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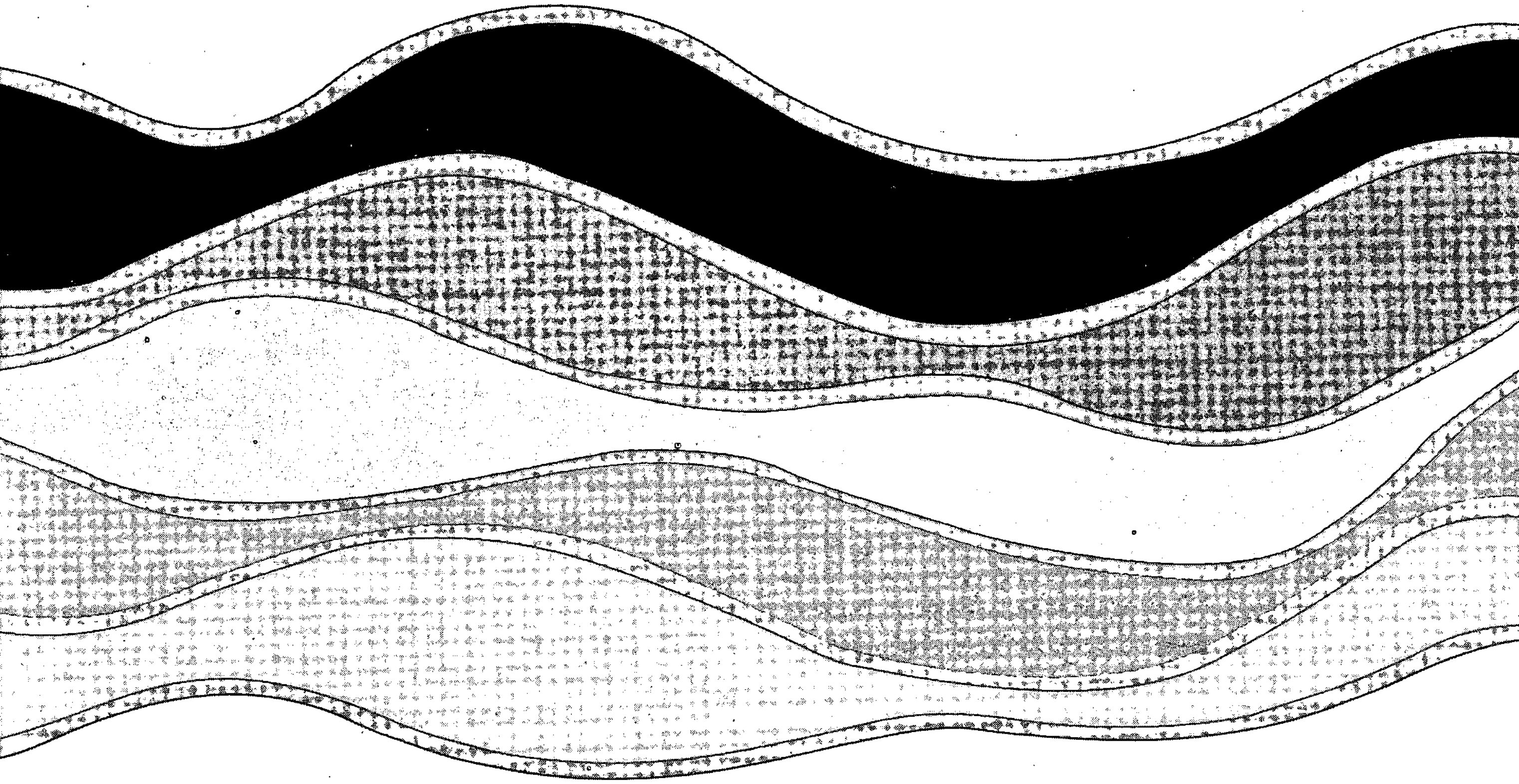

THE EFFECT ON LONG-TERM CLIMATIC CHANGE ON GROUNDWATER - LAKE SYSTEMS

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THE EFFECT ON LONG-TERM CLIMATIC CHANGE ON GROUNDWATER - LAKE SYSTEMS

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MANAGEMENT PERSPECTIVE

Concerns over global warming have resulted in a number of studies focusing on the effects of temperature and precipitation changes on water resources. Although much research has investigated the effects on stream flow and soil moisture, little work has addressed the impact on the groundwater flow regime. Because long-term groundwater studies on a regional scale require a considerable amount of costly instrumentation, and this instrumentation must be monitored for many years, conventional groundwater studies are not appropriate for hydrogeological studies related to global warming. The approach taken here to assess the impact of long-term climatic changes on the groundwater flow regime is by examining the impact of climatic change on lake watershed systems. In many cases, where the contribution of groundwater to the hydrological balance of a lake is important, lakes are essentially a surface expression of the groundwater flow regime. A lumped parameter lake-watershed model is used to provide insight into the effects of long-term climatic change on a groundwater-lake system in the prairie region of Alberta, Canada. The model used in this study is based on an extension of conventional water balance methods. The model was successfully calibrated against a 50-year record of climatic and lake records. The effects of climatic change on this watershed indicate that groundwater recharge and storage will decline at a greater rate than other hydrological components affecting the lake. The salinity of the lake water will increase dramatically in response to small changes in temperature and precipitation. The changes to the volume of water in the lake will change but not as significantly as lake salinity. This paper was written as an invited contribution to special issue of the Journal of Hydrology on the *Hydrogeology of Wetlands*, based on a symposium held at the 28th International Geological Congress, Washington D.C., July, 1989.

