Diefenbaker area. The results of this study are then compared to those obtained for the same model and another, but similar area, as well as results obtained for the same area (Lake Diefenbaker) by other methods and models. Finally, the results of running the model with several different types of simulated data are presented.

5.1 Evaporation and Evapotranspiration Models

The models selected for use in this study are those developed by Morton: the complementary relationship areal evapotranspiration (CRAE) model and the associated complementary relationship lake evaporation (CRLE) model. (Another associated model, complementary relationship wet-surface evaporation (CRWE) model, is not used in this study.)

There are several publications available, some of which are listed in the Evaporation and Evapotranspiration Section of the References, on the concept of complementary relationship and the associated models. The following excerpt from Morton et al. (1985) describes the principles and processes that are the conceptual basis of CRAE and CRLE models.

> The equation describing the complementary relationship is expressed as follows: $E_T + E_{TP} = 2E_{TW}$, where:
>
> E_T = areal evapotranspiration, the actual evapotranspiration from an area so large that the effects of the evapotranspiration on the temperature and humidity of the overpassing air are fully developed.
>
> E_{TP} = potential evapotranspiration, as estimated from a solution of the energy balance and vapour transfer equations and representing the evapotranspiration that would occur from a hypothetical moist surface with radiation absorption, heat transfer and vapour transfer characteristics similar to those of the area, and so small that the effects of the evapotranspiration on the overpassing air would be negligible.
>
> E_{TW} = wet environment evapotranspiration, the evapotranspiration that would occur if the soil-plant surfaces of the area were saturated and there were no limitations on the availability of water for evapotranspiration.
>
> Figure 5.1 provides a schematic representation of the workings of the complementary relationship under conditions of a relatively high radiant-energy supply (solid line) and of a relatively low radiant-energy supply (dashed line). The ordinate represents evapotranspiration and the abscissa represents water supply to the soil-plant surfaces of the area, a quantity that is usually unknown. When there is no water available for areal evapotranspiration (extreme left of Figure 5.1), it follows that $E_T = 0$, the air is very hot and dry, and E_{TP} is at its maximum rate of $2E_{TW}$ (the dry environment potential evapotranspiration). As the water supply to the soil-plant surfaces of the area increases (moving to the right in Figure 5.1) the resultant equivalent increase in E_T causes the

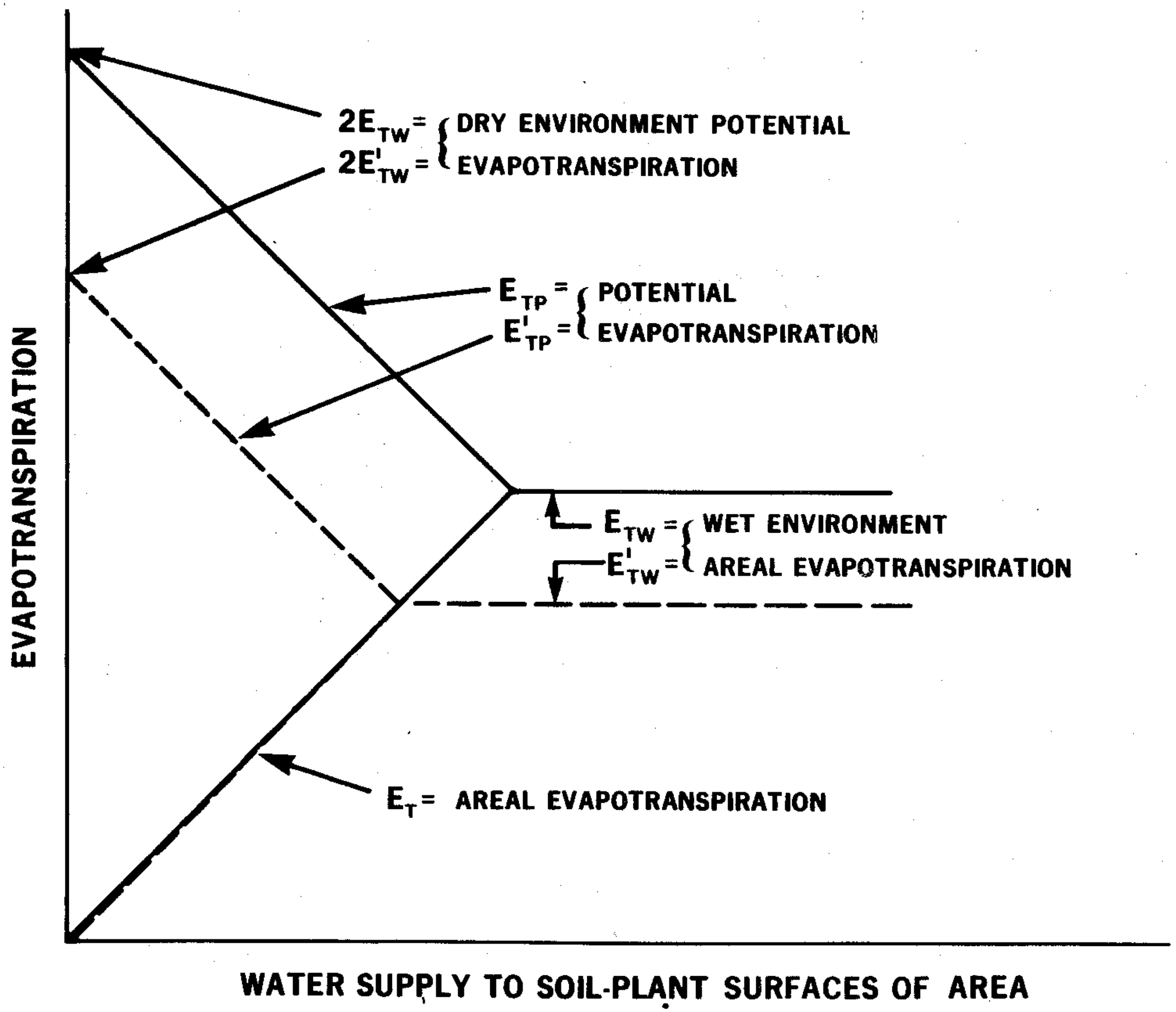

Figure 5.1 Schematic Representation of the Complementary Relationship

Source: Morton et al., 1985.

overpassing air to become cooler and more humid, and this in turn produces an equivalent decrease in E_{TP}. Finally, when the supply of water to the soil-plant surfaces of the area has increased sufficiently, the values of E_T and E_{TP} converge to that of E_{TW}. Thus, the potential evapotranspiration under completely humid conditions is equal to one-half the potential evapotranspiration under completely arid conditions. Neither E_T nor the availability of water are known, but both E_{TP} and E_{TW} can be estimated from routine climatological observations. Therefore, the CRAE model uses the complementary relationship in the following form: $E_T = 2E_{TW} - E_{TP}$.

In the CRAE model, E_{TP} is estimated from a quickly converging solution of the energy balance and vapour transfer equations, and E_{TW} is estimated from the equation for potential evaporation proposed by Priestley and Taylor (1972) as adjusted to take into account the effects of large scale advection during winter. The two coefficients needed for the adjustment and the vapour transfer coefficient needed in the computation of E_{TP} have been calibrated using data for dry months in arid regions where the sum of E_{TP} and the precipitation approximates $2E_{TW}$ (Morton, 1983a).

The outputs of the CRAE (model) are E_{TP} and E_T in millimetres, and R_T, the net radiation corresponding to soil-plant surfaces at air temperature, in millimetres of evaporation equivalent. The value of E_{TW} is not normally of interest, but if required it can be computed from the following version of the complementary relationship: $E_{TW} = (E_T + E_{TP})/2$.

The evaporation from a lake-size wet surface, E_W, differs from the wet-environment areal evapotranspiration, E_{TW}, only because the radiation absorption and vapour transfer characteristics of water differ from those of vegetated land surfaces. The potential evaporation (hereinafter referred to as pan-size wet surface evaporation and denoted by the symbol E_{WP}) differs from the potential evapotranspiration, E_{TP}, for the same reasons. Although the E_W is equal to the value of E_{WP} estimated from observations in the lake environment, it can differ significantly from the value of E_{WP} estimated from observations in the land environment.

Figure 5.2 provides a schematic representation of the relationship between the lake-size wet surface evaporation and the pan-size wet surface evaporation in the land environment under conditions of constant radiant-energy supply. The ordinate represents evaporation and the abscissa represents the water supply

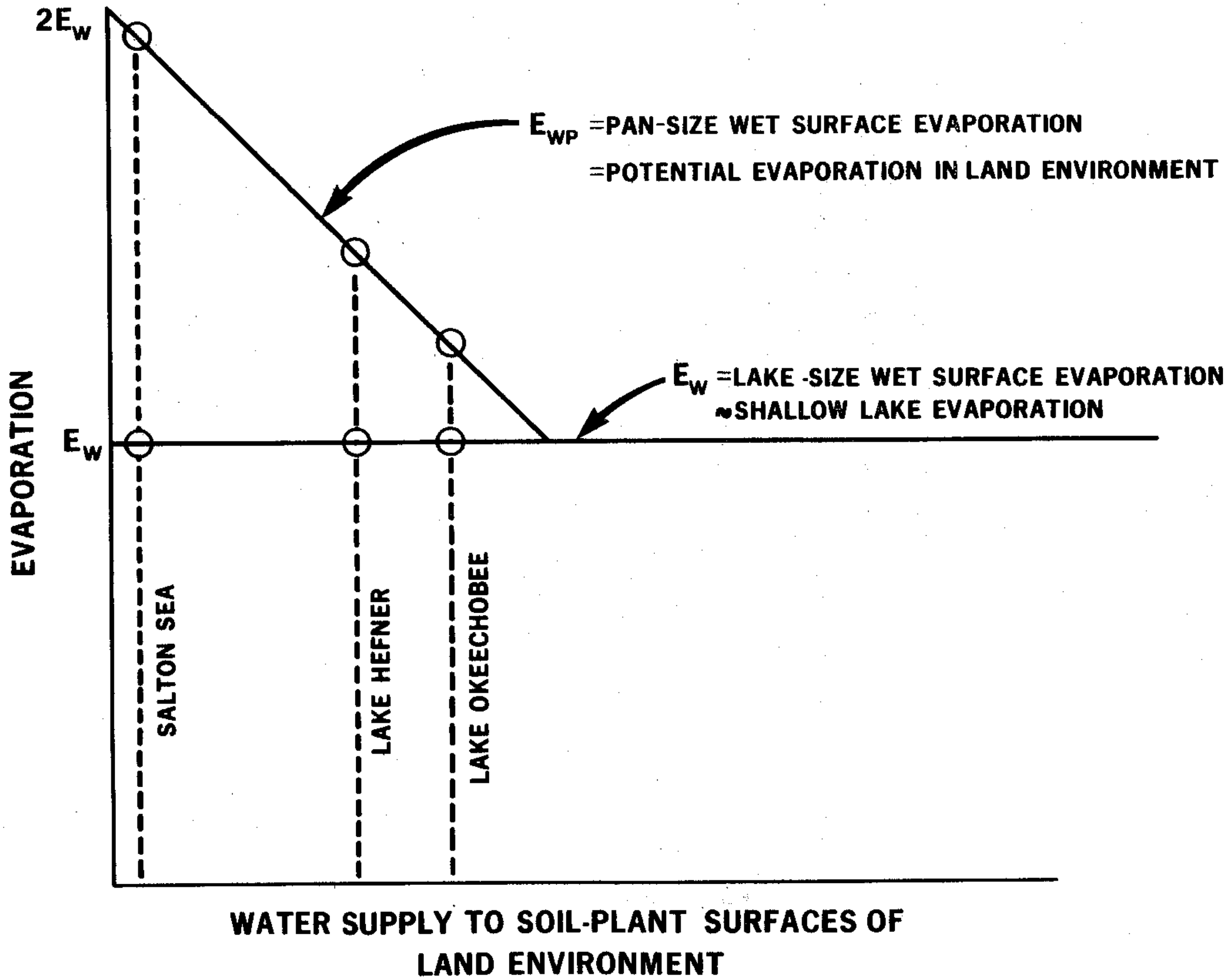

Figure 5.2 Schematic Representation of the Relationship Between Pan-Size and Lake-Size Wet Surface Evaporation.