PERSPECTIVE DE LA DIRECTION

Les préoccupations relatives au réchauffement de la planète se sont traduites par la réalisation de plusieurs études sur les effets des variations de la température et des précipitations sur les ressources en eau. Même si une grande partie des recherches ont porté sur les répercussions sur le débit fluvial et la teneur en eau du sol, quelques travaux ont porté sur les incidences sur le régime d'écoulement des eaux souterraines. Parce que les études à long terme sur les eaux souterraines menées à l'échelle régionale nécessitent un grand nombre d'instruments coûteux, et que ces instruments doivent être surveillés pendant plusieurs années, les études classiques sur les eaux souterraines ne conviennent pas aux études hydrogéologiques liées au réchauffement de la planète. L'approche adoptée pour évaluer les incidences des variations climatiques à long terme sur le régime d'écoulement des eaux souterraines consiste à étudier les répercussions des changements climatiques sur les réseaux de bassin versant des lacs. Dans plusieurs cas, lorsque l'apport d'eaux souterraines au bilan hydrologique d'un lac est important, les lacs sont essentiellement une expression en surface de l'écoulement des eaux souterraines. Un modèle à paramètres localisés bassin versant - lac est utilisé afin de comprendre les effets des changements climatiques à long terme sur le réseau eaux souterraines-lacs dans la région des prairies en Alberta (Canada). Le modèle utilisé dans la présente étude est fondé sur un élargissement des méthodes classiques d'équilibre hydrologique. Le modèle a été étalonné avec succès par rapport à des relevés climatiques et des lacs couvrant une période de 50 ans. Les effets des changements climatiques sur ce bassin versant montrent que l'alimentation d'une nappe souterraine et la retenue diminueront plus rapidement que les autres composantes hydrologiques agissant sur le lac. La salinité de l'eau du lac augmentera de façon spectaculaire en réponse aux faibles variations de la température et des précipitations. Les variations du volume d'eau dans le lac changeront, mais de façon moins importante que la salinité du lac. Le présent article a été rédigé suite à une sollicitation en vue d'un numéro spécial du Journal d'hydrologie portant sur l'hydrogéologie des terres humides (Hydrogeology of Wetlands) à partir d'un colloque qui a eu lieu lors du Vingt-huitième congrès international de géologie à Washington (D.C.), en juillet 1989.

ABSTRACT

Concerns over global warming have resulted in a number of studies focusing on the effects of temperature and precipitation changes on water resources. Although much research has investigated the effects on streamflow and soil moisture, little work has addressed the impact on the groundwater flow regime. A lumped parameter lake-watershed model is used to provide insight into the effects of long-term climatic change on a groundwater-lake system in the prairie region of Alberta, Canada. This model is based on an extension of conventional water balance methods. The model was successfully calibrated against a 50-year record of climatic and lake records. The effects of climatic change on this watershed indicate that groundwater recharge and storage will decline at a greater rate than other hydrological components affecting the lake. The salinity of the lake water will increase dramatically in response to small changes in temperature and precipitation. The changes to the volume of water in the lake will change but not as significantly as lake salinity.

RÉSUMÉ

Les préoccupations relatives au réchauffement de la planète se sont traduites par la réalisation de plusieurs études sur les effets des variations de la température et des précipitations sur les ressources en eau. Même si une grande partie des recherches ont porté sur les répercussions sur le débit fluvial et la teneur en eau du sol, quelques travaux ont porté sur les incidences sur le régime d'écoulement des eaux souterraines. Un modèle à paramètres localisés bassin versant - lac est utilisé afin de comprendre les effets des changements climatiques à long terme sur le réseau eaux souterraines-lacs dans la région des prairies en Alberta (Canada). Le modèle utilisé dans la présente étude est fondé sur un élargissement des méthodes classiques d'équilibre hydrologique. Le modèle a été étalonné avec succès par rapport à des relevés climatiques et des lacs couvrant une période de 50 ans. Les effets des changements climatiques sur ce bassin versant montrent que l'alimentation d'une nappe souterraine et la retenue diminueront plus rapidement que les autres composantes hydrologiques agissant sur le lac. La salinité de l'eau du lac augmentera de façon spectaculaire en réponse aux faibles variations de la température et des précipitations. Les variations du volume d'eau dans le lac changeront, mais de façon moins importante que la salinité du lac.

INTRODUCTION

The recent awareness about global warming has raised concerns about the potential impact of long-term climatic change on the environment. While it is widely recognized that the cause of global warming is the unregulated rise in the quantities of man-made emissions into the atmosphere (SO_4, NO_3, CH_4, CFC's, and primarily CO_2), predicting the long-term consequences of global warming, and especially how it will affect the hydrological balance on a regional scale, is much more difficult. In areas where this climatic change could impact negatively on a regional water supply, it is important to quantifying this impact to determine if, and what type of, water management programs should be implemented.

An area where climatic change could adversely affect the hydrological balance is the prairies or plains of western Canada and the United States, a region where present water resources are constrained. Of particular concern is the effect of global warming on the groundwater resources of this region. For example, in western Canada, over 90% of the rural population and many municipalities rely on groundwater for their domestic needs (Hess, 1986). However, research on how global warming will affect water resources typically has not addressed the groundwater environment, but has primarily focused on soil moisture (Smit et al., 1983; Manabe et al., 1981; Manabe and Wetherald, 1986; Manabe and Delworth, 1990) and stream flow/runoff (Němec and Schaake, 1982; Revelle and Waggoner, 1983; Wigley and Jones, 1985; Cohen, 1986; Gleick, 1987; Karl and Reibsame, 1989; Lettenmaier and Gan, 1990). It is important that the effects on the groundwater flow system also be addressed because it is an integral component of the hydrological budget, ultimately affecting the quantity and quality of water in wetlands, rivers and lakes.

Studies have shown that is difficult to monitor the effects of external stress on groundwater flow systems at a regional scale in the plains or prairies because they respond very slowly to the applied stress due to the generally low hydraulic conductivity and groundwater recharge rates (Toth, 1978, Schwartz and Crowe, 1985). One means of assessing the groundwater flow regime is to examine the effects of long-term climatic changes on lakes, which in this region are often surface expressions of the groundwater flow system, acting as a source and/or a sink for groundwater flow.

The objective of this paper is to gain an insight into the effects of long-term climatic change (due to global warming) on the prairie groundwater and lake environment, by examining a lake-watershed system in Alberta, Canada using a water-balance modelling approach. Quantifying the role of groundwater in the hydrology of a lake-watershed system using deterministic models or field methods, require detailed spatial and temporal data which are typically not available. The data required for the hydrological balance techniques are, however, generally readily available. The value of modelling the effects of both short-term and long-term climatic change on the hydrological balance of a watershed with water balance models has been recognized (Crowe and Schwartz, 1981a; Cohen, 1986; Gleick, 1986, 1987). Both Cohen (1986) and Gleick (1987) used this technique to provide a valuable assessment of the changes occurring to the water balance of a watershed, and specifically lakes and stream runoff, due to long-term climatic changes. However, these studies did not incorporate a groundwater component, which they assumed was negligible. In contrast to earlier studies, the primary objective of this work is focused on the impact to both the lake and the groundwater flow regime. The model used here is an extension of the convention water balance technique, and was originally developed by Crowe and Schwartz (1981a) for the purpose of assessing the contribution of groundwater to the hydrological balance of lakes in a Canadian prairie setting and successfully applied (Crowe and Schwartz, 1891b, 1985). The first step in this process will be a simulation of the watershed that will reproduce the observed lake-surface elevation fluctuations and lake salinity records in order to verify the accuracy of the model. This process will result in an assessment of the importance of groundwater in the hydrological balance of the lake. Secondly, a series of sensitivity analyses will be undertaken with the model in which the known climatic and hydrological trends are extrapolated into the future to assess the effects of long-term climatic changes on the watershed.

QUANTIFYING THE GROUNDWATER CONTRIBUTION TO LAKES

Stream flow, surface runoff, precipitation and evaporation are generally studied as important hydrologic components affecting the quantity and quality of water in lake. However, the influence of groundwater flow into, or from, a lake is seldom considered. Several field-oriented studies have shown that groundwater flow may be responsible for a large portion of the recharge to, or the discharge from, a lake. In such cases, the groundwater component of the hydrological balance of a lake can not be ignored. There are generally three methods that can be used to quantify groundwater flow into and from a lake. These include: (1) a field-oriented approach, (2) numerical simulations and (3) hydrological balance of the lake-watershed. The following discussion outlines the applications, and advantages and disadvantages each method.