Source: Morton, F.I., 1985

> to the soil-plant surfaces of the land environment. Since a lake is defined to be so wide that the effects of upwind shoreline transitions are insignificant (Morton, 1983a,b) the lake-size wet surface evaporation is independent of variations in the water supply to the soil-plant surfaces of the land environment. The complementary relationship, however, predicts that the pan-size wet surface evaporation in a completely dry land environment would be twice the lake-size wet surface evaporation and that it would decrease in response to increases in the water supply to the soil-plant surfaces until it reached a minimum equal to the lake-size wet surface evaporation as shown in Figure 5.2. (Morton et al., 1985.)

Both the CRAE and CRLE models require data for only three basic variables - temperature, humidity (expressed as dew point temperature or vapour pressure or relative humidity) and insolation (expressed as sunshine duration or sunshine ratio or observed global radiation). Other data required are: average atmospheric pressure (replaceable by altitude), average annual precipitation (only for CRAE model), depth of lake (for CRLE), and salinity (for CRLE and only for significantly saline lakes). Program WREVAP which calculates CRAE and CRLE models also requires several option-selecting control parameters. A detailed description of this program can be found in Morton et al., 1985.

An application of the CRAE and CRLE models to the Lake Diefenbaker study area should follow three logical steps:

1) application using historical data;

2) comparison of historical simulations with those of the CRAE and CRLE models for similar geographical areas; and

3) experiments with forecast data.

Section 5.2 below deals with steps 1 and 2. Step 3 is addressed in subsequent sections. Figure 5.3 schematically shows the individual steps described above.

5.2 Simulating Historical Evaporation for Lake Diefenbaker

The CRLE model was applied by Morton on Last Mountain Lake, Saskatchewan (see Morton, 1983a). Morton used data for the years 1973 and 1977, and because of the limited time-scope of this study, the same two years were used for data purposes. Data from the following climatological stations were used: Saskatoon, Swift Current and Outlook. These data (air temperature, dew point temperature, and sunshine, where available) are listed in Appendix C-1. The sunshine ratio data from Outlook are for some reason systematically lower than data from the other two stations. Also, the station at Outlook does not provide dew point temperature or any humidity measurement. Therefore, for the purposes of this study the average temperature (T) and average dew point temperature (TD), calculated from Saskatoon and Swift Current data, were used. However, three versions of sunshine ratio data (S), Saskatoon plus Swift Current average (Version I), Outlook only (Version II), and Swift Current only (Version III), were used. Output data for all three versions are listed in detail in Appendix C-2 and summarized in Table 5.1.

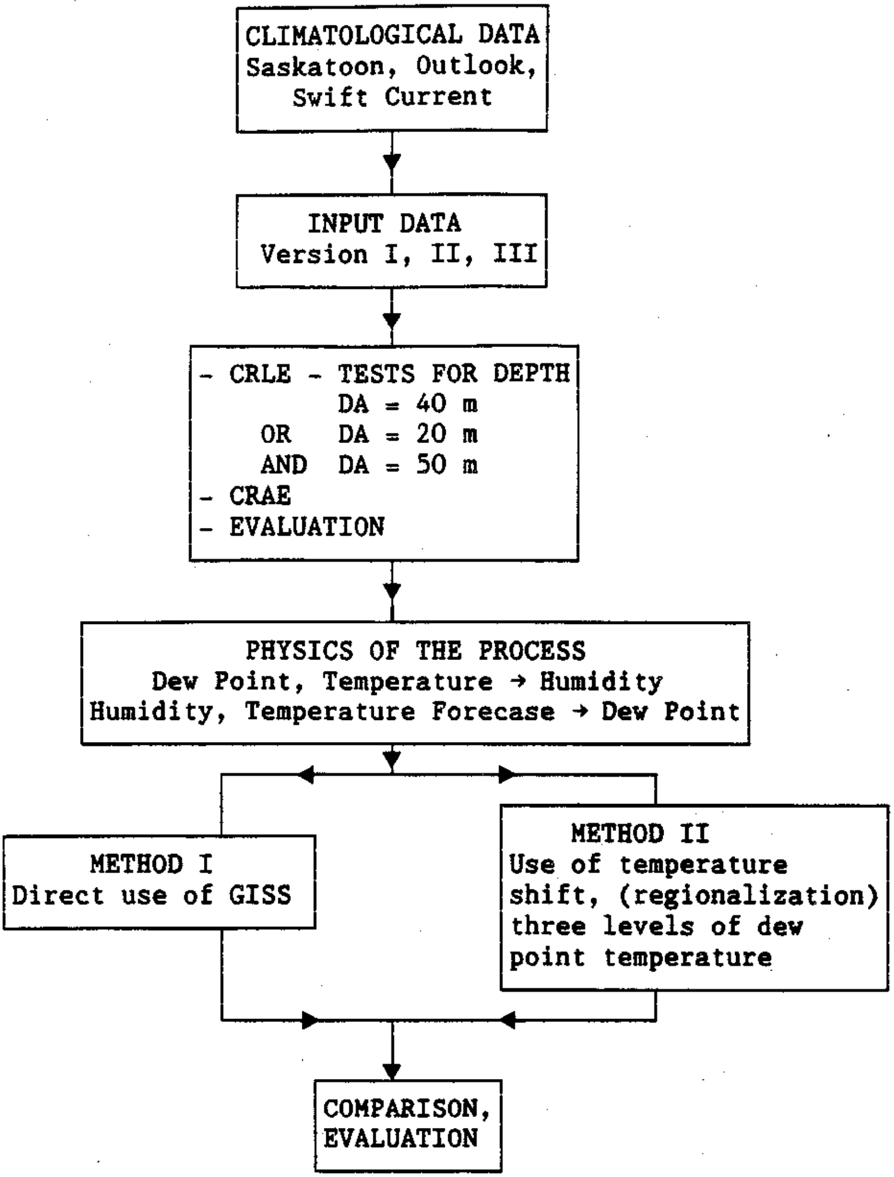

Figure 5.3. **Calculation of Evaporation and Evapotranspiration for Lake Diefenbaker Area**

LOCATION SIMULATED*	LAKE EVAPORATION MODEL USED*				
	CRLE (Present Study Versions)			CRLE	Meyer
	I	II	III	(Morton)	(Hopkinson)
	(mm/yr)				
Last Mountain Lake (Depth = 10 m)	696	-	704	695	-
Lake Diefenbaker (Depth = 40 m)	650	619	658	-	863
Upper Lake Diefenbaker (Depth = 20 m)	679	-	687	-	891
Lower Lake Diefenbaker Depth = 50 m	619	-	627	-	781

* See text for explanation.

Table 5.1 Historical Lake Evaporation Simulation Results

The three versions of input data were first tested with an approximate average lake depth (DA) of 40 m. Lake evaporation results simulated for Lake Diefenbaker were 650 mm/year, 619 mm/year and 658 mm/year for Versions I, II and III, respectively (Appendix C-3). To compare current test results with those for Last Mountain Lake, Versions I and III data were then tested for a hypothetical depth of 10 m, which is the approximate depth of Last Mountain Lake. The results were 696 mm/year for Version I and 704 mm/year for Version III. The original result obtained by Morton (see Appendix B) for Last Mountain Lake was 695 mm/year, which is a very good agreement considering the fact that Morton used different climatic stations. As stated above, the sunshine data for Version II (Outlook) seemed to be untypically low for the area and were not tested further.

Version I and III data were then tested for DA = 20 m and DA = 50 m, which are the approximate depths of the upper and lower parts respectively of Lake Diefenbaker (Hopkinson, 1985). The results differ considerably (see Table 5.1), but as expected, from the evaporation values for Lake Diefenbaker as calculated by Hopkinson using the Meyer equation. The Meyer equation is a formulation of Dalton's law

> which postulates that the evaporation is a function of the vertical vapour pressure gradient in a specified layer over a water body and the wind at a specified height above the water surface. (Hopkinson, 1985)

Driven by the "complementary relationship" concept as explained in Section 5.1, the CRLE model calculates lower values for Lake Diefenbaker than those of Hopkinson. With regard to the influence of lake depth, the shallow, upper part of the reservoir is intuitively warmer and therefore loses more water due to evaporation than the deeper, lower part with its cooler water temperatures.

Version I and III data were also used as input into the CRAE model, giving actual evapotranspiration results of 351 and 361 mm/year, respectively (Appendix C-3). Normal precipitation for Lake Diefenbaker area is about 349 mm (Appendix C-1). These results suggest that there are little or no local runoff flows in the Lake Diefenbaker catchment area and that the only significant inflow into the reservoir is that of the South Saskatchewan River. The results for both Versions I and III are, therefore, considered acceptable. However, since Version I used data from Saskatoon and Swift Current, while Version III used Swift Current data only, Version I was assumed to be more representative with regard to the study area and was chosen for further work.

5.3 Estimating Evaporation and Evapotranspiration for the Lake Diefenbaker Area for 2 x CO_2 Climate Change Scenarios

As noted above, to calculate evapotranspiration using the CRAE and CRLE models, temperature, humidity and insolation data and, for the CRAE model, average annual precipitation, are required. Temperatures for a 2 x CO_2 climate change situation are available in the form of GCM output, specifically from the GFDL and GISS models (i.e. two sets of hypothetical temperature input). Similar humidity and insolation scenario data are not available. Therefore, direct estimation of evaporation and evapotranspiration for 2 x CO_2 scenarios was not performed. Instead, some assumptions about data were made and used for several climate change experiments with the CRAE and CRLE models.

GISS and GFDL model forecasts of temperature are available for latitude-longitude grid points (see Chapter 4). The location of these points unfortunately does not take into consideration the data-measurement needs of specific water resources systems. The problem is that hydrological processes such as precipitation, evaporation and cloud formation occur naturally at finer scales than those of the GCM data networks. Therefore, there are two basic ways of working with the GCM-derived temperature data. The first is the direct use of grid point data, in either raw or weighted form. The second is the 'regionalization' of an expected change, as suggested in Beran (1986) and Gleick (1986). Both these basic approaches are attempted in this study.

5.3.1 Direct use of grid-point data - Method I

Figure 1.1 shows that the two grid points closest to Lake Diefenbaker are 50°N110°W and 50°N105°W. Method I uses the average temperature from these two grid points as the 'forecast' temperature for both the GISS and GFDL data, given a 2 x CO_2 situation (Appendix D-1-1). As far as humidity and insolation are concerned, several assumptions are necessary. First, assuming that insolation will not change under a 2 x CO_2 scenario, the average from sunshine ratio data for the years 1973 and 1977 is used. These two years of data were originally used by Morton for his Last Mountain Lake evaporation calculation and being readily available, they were incorporated into the data base simply because of the time limitations of this study. Second, using temperature and relative humidity one can calculate dew point temperature, or from temperature and dew point temperature one can calculate relative humidity. To accomplish this, the programs RELHUMID and DEWPOINTS were written (see the Programs Section at the end of this report).