Field-oriented approaches consist of either the installation of shallow piezometers in the vicinity of a lake or the use of seepage meters placed on the bottom of the lake. Hydraulic head measurements obtained from piezometer nests can be used to infer potential pathways for groundwater flow into or from a lake (Jaquet, 1976; Karnauskas and Anderson, 1978; Rhinaldo-Lee and Anderson, 1980; Winter, 1986). Values of hydraulic head, hydraulic conductivity and hydraulic gradient applied through the Darcy Equation have been used to quantify groundwater flux (Loeb and Goldman, 1979; Rhinaldo-Lee and Anderson, 1980). The use of seepage meters placed on the bottom of a lake will supply accurate data on groundwater and solute flux (Lee, 1976; Lock and John, 1978; Lee et al., 1980; Brock et al., 1982; Belanger and Mikutel, 1985). In both cases, the information obtained is applicable only on a localized scale. When attempting to scale these data over even small lake-watersheds, the estimates generally are not accurate because of (1) the considerable spatial variability in the structure and permeability of the subsurface, (2) the spatial and temporal variability of the hydraulic gradient, and (3) the placement of the piezometers and seepage meters within hydrostratigraphic zones representative of the watershed. For example, studies have shown that certain locations of seepage meters along the bottom of a lake will lead to errors when extrapolating point specific measurements to an entire lake (Brock et al., 1982; Cherkauer and McBride, 1988; Cherkauer and Nader, 1989), especially if the lake is large. To adequately estimate groundwater flux, both the piezometer and seepage meter approach require extensive (and costly) instrumentation in order to characterize groundwater flux from all the hydrostratigraphic units and to ensure that important discharge zones are not missed.

Numerical modelling of groundwater flow systems in the vicinity of lakes is very useful in understanding the controlling parameters and processes affecting groundwater flow and flux near a lake. However, existing modelling studies are typically limited to hypothetical scenarios (McBride and Pfannkuch, 1975; Winter, 1978a, 1978b, 1981b, 1983; Pfannkuch and Winter, 1984; Winter and Pfannkuch, 1985) because detailed field data, as discussed above, required for an accurate representation an actual lake-watershed are not available. Models of actual lake-watersheds have been used to provide a quick assessment of groundwater flux under a variety of hydrological conditions (Rhinaldo-Lee and Anderson, 1980; Anderson and Munter, 1981; Munter and Anderson, 1981), but these watersheds are very small (several km^2).

Hydrological balance or budget techniques are the most common methods of assessing the sources and volume of water and nutrients entering and leaving a lake. Balance techniques are based on an accounting of the hydrologic contributions to a lake and ignore the spatial variability of the physical components of the watershed. Because this technique does not represent the physical structure of the lake-watershed, it can not be used to determine flow pathways, point sources and concentrations of solutes. However, a balance approach has advantages over the previous methods in that it calculates the net contribution of groundwater to the hydrological balance of a lake, and it eliminates problems associated with a lack of adequate field data. Hydrological studies of lake-watersheds are typically based on quantifying the role of precipitation, evaporation, surface runoff, lake discharge and groundwater inflow/outflow, in the water balance of a lake. Additional factors may also affect the volume of lake storage (eg. irrigation, industrial withdrawal). Mathematically, this balance is expressed with respect to the change in the volume of water in the lake:

$$\Delta S_{lake} = P + SW_{in} + GW_{in} + SR - E - SW_{out} - GW_{out} \pm \text{others} \qquad (1)$$

where: ΔS_{lake} = change in volume of water in the lake,

P = volume of precipitation falling directly on the lake,

SW_{in} = volume of surface water inflow to lake (eg. rivers, streams),

GW_{in} = volume of groundwater discharge to the lake,
SR = volume of surface runoff directly to the lake,
E = volume of evaporation directly from the surface of the lake,
SW_{out} = volume of surface discharge from the lake (eg. river, stream),
GW_{out} = volume of discharge from the lake via groundwater,
other = volume of other factors affecting lake storage.

Contributions to the volume of water within a lake from the hydrological components other than groundwater are measurable, or in the case of evaporation, calculated by standard formulae (Gray et al., 1970). However, the quantities of groundwater flow into, or from, a lake can not be measured accurately due to the complexity of a flow regime and the amount of field instrumentation required to adequately characterize the hydrostratigraphy. Therefore, equation (1) can not be used to uniquely assess the role of groundwater inflow and outflow in the water budget of a lake, or its associated contaminant or nutrient input. The substitution of all values that can be measured into equation (1) will produce one equation with two unknowns (GW_{in} and GW_{out}). The difference between these two terms is typically represented in the balance equation with a groundwater flux term:

$$\Delta S_{lake} = P + SW_{in} + SR - E - SW_{out} + \Delta GW_{lake} \pm \text{others} \qquad (2)$$

where: ΔGW_{lake} = groundwater flux to the lake ($\Delta GW_{lake} = GW_{in} - GW_{out}$)

Thus, there is not a unique solution to estimating groundwater inflow to, or outflow from, a lake. At best, only the net groundwater flux to the lake (ΔGW_{lake}) can be estimated, or as is often done, one of the two terms in equation (2) is set to zero to allow the other to be estimated (Cook et al., 1977; Karnauskas and Anderson, 1978; Cole and Fisher, 1979; Rhinaldo Lee and Anderson, 1980; Enell, 1982; Steenbergen and Verdouw, 1982). However, most hydrologic balance studies assume that groundwater has little significance in the water budget or ignore the groundwater component completely. Under these assumptions, the balance equation typically is written as:

$$\Delta S_{lake} = P + SW_{in} + SR - E - SW_{out} \pm \text{others} \qquad (3)$$