Using the RELHUMID program with 1973 and 1977 data, relative humidity was calculated and the results were added to the database (see Appendices C-1-2, C-1-3, C-1-5, C-1-6). Average relative humidity was assumed unchanged primarily because specific grid-point results from GCM 2 X CO_2 experiments were not available. However, global isolines of changes in humidity under enhanced insolation scenarios (i.e. a proxy for greenhouse surface warming) indicate relatively minor fluxes of ± 1% for the study area (Schlesinger and Mitchell, 1985). New dew point temperatures were calculated using the DEWPOINTS program with this average relative humidity and GISS and GFDL-derived temperatures for 2 x CO_2 scenarios. These new dew point temperatures, which look quite reasonable when related to temperature data and sunshine ratio data, were used as input into CRAE and CRLE models. At this stage, to change more than one of the three interdependent variables (temperature, relative humidity, dew point temperature) would mean to ignore completely system feedback processes. Therefore, the approach adopted here is to investigate the significance of unknown variables one at a time in terms of model sensitivity. The results of applying Method I are summarized in Table 5.2.

Lake evaporation results, for lake depths of 40 m (average), 20 m (low) and 50 m (high), were 754, 777 and 727 mm/year, respectively, using

		SOURCE OF INPUT DATA*				
a) Lake Evaporation (CRLE, Version I)	Average Lake Depth (m)*	Historical Records	GISS $2xCO_2$	GFDL $2xCO_2$	GISS	GFDL
		(mm/yr)			(percent change from historical)	
	20	679	777	721	14	6
	40	650	754	694	16	7
	50	619	727	669	17	8
(b) Areal Evapotranspiration (CRAE)	Actual	351	341	340	-3	-3
	Potential	1040	1167	1097	12	6

* See text for explanation.

Table 5.2 2 x CO_2 Evaporation and Evapotranspiration Estimation Results - Method I

GISS-derived temperature data, and 694, 721 and 669 mm/year, respectively, using GFDL (with GISS grid) data. For detailed CRLE results showing monthly data see Appendix D-1-2 to D-1-7. Both GISS and GFDL data indicate an increase in lake evaporation when compared to the results based on historical data, which are 650, 679 and 619 mm/year respectively for the three lake depths.

The CRAE applications of the same data (Appendices D-1-8, D-1-9) show an increase in potential evapotranspiration (1167 mm/year for GISS, 1097 mm/year for GFDL as compared with 1040 mm/year for CRAE-simulated historical data), but actual evapotranspiration decreases slightly, apparently due to a new temperature/dew point temperature relation caused by changed temperature and unchanged relative humidity. The actual evapotranspiration results are 341 and 340 mm/year for GISS and GFDL-derived data, respectively, while CRAE-simulated average annual areal evapotranspiration from historical data is 351 mm/year.

5.3.2 Regionalization of grid-point data - Method II

Method II was devised as an attempt to minimize the two main drawbacks of Method I, which are as follows:

1) temperature data for 2 x CO_2 scenarios are available for grid-point networks that are insensitive to a regional scale assessment of water resource impacts; and

2) only dew point temperature data for unchanged relative humidity were calculated.

The first problem can be mitigated by calculating the average temperature change for pertinent grid point data, and then applying this shift to real data from existing meteorological stations. For Lake Diefenbaker, the three closest grid points are 50°N110°W, 50°N105°W and 54°N110°W. The results of the regionalized temperature change calculations are listed in Appendices D-2-2 and D-2-3 for GISS and GFDL-models, respectively. The results show some consistency for GISS, with temperatures increasing some 3.3°C in summer and about 6°C in winter. On the other hand, the results for GFDL seem to be quite random.

The second limitation of Method I was addressed as follows. The average normal temperature for the Lake Diefenbaker area was calculated as the average from climate normals for Saskatoon and Swift Current and this temperature was modified for both GISS-data average shift and GFDL-data average shift (Appendix D-2-4). These new temperature data were used, as in Method I above, together with relative humidity data to calculate new simulated dew point data. But in this case the dew point data obtained for both types of simulated temperature and unchanged relative humidity were changed by ±10%, thus providing three sets of dew point data: unmodified calculated values, 90% of calculated values, and 110% of calculated values (Appendices D-2-6, D-2-7). Since relative humidity data for a 2 x CO_2 situation were not available, new values of relative humidity were calculated by the CRLE model using the modified dew point data and unchanged GCM temperature scenarios. Thus, lake evaporation was calculated again for three levels of dew point temperature, unchanged sunshine ratio and 'regionalized' temperature.

The detailed results, which are presented in Appendices D-2-8 through D-2-13, are summarized in Table 5.3. For GISS grid temperatures lake evaporation ranges from 718 to 742 mm/year for the three sets of calculated dew point temperatures, while for GFDL (GISS grid) results are between 672 and 688 mm/year for the associated sets of dew point temperatures. All calculations use an average lake depth (DA) of 40 m. The results of Method II are systematically lower than those of Method I. The main reason is that the 'regionalized' temperatures are lower than the temperatures derived from GCMs.

5.4 Discussion of Evapotranspiration Results

A comparison with historical results produced by other evaporation-measuring methods shows that the results of the CRLE model (for Lake Diefenbaker the typical historical value is 650 mm/year) are lower than the results of other methods. Hopkinson calculates the mean value for evaporation at Lake Diefenbaker to be about 863 mm/year based on 15 years of record (see Table 5.1 and Appendix B). These differences are not surprising, since the CRLE model emphasizes certain feedbacks of the natural system whereby a large body of water like Lake Diefenbaker simply cools itself. Therefore, the actual lake evaporation is lower than the potential lake evaporation. These feedbacks are not reflected in Meyer's formula used by Hopkinson (see Section 5.2).

Estimated Dew Point Temperature* (percent)	SOURCE OF INPUT DATA FOR CRLE, VERSION I*				
	Historical Records	GISS 2 x CO_2	GFDL 2 x CO_2	GISS	GFDL
	(mm/yr)			(percent change from historical)	
90	-	742	688	14	6
100	650	727	677	12	4
110	-	718	672	10	3

* See text for explanation.

Table 5.3 2 x CO_2 Lake Evaporation Estimation Results - Method II

The CRLE model is unique since it simulates lake evaporation based primarily on perceived feedback processes among system parameters. The complementary relationship principle seems plausible from the atmospheric physics point of view, from the logical point of view and from the system theory point of view. The results for Last Mountain Lake and Lake Diefenbaker using a hypothetical depth of 10 m (695 mm/year and 696 mm/year, respectively - see Table 5.1) are almost identical, despite being derived from different sets of data and without using any 'adjustment' coefficients. The CRLE model appears to describe well how changes in temperature, humidity and lake depth modify lake evaporation. Feedbacks for temperature, relative humidity, and dew point temperature interrelation seem accountable by the current version of the model. What is not included in the CRLE model and holds significant potential, based on the results of this study, is the feedback modelling of how lake evaporation changes influence air temperature. Implementation of this capability would enable the CRLE model to become a more complete climate modelling tool and, therefore, merits further investigation.

CHAPTER 6

STREAMFLOW ESTIMATION FOR THE SOUTH SASKATCHEWAN RIVER ABOVE LAKE DIEFENBAKER

As noted earlier in this report, climate change induced impacts on water resources will occur at the watershed level and, therefore, sensitivity assessments must be conducted at the regional scale. The recommended approach (see Beran, 1986; Gleick, 1986; and Klemes, 1985) is to couple appropriate GCM results with modified water-balance models. Due to time and resource limitations, the following version of the basic water balance equation was chosen for the streamflow estimation purposes of this study:

$$R = P - E - S,$$

where R is runoff, P is precipitation, E is evaporation and S is storage change. Consequently, the types of information required in order to adequately estimate flows for the South Saskatchewan River into Lake Diefenbaker under a 2 x CO_2 climate change situation are as follows:

1) present time flows,
2) changes in precipitation,
3) changes in actual evapotranspiration,
4) changes in water storage of the basin, and
5) representativeness of point data, particularly precipitation measurements, for the basin (i.e. the need for weighting or modelling factors).

The purpose of this chapter is to discuss and test the availability and suitability of data and methodologies for streamflow estimation, given climate change.

Flow data used in this study are the monthly and annual natural (or so-called 'naturalized', i.e. measured flows adjusted for human influences) flows for the time period 1912 to 1982 as recorded at the Alberta-Saskatchewan border where shortly thereafter the South Saskatchewan River flows into Lake Diefenbaker. The mean annual flow for the entire period of record is 299 m^3/s. The mean annual flow for the period 1951-1980, used for this study as the standard or 'normal' period, is 310 m^3/s. The latter flow value translates to a mean normal runoff of 88.8 mm/year for a gross drainage area at the Alberta-Saskatchewan border of approximately 110 650 km^2.

Precipitation data are available as monthly and annual averages for the five representative GCM grid points for both the 'normal' time period (i.e. 1951-1980) and for the 2 x CO_2 situation (see Chapter 4). Since there are no actual evapotranspiration data available, potential evapotranspiration data, calculated using GCM results with the Thornthwaite water balance approach (Cohen, personal communication), were tested extensively for possible use with the CRAE model. Annual values of potential evapotranspiration generated using the GCM results and the Thornthwaite model are about 500 mm/year for the normal situation and about 600 mm/year for 2 x CO_2 scenarios (see Appendices A-5, A-6a,b). In this study, the CRAE model was extensively tested with the same GCM simulated temperature data, including extreme variations, and the potential evaporation values ranged between 750 and 1200 mm/year (see Appendices D-1, D-2).

Obviously, the results of the two approaches for estimating potential evapotranspiration differ significantly. One likely reason for the large dissimilarity of results is the different conceptual bases of the two models. The CRAE model is a more physically based method than the empirical method of Thornthwaite. The main concept and associated simulation of key hydrological processes that drive the CRAE model are not included in the Thornthwaite model. Furthermore, the results of the Thornthwaite model are considered generally less reliable if the study area exhibits large short-term variations in wind or humidity (Cohen, 1988).

Specific water storage information for the study area was not readily available, and also considered non-essential, given the limitations and scope of the study. Alternatively, Figure 6.1 shows that if actual evapotranspiration is known, the average annual runoff can be estimated as the difference between the average annual precipitation and average annual areal evapotranspiration with reasonable accuracy. The relationship is based on areal evapotranspiration estimates made for 143 river basins located in Africa, Australia, Canada, Ireland, New Zealand, and the United States. Therefore, for the purposes of this study, it is assumed that short-term changes in water storage "average themselves out" over the long term.