MODELLING OF THE WABAMUN LAKE WATERSHED

The main objective of this study is to assess the impact of long-term climatic change on a watershed, and specifically, how the climatic change affects the groundwater domain through an analysis of the hydrological balance of a lake. In order to understand how an actual watershed will respond to long-term climatic changes, it must be demonstrated that, firstly, a modelling technique can be used to simulate the responses of a lake and its watershed to various hydrological stresses, and secondly, this modelling technique can precisely define the water balance of an existing lake-watershed system. Because hydrological balance techniques offer a practical and efficient method of assessing the importance of groundwater in the hydrology of lakes, the model described in this section is based upon this approach.

The Framework of the Model

The hydrological balance model used here is the same one described earlier by Crowe and Schwartz (1981a) and readers can refer to this paper for a detailed discussion of the modelling approach. The specific objective for developing this model was to provide a good estimate of groundwater inflow to, and outflow from, a lake, using readily available field and climatic data. The model extends conventional water balance techniques in three ways.

Firstly, a simple water balance expression, such as Equation (1), only considers the storage of water at a fixed moment in time rather than considering temporal fluctuations. Routing calculations allows temporal variability of the watershed parameters to be considered as a simulation moves forward in time. Thus, by simulating both storage within the hydrological components and the routing of water among the components at a number of time steps, a series of dependent equations of the following form results:

$$\Delta S_{lake}(t_i) = P(t_i) + SW_{in}(t_i) + GW_{in}(t_i) + SR(t_i) - E(t_i) - SW_{out}(t_i) - GW_{out}(t_i) \pm \text{others}(t_i) \quad (4)$$

where: t_i = the time step at which a balance is calculated.

This technique is more accurate than a conventional long-term average because as the number of time steps increase and the size of the time step decreases, the number of dependent balance equations in the form of Equation (1) that must be solved simultaneous increases.

Secondly, because the focus of this model is towards estimating both groundwater inflow to, and outflow from, a lake, the groundwater flow system is represented in more detail than in typical balance models. The major hydrostratigraphic units within the watershed are represented as a series of groundwater storage elements. Recharge to these elements may occur directly from precipitation or through flow from, the unsaturated zone, the lake or from other storage elements. Discharge occurs through evaporation, flow to rivers, the lake, other elements or out of the watershed. Groundwater discharge from a storage element is a function of recharge and discharge from the present and previous time step. These are related through a series of routing coefficients defined by a storage delay time and time for recharge to an element as defined by Dooge (1960).

The third improvement incorporated that this model exhibits over the simple balance techniques (i.e. Equation (1)) is that dissolved mass, in the form of ions, is also routed through the various components of the watershed. Although using a model based on Equation (4) will provide a better estimate of the groundwater recharge and discharge to, a lake, it is still possible to arrive at a non-unique estimate of the balance components. The problem of a non-unique solution is resolved by adding a second balance equation which is based on the chemistry of the hydrological components of the watershed. Water entering or leaving the lake may either decrease the salinity of the water in the lake (surface discharge, precipitation, melting of ice), increase its salinity (groundwater inflow, formation of ice, evaporation), or simply remove salts without a net change in the salinity of the lake water (discharge as stream flow or groundwater flow). These hydrological components and processes affecting the lake are incorporated into the model, and are summarized by Figure 1. The long-term chemical character of the lake is simulated as a mixture of all water entering the lake and is modified by processes such as evaporation, ice formation/melting, snow accumulation/melting and spring runoff. Because concentrations can be transported, the concentrations of the various components are converted to mass, and this mass is routed from one hydrological component to another. Thus, the solute balance calculation for the long-term fluctuations in the chemistry of the lake is:

$$\Delta C_{lake}(t_i) = [C_{lake} \bullet S_{lake}(t_i) + C_P \bullet P(t_i) + C_{SWin} \bullet SW_{in}(t_i) + C_{GWin} \bullet GW_{in}(t_i) + C_{SR} \bullet SR(t_i) - C_{SWout} \bullet SW_{out}(t_i) - C_{GWout} \bullet GW_{out}(t_i) \pm C_{other} \bullet other(t_i)] \, / \, [S_{lake}(t_i) + P(t_i) + SW_{in}(t_i) + GW_{in}(t_i) + SR(t_i) - E(t_i) - SW_{out}(t_i) - GW_{out}(t_i) \pm ice(t_i) \pm others(t_i)] \quad (5)$$

where: $\Delta C_{lake}(t_i)$ = change in concentration of the lake,

C_n = concentration of the n^{th} hydrological component,

$ice(t_i)$ = water removed from or added to the lake during the formation or melting of ice at the surface of the lake.