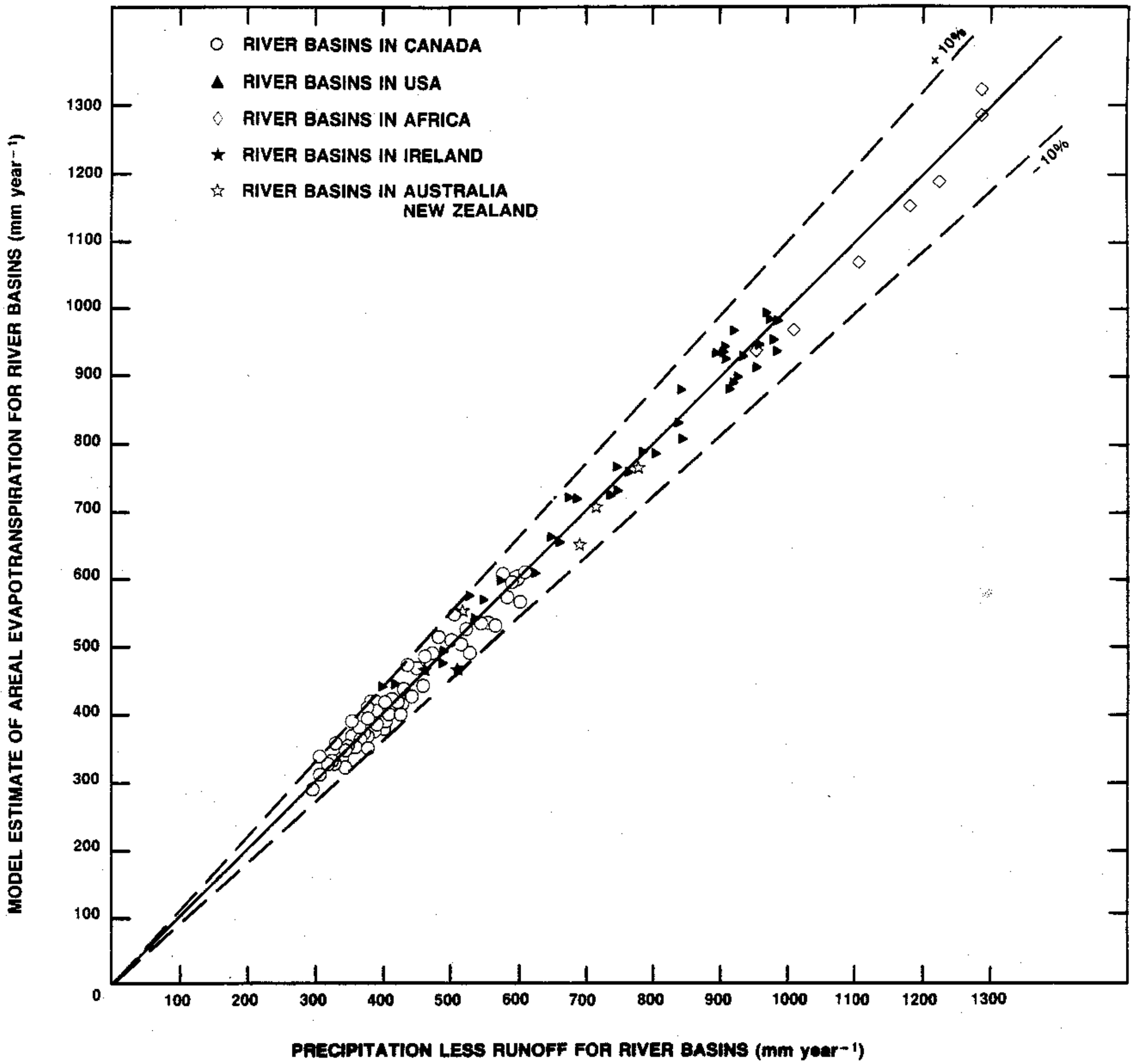

Figure 6.1 Comparison of Evapotranspiration Estimates Using the Complementary Relationship Model and Water-Budget Components

Source: Morton, 1983(a).

Some researchers believe that a weighting or modelling factor, which proportions data point representation of the study area, should be introduced under certain conditions of streamflow estimation. For example, the so-called "effective/gross drainage area" method represents an attempt to adjust for any differences between the normal drainage area and total land area in a watershed as well as for relative basin coverage by GCM data points (Cohen et al., 1988). The results of applying this method, as well as an alternative approach, to estimating streamflow are the subject of this chapter.

6.1 Testing of the CRAE Model as Input to Streamflow Estimation for 2 x CO_2 Climate Change

The method used for applying the CRAE model to streamflow estimation is schematically shown in Figure 6.2 The CRAE model is influenced by three types of monthly data, temperature, relative humidity, and insolation, and by average annual precipitation. For the purpose of providing evapotranspiration data for estimating streamflow, given 2 x CO_2 conditions, GCM temperature data and average annual precipitation values are used in their unaltered forms. Since relative humidity and insolation for a 2 x CO_2 situation are not known, it was assumed that the future 'normals' for these variables could occur somewhere between the lower and higher extremes of the present. Therefore, the approach adopted begins by defining hypothetical 'normal ranges' for relative humidity and insolation under 2 x CO_2 climate change conditions.

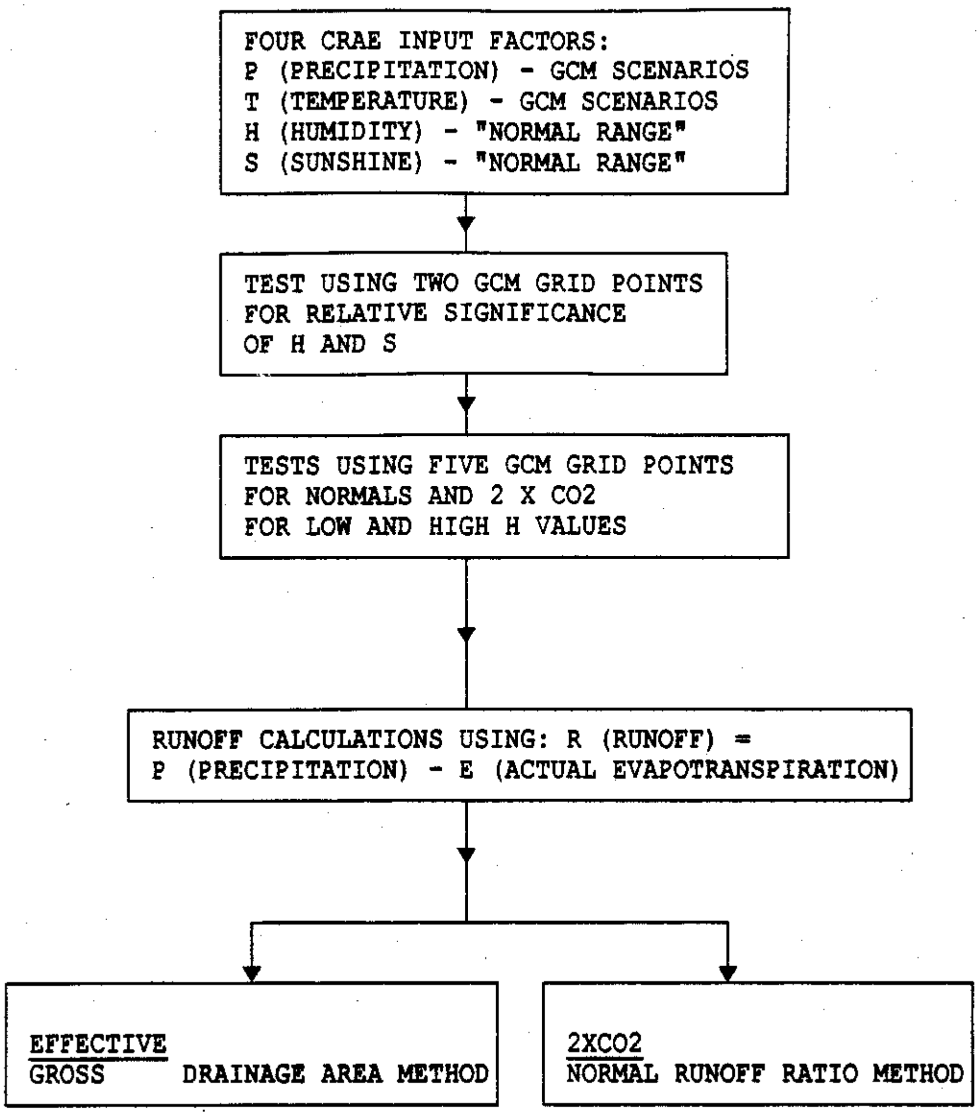

Figure 6.2. Methodology of Runoff Change Evaluation

6.2 Sensitivity of Evapotranspiration to Changes in Relative Humidity and Insolation

To test some 'low' and 'high' range limits, for both relative humidity and insolation, for five grid points and for two sets of GCM results (GISS and GFDL with GISS grid), would require 40 different combinations, which is beyond the scope of this study. Instead, the influence of 'low' and 'high' limit values of relative humidity and insolation on changes in evapotranspiration was tested in order to evaluate their relative importance. The minimum and maximum values for each month were selected from the historical data on relative humidity contained in Appendix C. The relative humidity varies much more in the cooler 'winter' months of November to February (from .037 to .890) than in the warmer 'summer' months of March to October (from .397 to .745). Therefore, the minimum and maximum limit values are defined for the winter period as 0.05 and 0.90 respectively and for the summer period as .40 and .75 respectively (see Appendix E-1). The terms 'winter' and 'summer' are used here to distinguish between the periods of the year with significantly different values of relative humidity. The months associated with each period obviously do not correspond to those normally used to delimit the actual seasons.

Since sunshine ratios seem to vary locally considerably more than relative humidity, an expanded, more representative data set is needed to define minimum and maximum values of insolation (expressed as sunshine ratios) for the South Saskatchewan River basin. Therefore, additional sunshine ratio data were used from Calgary, Lethbridge, Medicine Hat, Outlook and Swift Current for the years 1978 to 1981 (Appendices E-2 to E-5). The average monthly values for each station and the average monthly values for all five stations were calculated (Appendix E-6) and minimum and maximum values for each month were identified (Appendix E-7). Table 6.1 lists together the 'minimum' and 'maximum' limit values for relative humidity (the 'low' and 'high' limit will be explained later), as well as the minimum and maximum data values for sunshine ratio.

The 'minimum' and 'maximum' relative humidity limits and the 'minimum' and 'maximum' sunshine data were tested with temperature data and average annual precipitation from two grid points - 50°N115°W (mountains) and 50°N110°W (prairies). The results, shown in Appendix F, indicate that areal evapotranspiration is more sensitive to changes in relative humidity than to changes in insolation. Therefore, for the rest of this study only the 'average' monthly values of sunshine ratio are used, thus reducing the number of combinations for the five grid points from 40 to only 23. Also, by not using the extreme 'minimum' and 'maximum' limit values for sunshine, the occurrence of improbable values for simulated areal evapotranspiration is avoided. Similarly, more moderate 'low' and 'high' limits (0.30 and .60 for 'winter'; 0.40 and 0.50 for 'summer') are used as the range scenario for relative humidity under 2 x CO_2 conditions (Table 6.1).

	Relative Humidity				Sunshine Ratio		
	Min. Limit	Max. Limit	Low Limit	High Limit	Data Min.	Data Max.	Average
Jan.	0.050	0.900	0.300	0.600	0.37	0.52	0.42
Feb.	0.050	0.900	0.300	0.600	0.37	0.47	0.42
Mar.	0.400	0.750	0.400	0.500	0.42	0.50	0.46
Apr.	0.400	0.750	0.400	0.500	0.45	0.53	0.50
May	0.400	0.750	0.400	0.500	0.50	0.61	0.56
June	0.400	0.750	0.400	0.500	0.60	0.67	0.64
July	0.400	0.750	0.400	0.500	0.63	0.72	0.67
Aug.	0.400	0.750	0.400	0.500	0.64	0.70	0.67
Sept.	0.400	0.750	0.400	0.500	0.51	0.61	0.55
Oct.	0.400	0.750	0.400	0.500	0.48	0.55	0.51
Nov.	0.050	0.900	0.300	0.600	0.41	0.50	0.46
Dec.	0.050	0.900	0.300	0.600	0.32	0.42	0.36

Table 6.1. Extreme Values of Relative Humidity and Sunshine Ratio.

6.3 Effective/Gross Drainage Area Method of Runoff Estimation

One approach for refining runoff estimates is to determine the relative contribution of individual GCM grid squares to the total runoff from the basin. The effective/gross drainage area method of calculation (Cohen et al., 1988) was applied to estimate runoff for both the 'normal' and 2 x CO_2 situations. To test the method for the South Saskatchewan River drainage area to Lake Diefenbaker, it was necessary to calculate the so-called "effective/gross ratio", then the "area weight", for each grid point representing the study area. The effective/gross ratios were calculated using the relevant detailed information provided by Mowchenko and Mead (1983). These ratios were then applied to the portions of the gross drainage area contained in each grid square, measured by planimeter, to determine the associated effective drainage area. Finally, the area weight for each grid point was calculated by dividing the effective area contained in the grid square by the total effective area for the drainage basin. The results are presented in Table 6.2.

Since the area weight is applied to the runoff estimated for each grid point, it was necessary to determine the latter using the simplified water balance equation: $R = P - E$. Precipitation data were available (Appendices A-1 to A-4), but the actual evapotranspiration component was missing. Therefore, potential evapotranspiration data (Appendices A-5 and A-6) were adjusted, using "actual/potential ratios" determined from Table 5.2 for normal (0.33), GISS (0.29) and GFDL (0.31), to estimate

Grid	Gross Area		Effective Gross	Effective Area	Area
Point	(km2)	(% Total)	Ratio	(km2)	Weight*
N50W115	62 950	40.12	0.87	54 770	0.5730
N50W110	75 990	48.38	0.37	28 120	0.2942
N50W105	6 280	4.00	0.52	3 270	0.0342
N54W115	10 700	6.82	0.88	9 420	0.0986
N54W110	960	0.61	0.00	0	0.0
Total	156 880	100.00		95 580	1.0000

* See text for explanation.

Table 6.2 Values of Effective/Gross Ratio and Weighting Factors for South Saskatchewan River Drainage Area to Lake Diefenbaker values of actual evapotranspiration (Table 6.3). The annual runoff for each grid point was then calculated as the difference between the annual values for precipitation and actual evapotranspiration. Finally, these "raw" runoff values were adjusted using the previously calculated area weights (Table 6.4).

The study area estimates for runoff were assessed in terms of the magnitude and direction in comparison to a similar study applied to the same region. Cohen et al. (1988), however, used a much larger study area and a more involved analytical approach. Nevertheless, the South Saskatchewan River-Lake Diefenbaker drainage basin is a sizeable portion of the larger study area and the present study used a basic research methodology similar to that of Cohen et al. The weighted runoff results in Table 6.4 are closest in magnitude to the unweighted runoff estimates for the same grid points provided by Cohen et al. (see Table 6.5). This is particularly evident for the respective normal and GISS situations, of which the total basin runoff values are surprisingly similar, with less than 10% difference. Also for these two sets of conditions, the grid point representing the Rocky Mountains portion of the study area (50°N115°W) dominates in terms of contributed precipitation and runoff. These parallels do not hold true for the GFDL scenario.

Both studies have runoff estimates for a 2 x CO_2 situation that show for all grid points an increase in runoff using the GISS input and a decrease in total basin runoff using the GFDL input. Cohen et al. estimated climate change-induced impacts on total basin runoff of +37% for

GCM GRID POINT	Potential Evapotranspiration (GCM-Derived)*			Actual Evapotranspiration (PE-Derived)*		
	Normal	GISS	GFDL	Normal	GISS	GFDL
			(mm/yr)			
50N115W	477	551	592	157	160	183
50N110W	548	665	589	181	193	183
50N105W	544	657	595	180	191	184
54N115W	505	584	571	167	169	177
54N110W	514	609	570	170	177	177

* See text for explanation.

Table 6.3 Normal and 2 x CO_2 Potential and Actual Evapotranspiration Estimation Results

GCM GRID POINT*	ANNUAL WATER BALANCE COMPONENTS*				
	Precipitation (mm/yr)	Actual Evapotrans-piration (mm/yr)	Runoff (mm/yr)	Area Weight	Weighted Runoff (mm/yr)
a) <u>Normal</u>(1951-1980)					
50N115W	727	157	570	0.5730	327
50N110W	390	181	209	0.2942	61
50N105W	408	180	228	0.0342	8
54N115W	478	167	311	0.0986	31
54N110W	435	170	265	0.0	0
			Total Basin Runoff:		427
b) <u>GISS</u> (2 X CO_2)					
50N115W	901	160	741	0.5730	425
50N110W	453	193	260	0.2942	76
50N105W	463	191	272	0.0342	9
54N115W	568	169	399	0.0986	39
54N110W	516	177	339	0.0	0
			Total Basin Runoff:		549
c) <u>GFDL</u> (2 X CO_2)					
50N115W	493	183	310	0.5730	178
50N110W	515	183	332	0.2942	98
50N105W	608	184	424	0.0342	15
54N115W	683	177	506	0.0986	50
54N110W	670	177	493	0.0	0
			Total Basin Runoff:		341

* See text for explanation.

Table 6.4 Normal and 2 x CO_2 Weighted Water Balance Estimation Results

GISS data and -58% for GFDL input. The present study estimates changes in runoff of +28% and -20% for the GISS and GFDL scenarios respectively. Given the discrepancies of scale and analytical depth between these two studies, no attempt is made here to further explain apparent similarities and dissimilarities.

6.4 Alternative Method of Runoff Estimation

Evaluation of the relative importance of individual GCM grid points in terms of regional hydrological impacts of climate change is highly uncertain for two reasons. First, these grid points serve global-scale climatological models and, therefore, are not designed for evaluating possible impacts on a river basin scale. Second, the present physical characteristics (i.e. topography, vegetation) of sub-basin areas represented by certain grid points will probably change, particularly by the time a 2 x CO_2 situation is realized. A method is required that avoids using data point weighting systems, for example, which are based on present conditions, to estimate future scenarios.

The approach developed for this study begins by estimating the evaporation component of the water balance equation using 'normal range' relative humidity data and 'average' sunshine ratio data as the input into the CRAE model (see Sections 6.1 and 6.2). The other data used for the water balance calculations were the 'normal' and 2 x CO_2 results for monthly temperature and annual precipitation from the GISS and GFDL models.

When the water balance equations were solved for each grid point, the differences in runoff between the GCM 2 x CO_2 scenarios and 'normal' simulation were calculated. Thus, the direction and magnitude of possible runoff changes were evaluated without considering the relative importance of the grid points within an overall basin context. By not using a weighting or adjustment factor, the potential for introducing additional error into the estimates is avoided.

Detailed results of the areal evapotranspiration experiments with the CRAE model, using 'low' and 'high' limits for relative humidity and the 'average' sunshine ratio from Table 6.1, are listed in Appendices G-1 through G-30. The results of solving the water balance equation for each GCM grid point are presented in Table 6.5. Annual precipitation data are the sums of the monthly normal and 2 x CO_2 scenario values generated by the two GCMs for the GISS grid points. 'Low' and 'high' indicate actual annual areal evapotranspiration calculated by the CRAE model with low relative humidity and high relative humidity respectively. The runoff estimates were calculated as the difference between precipitation and evaporation for each grid point, with the results differentiated by use of the 'low' and 'high' (relative humidity) versions of evapotranspiration.

The runoff results for the normal and 2 x CO_2 situations derived from the GISS data appear logical. For example, the 50°N115°W (mountains) grid point has the highest runoff value, while grid point 50°N110°W (prairies) has the lowest amount of runoff. The 2 x CO_2 runoff results based on the GFDL (GISS grid) data, however, are similar to the GFDL-generated

GCM GRID POINT	ANNUAL WATER BALANCE COMPONENTS* Precipitation Mean (mm/yr)	Evapotranspiration Low (mm/yr)	Evapotranspiration High (mm/yr)	Runoff Low (mm/yr)	Runoff High (mm/yr)	Runoff Cohen et al. (mm/yr)
a) <u>Normal</u> (1951-1980)						
50N115W	727	304	412	424	314	319
50N110W	390	224	339	166	51	24
50N105W	408	221	323	187	85	8
54N115W	478	231	322	247	156	34
54N110W	435	202	294	233	141	7
b) <u>GISS</u> (2 X CO_2)						
50N115W	901	258	385	643	516	422
50N110W	453	171	311	282	142	37
50N105W	463	174	306	289	157	20
54N115W	568	186	300	382	268	61
54N110W	516	164	272	252	244	24
c) <u>GFDL</u> (2 X CO_2)						
50N115W	493	252	374	241	119	0
50N110W	515	212	326	303	189	0
50N105W	608	201	309	408	299	14
54N115W	683	207	304	477	379	48
54N110W	670	182	279	489	392	41

* See text for explanation.

Table 6.5 Normal and 2 x CO_2 Unweighted Water Balance Estimation Results temperature and precipitation data themselves in that they are difficult to explain empirically. This might be partially due to the fact that the original GFDL grid values were interpolated onto the finer GISS grid after it was determined that the GISS network more adequately described the regional hydroclimate (Cohen et al., 1988).

Table 6.6 shows the ratios of runoff values for the 2 x CO_2 scenarios compared with the 'normal' grid point conditions. This table shows results for the GISS and the GFDL models. Again, the GFDL-model results are difficult to interpret; however, the GISS model results are quite interesting. For 'low' relative humidity the GISS-based ratio (i.e. 'runoff' increase) is surprisingly similar for all five grid points. Four grid points have ratios of between 1.51 and 1.55, while the ratio for grid point 50°N110°W, representing the driest, most sensitive area, is 1.70. Generalizing, the ratio method suggests that the runoff from the basin would increase about 1.55 times under 2 X CO_2; that is, from 88.8 mm/year to about 138 mm/year at the Alberta-Saskatchewan border, without weighting the grid points and without forcing data through the simulation model.

For 'high' relative humidity the driest grid point 50°N110°W (i.e. prairie) again shows the highest GISS-based ratio, 2.73, while results for the other four points again show very similar ratios of change, ranging between 1.64 and 1.84. One might speculate that the change for grid point 50°N110°W seems to indicate some qualitative change. In any case, the ratio for the whole basin is somewhere between 1.7 and 2.2, which would indicate possible 2 X CO_2 runoffs of between 151 and 195 mm/year at the Alberta-Saskatchewan boundary (i.e. as South Saskatchewan River inflow for Lake Diefenbaker).

GCM GRID POINT*	RUNOFF RATIO OF 2 X CO_2 TO NORMAL* CRAE-GISS Low	High	Cohen et al.
a) <u>GISS</u>			
50N115W	1.52	1.64	1.32
50N110W	1.70	2.73	1.54
50N105W	1.54	1.84	1.20
54N115W	1.55	1.72	1.79
54N110W	1.51	1.73	3.43
b) <u>GFDL</u>			
50N115W	0.57	0.38	0.0
50N110W	1.82	3.69	0.0
50N105W	2.17	3.51	1.75
54N115W	1.93	2.43	1.41
54N110W	2.10	2.77	5.86

* See text for explanation.

Table 6.6 Values of 2 x CO_2-to-Normal Runoff Ratio

Similar 2 x CO_2-to-normal ratios were calculated for the same GCM grid points using the unweighted runoff results of Cohen et al. (1988). The GISS-based ratios ranged from 1.20 to 1.79, with the anomalous value of 3.43 occurring at the 54N100W grid point ('boreal forest'). These values display a greater variability, even among the four closest, than do those calculated for the present study (Table 6.6). Unlike the results of Cohen et al., the most extreme runoff change for the present study occurs at the 'prairie' grid point. The GFDL-based runoff ratios are highly variable for both studies, with little similarity of values within and between the sets of results.

CHAPTER 7

INFLUENCE OF CLIMATE CHANGE ON THE RELIABILITY OF LAKE DIEFENBAKER FLOW DATA

The purpose of this chapter is to first describe briefly the method of reservoir performance evaluation developed by Klemes (see Klemes, 1984a) and then to apply this method to Lake Diefenbaker data. It is understood that this approach is applied to illustrate one possible method of statistical evaluation. Realistic operation of the Lake Diefenbaker reservoir is obviously a much more complicated process.