The ability of the model to route mass provides an independent test of the uniqueness of the values assigned to the model variables. The solute transport and balance portion of the model is simplified by not considering possible chemical reactions. Non-reactive solutes such as Cl^-, Na^+, or total salinity of the waters are cycled through this model. Because solutes such as Na^+ and Cl^- are not influenced significantly by biological or chemical processes, their concentrations are essentially controlled by physical processes with the watershed.

The major hydrological components characterizing a watershed are represented by lumped-parameter storage elements. The structure of this watershed model (Figure 1) is similar to other lumped-parameter watershed models (e.g. Crawford and Linsley, 1966; Croley, 1983). However, unlike these models, this model is focused towards the hydrological characteristics of lakes rather than runoff hydrographs. It also cycles dissolved mass through the watershed, and requires only basic climatic and hydrological data which are commonly available from field studies. Most existing watershed models are quite complex and require a variety of input parameters, many of which are not routinely measured (eg. slope of ground surface, solar radiation, wind speed, interception of precipitation by tree species, etc).

Values of the climatic, hydrological and watershed parameters required for a simulation should be obtained from field data where possible. These data include temperature, precipitation, potential evaporation, lake surface elevations, lake chemistries, and the chemistries of water in the various watershed components. The values of other parameters, such as unsaturated zone moisture capacity, storage delay time and routing paths among the groundwater elements are initially inferred from field observations, but require a trial and error procedure of matching measured lake levels and chemistry to determine acceptable values.

Calibration of the Model

In order to assess the effects of long-term climatic changes on an actual watershed, the improved model is applied to the Wabamun Lake watershed in Alberta, Canada. This watershed was chosen because (1) lake-surface elevations have been recorded for a considerable period of time (several times each month during May to October from 1915 to 1959; daily or every 2-4 days throughout the year since 1960), (2) meteorological data (daily temperature and precipitation) have been recorded at Environment Canada meteorological stations in the area since 1914, and (3) several previous limnological and hydrogeological studies have been undertaken during the last 25 years within the watershed, and thus considerable data are available. Thus, the simulation of the long-term effects of climate change need not be assessed theoretically because the hydrological characteristics of the lake and watershed are well defined.

Wabamun Lake occupies a relatively large portion of its watershed (Figure 2), covering 78 km^2 of its 418 km^2 watershed or 20% of the watershed. The watershed is mainly forested, being within an aspen parkland natural vegetation region, or is cleared for agriculture. Development consists of summer cottages along the shore of Wabamun Lake, two large coal strip mines and two major thermal electric generating stations on the shore of the lake. The topography of the watershed is rolling to hilly. With the exception of spring runoff, there is essentially no continuous stream flow into the lake and discharge through the single outlet, Wabamun Creek, is intermittent and often obstructed. Other hydrological information for Wabamun Lake, its watershed and climate is summarized in Table 1.

An interesting characteristic of Wabamun Lake is that the salinity of the lake is very low even though the total annual evaporation from the lake exceeds total annual precipitation, and there is essentially no stream inflow which would replenish the lake with freshwater, nor stream discharge from the lake which would flush the saline water from the lake. Because the chemical character of the lake water is very similar to local groundwaters, several studies have indicated that the lake is strongly influenced by groundwater discharge to the lake and that the low salinity of

Wabamun Lake is due to discharge from the lake as groundwater (Nursall et al., 1972; Fritz and Krouse, 1973; Schwartz and Gallup, 1978). These studies indicate that groundwater recharge to the lake occurs through the coal, sandstone and shale units north and west of Wabamun Lake, and groundwater discharge from the lake occurs only through the deep bedrock units south of the lake (coal and sandstone/shale below the coal) or an alluvial deposit at the east end of the lake.

Climatic data used for the simulation consists of mean monthly temperatures and total monthly precipitation. The total monthly potential evaporation was calculated using an empirical formulation of Thornthwaite (Thornthwaite, 1948; Thornthwaite and Mather, 1955; Gray et al., 1970), which utilizes mean monthly temperature, a daylight hours factor and a heat index function. Where possible, data were taken from Environment Canada's Highvale (1977-1987) or Magnolia (1965-1982) weather stations which are within several kilometres of the lake. Missing data were obtained by correcting data from the next closest Environment Canada stations with long-term records, Sion (1906-present), Thornsby (1932-1968) and Calmar (1914-present), to a corresponding value at Highvale or Magnolia.