7.1 Evaluation of Reservoir Reliability for Given Minimum and Maximum Storage and Given Target Flow

Klemes studied the reliability of two reservoirs, one in a humid river basin and one in an arid river basin, first by using the existing, historical time series and then by applying a simulated time series of flow generated by the Sacramento hydrological model for given changes in precipitation (P) and evapotranspiration (E). Both the historical and generated flow series are assumed to have log-normal distributions. Klemes calculated means and standard deviations of simulated flow and studied how changes in P and E change the reliability of a reservoir for a given target flow. He further studied different levels of change of P for one given value of E and evaluated new means and standard deviations of the log-normal distribution. An interesting finding is that the mean and standard deviation changes are linear for the humid river basin and are 'more than linear' for the arid river basin. He also studied different reservoir volumes for different levels of reliability and target flow.

The Klemes method for evaluating reservoir reliability can be applied to Lake Diefenbaker for given target flows using historical flow data. Also, assumptions can be made about means and standard deviations of simulated climate change scenarios for streamflow. However, an evaluation of reservoir reliability for Lake Diefenbaker using simulated time series of flow was not possible. To generate such a set of data would require the calibration of a hydrological model (e.g. Sacramento, Tank, Maritime) for the South Saskatchewan River above Lake Diefenbaker. Also required would be simulated time series of temperatures, precipitation, evapotranspiration, and other climatological variables under 2 x CO_2 conditions. While satisfying these needs is considered feasible, as well as necessary for further research, the required work could not be done within this limited study. Therefore, for this study reservoir reliability is evaluated using only the historical time series of streamflow with a special program, FLOWSTOR, which calculates the time-based reliability of flow regulation.

7.2 Statistical Assessment of Lake Diefenbaker Data

In the case of Lake Diefenbaker, operational criteria require a total storage of 9.4 billion m^3 (maximum storage), usable storage of 4.0 billion m^3, and minimum storage (total storage minus usable storage) of

5.4 billion m^3 (SNC Group, 1987). The outflow extremes were set at 42.5 m^3/s (minimum release) and 420 m^3/s (maximum turbine discharge, or critical flow). These operational rules are constant on a monthly basis (i.e. never to be broken) and, therefore, can be used as annual critical values. Interval flows of 100, 150, 200, and 300 m^3/s were also tested. Results for these simplified year-long constant target flows are summarized in Table 7.1.

Monthly minimum and maximum required levels were then calculated for Lake Diefenbaker using the elevation-volume curve and monthly target flows as derived from historical operation reports (Environment Canada, 1987). The historical flow data used are the monthly and annual naturalized flows for the perid 1912 to 1982 as recorded at the Alberta-Saskatchewan boundary. The complete results of the procedure, using the FLOWSTOR program, are listed in Appendix H. In summary, the reliability for Lake Diefenbaker over the 71-year period is 89.9%, for a mean inflow of 299.05 m^3/s, with a standard deviation of 89.86 m^3/s.

The possible impact of inflows representing a climate change scenario on the operation of Lake Diefenbaker is based on the GISS-derived runoff estimates of Chapter 6. Using representative increase ratios of 1.55, 1.7 and 2.2, new means and standard deviations for given probabilities were calculated. The results are summarized in Table 7.2. Also calculated was the two-parameter log-normal distribution for the runoff ratios of 1.0, 1.55, 1.7, and 2.2, as well as a three-parameter log-normal distribution for the 1.0 runoff ratio. The results are summarized in Tables 7.3 to 7.7. The three-parameter log-normal distribution does not yield better results for Lake Diefenbaker data than the two-dimensional one.

Target Flow (m^3/s)	Reliability (%)	Flow above Critical (%)
42.5	100.0	25.2
100.0	100.0	23.5
150.0	100.0	20.1
200.0	100.0	14.8
300.0	80.5	7.0
420.0	51.5	4.0

Minimum Storage Size: 5 400 000 000 dam^3.

Maximum Storage Size: 9 400 000 000 dam^3.

Critical Flow: 420.0 m^3

Table 7.1 Reliability for Target Outflows at Lake Diefenbaker over a 71-year period.

Probability of Non-Exceedance	m (ln)	FLOW N	N*1.55	N*1.7	N*2.2
10	-1.2816	221.37	343.87	376.76	487.98
20	- .8416	246.25	382.45	418.47	542.73
30	- .5245	265.89	412.92	451.80	545.96
40	- .2533	283.92	440.89	482.41	625.65
50	0	301.87	468.72	512.86	665.14
60	0.2533	320.95	498.31	545.23	707.13
70	0.5245	342.72	532.06	582.17	755.03
80	0.8416	370.06	574.44	628.53	815.16
90	1.2816	416.64	638.88	699.05	906.62

Table 7.2 Alternative m(ln) and Inflows for 2 X CO_2-to-Normal Flow Ratio and Given Probabilities.

a) Cumulative Log-Normal Frequency Distribution

MEAN = 299.052
STANDARD DEVIATION = 89.861

PROBABILITY	Z
.050	176.574
.100	196.485
.200	223.634
.300	245.472
.400	265.847
.500	286.402
.600	308.545
.700	334.155
.800	366.786
.900	417.467
.950	464.542

b) Log-Normal Distribution-Table of Expected Frequencies

SAMPLE SIZE = 71
MEAN = 299.052
STANDARD DEVIATION = 89.861

CLASS LIMITS	FREQ.	f(I)	PROB.
- 140.00	.542	.021	.008
140.00 - 200.00	7.336	.189	.111
200.00 - 260.00	18.469	.378	.371
260.00 - 320.00	19.609	.371	.647
320.00 - 380.00	13.109	.251	.832
380.00 - 440.00	6.813	.137	.928
440.00 - 500.00	3.052	.066	.971
500.00 - 560.00	1.256	.030	.989
560.00 - 620.00	.494	.013	.995
620.00 - 680.00	.189	.005	.998
680.00 -	.130		1.000

Table 7.3 Two-Parameter Log-Normal Distribution for Runoff Ration = 1.0

a) Cumulative Log-Normal Frequency Distribution		b) Log-Normal Distribution-Table of Expected Frequencies			
MEAN = 463.531 STANDARD DEVIATION = 139.285		SAMPLE SIZE = 71 MEAN = 463.531 STANDARD DEVIATION = 139.285			
PROBABILITY	Z	CLASS LIMITS	FREQ.	f(I)	PROB.
.050	273.689	- 140.00	.017	.000	.000
.100	304.551	140.00 - 200.00	.234	.010	.004
.200	346.632	200.00 - 260.00	2.201	.076	.035
.300	380.482	260.00 - 320.00	6.972	.215	.133
.400	412.063	320.00 - 380.00	11.764	.347	.298
.500	443.922	380.00 - 440.00	13.434	.399	.488
.600	478.245	440.00 - 500.00	12.042	.368	.657
.700	517.941	500.00 - 560.00	9.104	.292	.785
.800	568.519	560.00 - 620.00	6.153	.209	.872
.900	647.074	620.00 - 680.00	3.858	.139	.926
.950	720.040	680.00 -	5.220		1.000

Table 7.4 Two-Parameter Log-Normal Distribution for Runoff Ratio = 1.55

a) Cumulative Log-Normal Frequency Distribution

MEAN = 508.388
STANDARD DEVIATION = 152.764

PROBABILITY	Z
.050	300.175
.100	334.024
.200	380.177
.300	417.303
.400	451.940
.500	486.883
.600	524.527
.700	568.064
.800	623.537
.900	709.694
.950	789.721

b) Log-Normal Distribution-Table of Expected Frequencies

SAMPLE SIZE = 71
MEAN = 508.388
STANDARD DEVIATION = 152.764

CLASS LIMITS	FREQ.	f(I)	PROB.
- 140.00	.015	.000	.000
140.00 - 200.00	.087	.004	.001
200.00 - 260.00	1.077	.041	.017
260.00 - 320.00	4.272	.144	.077
320.00 - 380.00	8.726	.280	.200
380.00 - 440.00	11.742	.376	.365
440.00 - 500.00	12.155	.397	.536
500.00 - 560.00	10.415	.356	.683
560.00 - 620.00	7.934	.284	.795
620.00 - 680.00	5.499	.209	.872
680.00 - 740.00	3.586	.145	.923
740.00 - 800.00	2.243	.096	.954
800.00 - 860.00	1.356	.061	.973
860.00 - 920.00	.802	.038	.985
920.00 - 980.00	.464	.023	.991
980.00 - 1040.00	.266	.014	.995
1040.00 - 1100.00	.151	.009	.997
1100.00	.211		1.000

Table 7.5 Two-Parameter Log-Normal Distribution for Runoff Ratio = 1.70

a) Cumulative Log-Normal Frequency Distribution

MEAN = 657.914
STANDARD DEVIATION = 197.694

PROBABILITY	Z
.050	388.462
.100	432.266
.200	491.994
.300	540.039
.400	584.863
.500	630.083
.600	678.800
.700	735.142
.800	806.930
.900	918.428
.950	1021.992

b) Log-Normal Distribution-Table of expected Frequencies

SAMPLE SIZE = 71
MEAN = 657.914
STANDARD DEVIATION = 197.694

CLASS LIMITS	FREQ.	f(I)	PROB.
- 140.00	.014	.000	.000
140.00 - 200.00	.003	.000	.000
200.00 - 260.00	.089	.004	.001
260.00 - 320.00	.658	.028	.011
320.00 - 380.00	2.279	.091	.043
380.00 - 440.00	4.834	.189	.111
440.00 - 500.00	7.436	.293	.216
500.00 - 560.00	9.100	.368	.344
560.00 - 620.00	9.529	.398	.478
620.00 - 680.00	8.839	.386	.603
680.00 - 740.00	7.471	.344	.708
740.00 - 800.00	5.968	.287	.792
800.00 - 860.00	4.493	.228	.855
860.00 - 920.00	3.259	.174	.901
920.00 - 980.00	2.303	.129	.933
980.00 - 1040.00	1.584	.093	.956
1040.00 - 1100.00	1.072	.066	.971
1100.00	2.069		1.000

Table 7.6 Two-Parameter Log-Normal Distribution for Runoff Ratio = 2.2

a) Cumulative Log-Normal Frequency Distribution

MEAN = 299.052
STANDARD DEVIATION = 89.861
SKEWNESS = .846

PROBABILITY	Z
.050	174.366
.100	195.196
.200	223.326
.300	245.751
.400	266.526
.500	287.353
.600	309.655
.700	335.286
.800	367.714
.900	417.623
.950	463.537

b) Log-Normal Distribution-Table of Expected Frequencies

SAMPLE SIZE = 71
MEAN = 299.052
STANDARD DEVIATION = 89.861
SKEWNESS = .846

CLASS LIMITS	FREQ.	f(I)	PROB.
- 140.00	.705	.026	.010
140.00 - 200.00	7.431	.193	.115
200.00 - 260.00	17.997	.377	.368
260.00 - 320.00	19.506	.373	.643
320.00 - 380.00	13.301	.253	.830
380.00 - 440.00	6.967	.137	.928
440.00 - 500.00	3.093	.064	.972
500.00 - 560.00	1.243	.028	.989
560.00 - 620.00	.473	.011	.996
620.00 - 680.00	.173	.004	.998
680.00 -	.110		1.000

Table 7.7 Three-Parameter Log-Normal Distribution for Runoff Ratio = 1.0

These results are used here for the purpose of statistical evaluation only, and are not intended for 'real-life' operational applications. Lake Diefenbaker cannot be studied in isolation of the overall Saskatchewan River basin and the complex human management system within which it functions. Nevertheless, the results seem to indicate much higher extreme flows, with all the necessary water resource planning and management consequences (Riebsame, 1988; Williams, 1987). For example, the probability of floods would likely increase substantially; however, the likelihood of drought would not be significantly reduced. A qualitative assessment of these changes, including socio-economic implications, is the logical next step for research. Unfortunately, such extended work is beyond the scope of this study.

CHAPTER 8

CONCLUSION

8.1 Summary of Results

The overall objective of this study has been to investigate methods, techniques and data for the purpose of assessing the possible impacts of climate change scenarios on the operation of a water-supply reservoir. The following presentation of the study results is based on the three specific study objectives as stated in the report Introduction.

8.1.1 Research Framework

Based on a comprehensive review of the relevant literature, a research framework consisting of five main methodological components was defined. Each component and its linkages within the framework were explained in detail. The result is a basic methodology that begins with the examinantion of climate change, due to primarily a human-enhanced "greenhouse effect", at the general, cursory level. The second major level of inquiry concentrates on the water-resource implications of climate change. The sequence of foci at this level begins with the impact of climate change variables on a specific hydrological variable, in this case evaporation and evapotranspiration. The results are then used as input for assessing impacts on the overall hydrological regime, in particular streamflow and runoff. Finally, the hydrological scenarios are analysed in terms of the performance of a water management activity, using the water-supply reservoir at Lake Diefenbaker as the study case.

8.1.2 Database

The database was designed and stored on a desk-top microcomputer. The data were organized in parallel blocks and block groups according to type of variable, origin of data and their research application. Special custom programs were written in a common FORTRAN language for the purpose of manipulating certain data. This basic structure and associated programming enhances freedom of movement of data blocks and specific files. The main types of information included in the resultant database are: climate change scenarios from two general circulation models (GCMs); historical records from selected climate stations; historical streamflow records; model-simulated evaporation and evapotranspiration data; and basic climate change scenarios for water balance components.

8.1.3 Case Study Application

The lake evaporation and areal evapotranspiration models, developed by Morton and based on the theorized complementary relationsihp between potential and actual evapotranspiration, were selected for use in this study. The application of these models to the South Saskatchewan River-Lake Diefenbaker study area involved simulation of historical conditions, comparison of results with those of other model simulations, and experiments with climate change scenario data. The results of the historical simulation of Lake Diefenbaker evaporation compared well with separate results for another lake within the general vicinity. However, the results differed considerably from comparative estimates for Lake Diefenbaker itself. The primary cause of this discrepancy is assumed to be the basic differences between the concepts and formulae that drive the respective models. The Morton models were the preferred choice for further applications in the study because they are physically based, extensively tested and relatively easy to use.

Estimates of evaporation and evapotranspiration under 2 X CO_2 climate change conditions used a combination of relevant GCM output and hypothesized alterations of historical values for other climatic variables required to run the CRAE and CRLE models. The results of one method of estimation indicate that annual evaporation at Lake Diefenbaker would increase approximately 16% according to GISS data, and about 7% based on GFDL input, in comparison to estimates of historical values. A second estimation method produced changes from normal of between 10 and 14% for GISS input and 3 and 6% for GFDL data. The overall results illustrate how lake evaporation decreases with increased average lake depth and decreased dew point temperature. In comparison, any changes in insolation values seemed to be of secondary importance. In terms of annual areal evapotranspiration in the study area, potential values were estimated to exceed historical data by 12% for GISS input and 6% for GFDL input, while actual evapotranspiration would decline by 3% for both GCM climate change scenarios.

Streamflow estimation was attempted using the basic water balance equation: R = P-E-S, where R is runoff, P is precipitation, E is evaporation and S is storage change. Storage changes were assumed to average themselves out over the long run and therefore the term was dropped from the equation. GCM precipitation scenarios were used and a combination of GCM temperature scenarios and hypothesized manipulations of historical values for other climatic variables were used to estimate evapotranspiration. Again, two methods of runoff estimation were tested. The first method adjusted runoff values at each GCM grid point according to an "effective/gross ratio" weighting factor for its portion of the total drainage area. This method estimated a 28% increase in runoff from normal values, according to the GISS scenario, and a 20% decrease based on the GFDL data. These results are similar in the direction of change but less in relative magnitude when compared to the results of a separate but parallel study done in the same region.

An alternative method of runoff estimation was tested in order to avoid considering the relative importance of individual GCM grid points within an overall basin context. This was accomplished by calculating for each grid point a "2 X CO_2/normal ratio" for runoff. Two hypothetical estimates for relative humidity, termed low and high, were also tested. The ratios were surprising constant at between 1.51 and 1.55 for four of the five grid points, based on the GISS scenario with low humidity. Both sets of GFDL-based ratios, as well as the results of using GISS data with high humidity values, displayed more variable results. In comparison, the GISS-based ratios calculated using the results of the same parallel study referenced above ranged form 1.20 to 1.79. In summary, the present study results suggest runoff changes from normal of approximately -20%, +30% and +50%, depending on the estimation method and the 2 X CO_2 scenario used.

The final step of the case study application involved a statistical assessment of the impact of climate change on reservoir reliability. A method proposed by Klemes for evaluating reservoir reliability was initially tested using historical data for Lake Diefenbaker. Then the GISS-derived runoff estimates, using the representative 2 X CO_2/normal ratios, were tested. The climate change results indicate that based on higher extreme flows, the likelihood of flood events would increase but the probability of drought would not be reduced significantly. It was noted that the specific results of this statistical evaluation are not intended for application in real-life operation of the Lake Diefenbaker reservoir.

8.2 Recommendations

The recommendations evolving from the research conducted and the results obtained are, as is so often the case, directly related to the limitations of the study. For this attempt at assessing the possible impacts of climate on the operation of a water-supply reservoir, the main difficiencies due to time and resource limitations are in the areas of data adequacy and analytical completeness. The following recommendations address these difficiencies as well as other pertinent issues.

8.2.1 FURTHER CLIMATE CHANGE IMPACT ASSESSMENT OF THE SOUTH SASKATCHEWAN RIVER-LAKE DIEFENBAKER CASE SHOULD BE CONDUCTED USING THE KEY RESULTS OF THIS STUDY AND OTHER RELEVANT INFORMATION FROM SOURCES, SUCH AS IWD WESTERN AND NORTHERN REGION, AS INPUT FOR A MORE COMPREHENSIVE APPLICATION OF A KLEMES-LIKE WATER-SUPPLY RELIABILITY ASSESSMENT AND FOR A DETAILED SOCIO-ECONOMIC ASSESSMENT USING THE WATER USE ANALYSIS MODEL (WUAM) OF INLAND WATERS DIRECTORATE.

Elaboration on the possible effects of the climate change estimates for the South Saskatchewan River Basin on the operation of Lake Diefenbaker is required in terms of: overall variability and seasonal distribution of hydrological variables; water levels and discharge; the storage-yield relationship (change in yield from a given storage and change in storage to maintain a given yield); and reliability of supply. The results of this type of analysis will complement an assessment of the socio-economic implications using the WUAM, which is the logical follow-up of this study as envisioned in the research rationale and incorporated in the research strategy.

8.2.2 THE RESEARCH FRAMEWORK AND METHODOLOGY OPTIONS DEFINED FOR THIS STUDY AND APPLIED TO THE LAKE DIEFENBAKER CASE SHOULD BE TESTED FOR OTHER GEOGRAPHIC LOCATIONS USING COMMON SOURCE, NON-GCM TYPES OF CLIMATE CHANGE INFORMATION.

As noted in this report, the Lake Diefenbaker case was considered a suitable natural system for testing the possible hydrological impacts of climate change. Its inputs and outputs are relatively well-defined and its location is within a semi-arid, marginal water-supply region where the earliest signals of climate change impacts are most likely to occur. However, some practitioners may consider this assessment of Lake Diefenbaker as over-simplified. Regardless of how one perceives the selected study area, the research framework developed for this study should be applied to the widest range possible of sample sites in order to test its sensitivity to water system complexity and location. Similarly, data sets generated by other GCMs and non-GCM sources should be applied using the proposed research framework. For example, records from climate stations that currently demonstrate the range of possible climate change conditions could be used a surrogate or proxy time series data sets.

8.2.3 EVALUATION OF THE RELIABILITY AND SUITABILITY OF THE FULL RANGE OF GCM RESULTS FOR 2 x CO_2 CLIMATE CHANGE SCENARIOS SHOULD BE CONSIDERED IN TERMS OF THEIR APPLICATION TO REGIONAL HYDROLOGICAL IMPACT ASSESSMENT.

Only temperature, precipitation and potential evapotranspiration data generated by the GISS and GFDL models were included in this study. Net radiation has been suggested as a substitute for temperature for estimating evaporation, for example. Results from other GCMs (NCAR, OSU, UKMO) and new versions of the GISS and GFDL models are now available for a variety of variables including humidity and wind. The first version of the Canadian Climate Centre GCM results are expected to be available in early 1989. The acquisition of required data generated by a common source, be it GCM, hypothetical or surrogate data, would enhance impact studies. Detailed assessments and comparisons of GCMs and other climatic and hydrologic models are available to aid informed applications by impact researchers.

8.2.4 ANALYSIS OF STREAMFLOWS UNDER CLIMATE CHANGE SCENARIOS SHOULD BE PERFORMED USING SIMULATED TIME SERIES INDICATIVE OF THE CURRENT ESTIMATED TIMING OF CLIMATE CHANGE.

Flow simulations to 2030 or 2050 (the estimated dates for realization of 2 x CO_2) were not readily available when this study was conducted. However, some work in this area relevant to Lake Diefenbaker has been attempted by Inland Waters Directorate in Regina. A simulation model, such as the TANK model used by Inland Waters Directorate or the SRM model, which were both positively evaluated by WMO, would need to be adapted and calibrated for the study area (Martinec, 1985). Whatever the choice of simulation model, hierarchical systematic testing as recommended by Klemes (1984b) should be performed.

8.2.5 FURTHER TESTING OF THE CRAE AND CRLE MODELS FOR CLIMATE CHANGE RESEARCH APPLICATIONS SHOULD BE CONDUCTED USING CONTINUOUS DATA SETS OF AT LEAST 30 YEARS FOR CRITICAL VARIABLES.

Evaluation of these models for the purposes of this study was largely based on two years of data, 1973 and 1977. Some researchers may consider this limitation problematic because the whole of 1973 was an abnormally dry year and the spring of 1977 was also unusually dry for the study area. A 30-year period is normally used for defining a characteristic climate for a particular location and, therefore, should be used in any further investigation of this type.

8.2.6 THE CRAE AND CRLE MODELS SHOULD BE ASSESSED FOR CAPABILITY ENHANCEMENT AND TESTED FOR OTHER APPLICATIONS IN TERMS OF THE IMPACT OF CLIMATE CHANGE ON EVAPORATION, EVAPOTRANSPIRATION AND RELATED CLIMATOLOGICAL AND HYDROLOGICAL PROCESSES.

The results of this study indicate that the CRLE model has considerable potential for feedback modelling of how lake evaporation changes influence interface air temperature. While extension of the model to implement this capability requires basic rather than applied hydrological research, it nevertheless deserves further study. Also, the potential of the two models to produce estimates of evaporation and evapotranspiration for the purpose of detecting and monitoring the effects of climate change should be investigated.