The choice of values assigned to the parameters for the model are based upon Crowe and Schwartz (1985) but have been modified slightly for the present simulations; the simulation period for the previous study was only 25 years (1956-1981). Groundwater storage elements represent surficial sand and till, and the shallow and deep bedrock units within the Wabamun Lake watershed (Table 2). In addition to the parameters characterizing the watershed, lake-functions specific to Wabamun Lake are required. These lake functions include stage-area and stage-volume curves for the lake and a stage-discharge curve for the outlet stream. Although the stage-area and stage-volume curves for the Wabamun Lake are well defined, it is impossible to produce a meaningful stage-discharge relationship for the outlet stream because of beaver activity and man-made adjustments (installation of culverts, new outlet, weir emplacement) on Wabamun Creek (Alberta Environment, 1982) which caused numerous blockages. Therefore, an approximating function (Gray et al., 1970) was used. Numerous trials were undertaken with the model in which the parameters, such as the routing coefficients, were adjusted in order to simulate the lake surface elevations and the lake chemistry. The values of these variables which are adjusted or inferred during the calibration of the model are typical of conditions in a Canadian prairie setting.

The resulting agreement between the simulated and measured lake levels and chemistry (Figure 3a and 3b, respectively) is good considering (1) the simplified form of the model, (2) only basic climatic watershed-characterizing data was required for the simulation, and (3) inaccuracies in measured values of the input parameters and lake-functions. The primary source of error in reproducing observed lake-surface elevations is due to errors in extrapolating meteorological data from the weather stations to Wabamun Lake and to the lack of an accurate stage-discharge curve for the actual discharge via Wabamun Creek (Winter, 1981a). Because of blockages and improvements to the creek over time (Alberta Environment, 1982), the simulated and observed lake-surface elevations may not match during specific months. However, over the 50 years of simulation, this error will be minimized. The results of the simulation indicates that the important components in the water balance for Wabamun Lake are precipitation, surface inflow, evaporation and discharge from the lake as groundwater. Inflow to and outflow from Wabamun Lake for all the hydrological components were calculated on a monthly basis. The yearly proportion of inflow to and outflow from Wabamun Lake attributed to groundwater varied from approximately 1-10% and 25-40%, respectively during the 50 year simulation period (Figure 4). The box and whisker plot on Figure 4 shows that over these 50 years, the median annual percentage of inflow to the lake via precipitation directly on the lake, surface water inflow and groundwater discharge to the lake was 51.9%, 42.8% and 3.8%, respectively. Also, there is little variance from the median, as illustrated by the interquartile ranges (Figure 4). For example, the ranges of groundwater inflow and outflow are the smallest, being 3.1% and 5.0%, respectively. The greatest interquartile range is displayed by precipitation (12.5%) and surface water outflow (14.9%). The median annual discharge from the lake as evaporation, surface discharge and groundwater flow was 49.6%, 2.4% and 37.8%, respectively. The points plotted outside of the outer hinge points of box and whisker plots on Figure 4 also shows that the percentage of groundwater outflow and evaporation were abnormally low in 1974 compared to the other 49 years, and that surface inflow and outflow were unusually high during 1974 because precipitation was much greater than normal that year.

The contributions of the various hydrological components of the watershed to the water balance of Wabamun Lake obtained by this 50 year simulation are essentially the same those obtained during the previous 25 year simulation (from 1956 to 1981) by Crowe and Schwartz (1985). For example, the results of Crowe and Schwartz (1985) indicate that the proportion of groundwater inflow to, and outflow from, the lake varied between 1-10% and 30-38%, respectively. The net result of the 25 year simulation is that the median percentages of recharge to the lake as precipitation, surface water and groundwater are 55.3%, 39.3% and 5.7%, respectively. Median percentages of evaporation, surface discharge and groundwater outflow are 59.6%, 4.3% and 36.2%, respectively. The successful simulation of the surface elevations and the chemistry of the lake, and a very close reproduction of the previous hydrological balance for the lake (Crowe and Schwartz, 1985) with little variation of the original modelling parameters, indicates that the calibration and verification of the Wabamun Lake watershed system was successful. Hence, the present model can adequately represent long-term changes to the natural hydrological conditions within the watershed.

This simulation shows that although Wabamun Lake is dominantly evaporitic, its low salinity is due to two factors. Firstly, most recharge enters the lake as precipitation falling directly on the lake, or as surface runoff or stream flow during the spring. The quantity of groundwater entering the lake, which is a principle source of dissolved mass, is very low. Thus, groundwater inflow has a very minor influence on the salinity of Wabamun Lake. Secondly, the salts which accumulate in the lake water due to evaporation and would otherwise not leave the system via Wabamun Creek are in fact flushed from the lake as discharge to groundwater, preventing an increase in the salinity of the lake.

The importance of groundwater in the hydrological budget of Wabamun Lake and the importance of supplementing the water balance with a chemical balance can be demonstrated by undertaking the same simulation, without a groundwater component. In this case, infiltration to the groundwater system was denied and thus, water which previously entered the lake as groundwater now enters as surface water inflow. Because water no longer leaves the lake via the groundwater flow system, the available discharge will leave Wabamun Lake as either increased evaporation from the lake surface or increased surface water outflow, via Wabamun Creek. The following three scenarios were simulated to illustrate the importance of the groundwater component and are compared to the previous or "best-fit" simulation.