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LIST OF PROGRAMS

```
        PROGRAM RELHUMID
C    CALCULATE RELATIVE HUMIDITY FROM DRY BULB TEMPERATURE AND DEW POINT
C    TEMPERATURE
C
        REAL*8    ALPHA(2),BETA(2)
        REAL*8    A,B,T,RH,TD
        CHARACTER ONAME*11,INAME*11,CHR*1
C
        ALPHA(1) = 17.27
        BETA(1)  = 237.3
        ALPHA(2) = 21.88
        BETA(2)  = 265.5
C
        WRITE(*,'(//A,\)')' INPUT FROM FILE ? [Y/N] : '
        READ(*,'(A)') CHR
        IF (CHR.EQ.'Y' .OR. CHR.EQ.'y') THEN
          WRITE(*,'(A,\)')' ENTER INPUT FILE NAME :
          READ(*,'(A)') INAME
          OPEN(1,FILE=INAME,STATUS='OLD')
        ENDIF
C
5       WRITE(*,'(/A,\)')' ENTER OUTPUT FILE NAME : '
        READ(*,'(A)',ERR=5) ONAME
        OPEN(2,FILE=ONAME,STATUS='NEW')
C
        DO 100 K=1,1000
          IF (CHR.EQ.'Y' .OR. CHR.EQ.'y') THEN
             READ(1,'(2(F9.0,1X))',END=999) TD,T
          ELSE
10           WRITE(*,'(//A,\)')' ENTER DRY BULB TEMPERATURE : '
             READ(*,*,ERR=10) T
             IF (T .LT. -100) GOTO 999
C
          IF (T .GE. 0) THEN
             I = 1
          ELSE
             I = 2
          ENDIF
C
          A=ALPHA(I)*T/(BETA(I)+T)
          B=ALPHA(1)*TD/(BETA(1)+TD)
          RH=DEXP(B-A)
C
          WRITE(*,'(/A,F7.2)')') ' RELATIVE HUMIDITY : ',RH
          WRITE(2,'(3(F9.3,1X))') TD,T,RH
100       CONTINUE
C
999       STOP
          END
```

```
        PROGRAM DEWPOINT
C
     CALCULATE DEW POINT TEMPERATURE FROM RELATIVE HUMIDITY AND DRY BULB
C    TEMPERATURE
C
        REAL*8    ALPHA(2),BETA(2)
        REAL*8    A,B,T,RH,TD,RHC
        CHARACTER INAME*11,ONAME*11,CHR*1
C
        ALPHA(1) = 17.27
        BETA(1)  = 237.3
        ALPHA(2) = 21.88
        BETA(2)  = 265.5
C
        WRITE(*,'(//A,\)')' INPUT FROM FILE ? [Y/N] : '
        READ(*,'(A)') CHR
        IF (CHR.EQ.'Y' .OR. CHR.EQ.'y') THEN
          WRITE(*,'(A,\)')' ENTER INPUT FILE NAME :
          READ(*,'(A)') INAME
          OPEN(1,FILE=INAME,STATUS='OLD')
        ENDIF
C
5       WRITE(*,'(/A,\)')' ENTER OUTPUT FILE NAME : '
        READ(*,'(A)',ERR=5) ONAME
        OPEN(2,FILE=ONAME,STATUS='NEW')
C
        WRITE(*,'(/A,\)')' ENTER MULTIPLICATION CONSTANT FOR REL. HUM. : '
        READ(*,*,ERR=7) RHC
C
        DO 100 K=1,1000
          IF (CHR.EQ.'Y' .OR. CHR.EQ.'y') THEN
             READ(1,*,END=999) T,RH
             WRITE(*,'(2F10.2)') T,RH
          ELSE
10           WRITE(*,'(//A,\)')' ENTER TEMPERATURE       : '
             READ(*,*,ERR=10) T
             IF (T .LT. -100) GOTO 999
C
20           WRITE(*,'(A,\)')  ' ENTER REL. HUMIDITY (%) : '
             READ(*,*,ERR=20) RH
             RH=RH/100.
          ENDIF
C
          RH=RH*RHC
          IF (T .GE. 0) THEN
             I = 1
          ELSE
             I = 2
          ENDIF
C
```

```
            A=DLOG(RH)+ALPHA(I)*T/(BETA(I)+T)
            TD=A*BETA(1)/(ALPHA(1)-A)
C
            WRITE(*,'(/A,F7.2)') ' DEW POINT TEMPERATURE : ',TD
            WRITE(2,'(3(F9.3,1X))') TD,T,RH
C
100         CONTINUE
C
999         STOP
            END
```

STOR.FOR

```
     NOFLOATCALLS
        PROGRAM FLOWSTOR
C
C    CALCULATE TIME-BASED RELIABILITY OF FLOW REGULATION
C
        REAL FL(12),MON(12),STOR1(12),STOR2(12),TFLOW(12)
        CHARACTER ONAME*11,INAME*11,CHR*1,FMT*10,IYR*4
        REAL LOW,HIGH
C
        DATA MON/31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.,31./
C
        WRITE(*,'(////A,\)')' ENTER INPUT FILE NAME (MONTHLY FLOWS) : '
        READ(*,'(A)') INAME
        OPEN(1,FILE=INAME,STATUS='OLD')
        READ(1,'(/////)')
C
5       WRITE(*,'(/A,\)')' ENTER OUTPUT FILE NAME : '
        READ(*,'(A)',ERR=5) ONAME
C
        CALL LEN (INAME,FMT)
        IF (ONAME .EQ. '           ') THEN
        WRITE(ONAME,FMT) INAME,'.RES'
        ENDIF
        OPEN(2,FILE=ONAME,STATUS='NEW')
        WRITE(ONAME,FMT) INAME,'.MNS'
        OPEN(3,FILE=ONAME,STATUS='NEW')
C
7       WRITE(*,'(/A,\)')
       .' ENTER STORAGE CAPACITY (MIL OF CUBIC M) : '
        READ(*,*,ERR=7) STOR
C        WRITE(*,*) STOR
        WRITE(2,'(A,F10.3)')
       .' STORAGE CAPACITY (MIL OF CUBIC M) : ',STOR
C
        WRITE(*,'(//A,A,\)')
       .' DO YOU WANT TO ENTER MONTHLY MIN&MAX STORAGE CAPACITY ',
       .'FROM FILE ? [Y/N] : '
        READ(*,'(A)') CHR
        IF (CHR .EQ. 'Y' .OR. CHR .EQ. 'y') THEN
8         WRITE(*,'(/A,\)')' ENTER FILE NAME : '
          READ(*,'(A11)',ERR=8) INAME
          OPEN(4,FILE=INAME,STATUS='OLD')
          DO 9 I=1,12
9            READ(4,* STOR1(I),STOR2(I)
          DO 10 I=1,12
10        READ(4,*,END=15) TFLOW(I)
        ELSE
11        WRITE(*,'(/A,\)')
       .  ' ENTER MINIMUM STORAGE SIZE (MIL OF CUBIC M) : '
          READ(*,*,ERR=11) STOR1(1)
12        WRITE(*,'(/A,\)')
       .  ' ENTER MAXIMUM STORAGE SIZE (MIL OF CUBIC M) : '
```

```
          READ(*,*,ERR=12) STOR2(1)
        IF (STOR2(1) .EQ. 0.0) STOR2(1)=STOR
          DO 13 I=2,12
             STOR1(I)=STOR1(1)
13           STOR2(I)=STOR2(1)
        ENDIF
        GOTO 20
C
15      WRITE(*,'(/A,\)')\ ENTER TARGET FLOW (CUBIC M/SEC) : '
        READ(*,*,ERR=15) TFLOW(1)
        DO 16 I=2,12
16      TFLOW(I)=TFLOW(1)
20      WRITE(2,'(/A,/A,/A)')
       .' MONTH STORAGE SIZE (MIL OF CUBIC M)    TARGET FLOW',
       .'             MINIMUM         MAXIMUM   (CUBIC M/SEC)',
       .' --------------------------------------------------'
        WRITE(2,'(I4,1X,3F16.3)') (I,STOR1(I),STOR2(I),TFLOW(I),I=1,12)
C
21      WRITE(*,'(/A,\)')' ENTER CRITICAL FLOW (CUBIC M/SEC) ; '
        READ(*,*,ERR=21) CFLOW
        WRITE(2,'(/A,F8.1)')' CRITICAL FLOW (CUBIC M/SEC) : ',CFLOW
        STOR=(STOR1(1)+STOR2(1))/2.0
        LOW=0.0
        HIGH=0.0
        QMEAN=0.0
        QSQ=0.0
        QMEANL=0.0
        QSQL=0.0
C
C
        WRITE(2,'(//A/A/A)')
       .' YEAR MONTH    INPUT   STORAGE      FLOW  FLOW-TFLOW',
       .'                       (IN MIL)',
       .' ---------------------------------------------------'
C
        DO 120 K=1,10000
          READ(1,'(4X,A4,12F9.0)',END=200) IYR,(FL(I),I=1,12)
          SUMX=0.0
          DO 100 I=1,12
             SUMX=SUMX+FL(I)
             STOR=STOR+(FL(I)*MON(I)*24.0*3600.0)/1000000.0)
             FLOW=(TFLOW(I)*MON(I)*24.0*3600.0)/1000000.0
             WRITE(2,'(5F20.3)')STOR,FLOW,STOR-FLOW,TFLOW(I),MON(I)
C
C
             IF (STOR-FLOW .LT. STOR1(I)) THEN
                FLOW=(STOR-STOR1(I))/(MON(I)*24.0*3600.0/1000000.0)
                STOR=STOR1(I)
                LOW=LOW+1
             ELSE IF (STOR-FLOW .GT. STOR2(I)) THEN
                FLOW=(STOR-STOR2(I))/(MON(I)*24.0*3600.0/1000000.0)
```

```
              STOR=STOR2(I)
              IF (FLOW .GE. CFLOW) HIGH=HIGH+1
           ELSE
              STOR=STOR-FLOW
              FLOW=TFLOW(I)
           ENDIF
      WRITE(2,'(1X,A4,I5,F10.1,F10.0,2F10.1)')
     .IYR,I,FL(I),STOR,FLOW,FLOW-TFLOW(I)
100   CONTINUE
      WRITE(2,'(52X,A4,A,F8.2)') IYR,' MEAN = ',SUMX/12.0
      WRITE(3,'(1X,A4,A,F8.2)') IYR,' MEAN = ',SUMX/12.0
      QMEAN=QMEAN+SUMX/12.0
      QSQ=QSQ+(SUMX/12.0)**2
      QMEANL=QMEANL+LOG(SUMX/12.0)
      QSQL=QSQL+LOG(SUMX/12.0)**2
120   CONTINUE
C
200   LOW=100.0-100.0*LOW/((K-1)*12)
      HIGH=100.0*HIGH/((K-1)*12)
      WRITE(2,'(//A,I2,A,F5.1,/,A,F5.1)')
     .' RELIABILITY (IN %) OVER ',K-1,' YEAR PERIOD : .',LOW,
     .' FLOW ABOVE CRITICAL (IN %) : ',HIGH
      QMEAN=QMEAN/(K-1)
      QSQ=SQRT( (QSQ/(K-1)-QMEAN**2) % ((K-1)/(K-2)) )
      QMEANL=QMEANL/(K-1)
      QSQL=SQRT( (QSQL/(K-1)-QMEANL**2) % ((K-1)/(K-2)) )
      WRITE(2,'(//A,F8.3,3(/A,F8.3))')
     .' MEAN : ',QMEAN,' S     : ',QSQ,
     .' MEAN(LN) : ',QMEANL,
     .' S(LN)    : ',QSQL
      WRITE(3,'(//A,F8.3,3(/A,F8.3))')
     .' MEAN : ',QMEAN,' S     : ',QSQ,
     .' MEAN(LN) : ',QMEANL,
     .' S(LN)    : ',QSQL
C
999   STOP
      END
      SUBROUTINE LEN (INAME,FMT)
      CHARACTER INAME*11,FMT*10,CHR*1
      DO 10 I=1,7
        WRITE(FMT,'(A2,I1,A4)') '(T',I,',A1)'
        READ(INAME,FMT) CHR
        IF (CHR .EQ. ' ' .OR. CHR .EQ. '.') THEN
           WRITE(FMT,'(A2,I1,A4)') '(A',I-1,',A4)'
           GOTO 99
        ENDIF
10    CONTINUE
      WRITE(FMT,'(A7)') '(A7,A4)'
C
99    RETURN
      END
```