In the first case, the model calculates how much water leaves as evaporation and how much leaves via the surface water outlet. The model routes almost all the available discharge as surface water outflow via Wabamun Creek. The results of this case show that the simulated fluctuations in the lake-surface elevations (Figure 5a) are different from the simulation with the groundwater component included (Figure 3a). When groundwater is not included, the elevation of the lake surface exhibits little long-term fluctuations, being consistently near 724.5 m amsl, and the elevations are approximately 5-30 mm above the previous simulated values. Also, the simulated lake salinity (Figure 5b) is approximately 75 µS/cm higher than the best-fit simulation (Figure 3b) during 1989. Discharge through Wabamun Creek often increased by 0.5-2.0 orders of magnitude. Because surface discharge for Wabamun Creek has been recorded seasonally since 1969, it is clear that this discharge dramatically exceeds the measured values, and hence the excess discharge cannot leave the lake as surface outflow.

Because the actual lake evaporation is not known, the uncertainty in the estimates of evaporation obtained in the best-fit simulation is larger than for the predicted estimates for surface discharge. It is possible that the value for evaporation may have been underestimated in the best fit simulation. Therefore, in this, the second case, all the former groundwater discharge from Wabamun Lake was converted to evaporation. Although this case reproduced the observed lake levels as well as the best-fit simulation (which includes a groundwater component, Figure 3a), the simulated values were 2-3 mm higher. However, the calculated salinity of Wabamun Lake dramatically increased without the flushing of dissolved mass from the lake via groundwater (Figure 5b), and had in fact reached a concentration of over 12,000 µS/cm by 1989. Therefore, not all the excess discharge can leave Wabamun Lake as evaporation.

The third case combines both increased surface discharge and increased evaporation from Wabamun Lake. Up to 20% of the former groundwater discharge was allowed to leave the lake as increased evaporation and the remaining excess water was discharged as surface outflow. Even at these values, the higher evaporation has increased the salinity of the lake by 450 µS/cm (Figure 5b) by 1989, and surface discharge, while not as dramatically over the measured values, was occasionally up to 2 orders of magnitude too high. Again, surface water discharge exhibits a strong influence on the simulated fluctuations in the lake-surface elevations (Figure 5a). In this case, the elevation of the lake surface exhibits little long-term fluctuations and the elevations are approximately 5-30 mm above the best-fit values.

Therefore, based on the results of these simulations, it is concluded that groundwater is an integral part of the hydrological balance of Wabamun Lake. These simulations also indicate that while assuming the groundwater contribution to the water balance of a lake can in most cases reproduce reasonable simulations of the measured lake-surface fluctuations, the chemical balance is essential in order to accurately and uniquely quantify the contributions from the various hydrologic components of a watershed.

RESPONSES OF THE WATERSHED TO CLIMATIC CHANGES

The goal of this section is to provide an understanding of how lake watershed systems respond to long-term changes in climate. The value of modelling the effects of both short-term and long-term climatic change on the hydrological balance of a watershed with water balance models has been recognized (Crowe and Schwartz, 1985; Gleick, 1986, 1987). Gleick (1987) used this technique to provide a valuable assessment of the changes occurring to the water balance of a watershed due to long-term climatic changes. However, this study did not incorporate a groundwater component. In contrast to earlier studies, the primary objective of this work is focused on the impact to both the lake and the groundwater flow regime. The watershed being studied is the Wabamun Lake watershed. Values assigned to the lake and the watershed, including the hydrogeological parameters, are the same as those used to obtain the best-fit simulation to the 1940 - 1989 records of lake-surface elevations and salinity. Because we do not know the exact meteorological events that will occur within the Wabamun Lake watershed in the future, we can not accurately predict the future watershed responses. The approach taken in this paper is to examine how the watershed would have responded had climatic change occurred during the last 50 years. Thus, insight into the effects of climatic change on Wabamun Lake can be obtained by comparing simulated changes to the lake-surface elevations and salinity of Wabamun Lake to the actual measured records and the best-fit simulation. Insight into the effects on the groundwater regime will been gained by comparing the following simulations to the best-fit simulation. The best fit simulation, described in the previous section, will henceforth be referred to as the reference case.

The effects of climatic change are analysed through a sensitivity analysis of the parameters most likely to change, these being temperature and precipitation. Because potential evaporation is calculated within the model as a function of temperature, evaporation is implicitly changed as temperature varies. The simulations undertaken are listed in Table 3. These simulations will examine the effects of (1) an increase in the mean monthly temperature without a change in monthly precipitation, (2) changes in the total monthly precipitation without a change in monthly temperature and (3) a change in both the monthly temperature and precipitation.

Effects of Increased Mean Monthly Temperature

This first set of simulations is designed to investigate the effect of temperature change, and corresponding change in evaporation, without a change in monthly precipitation, in order to examine how a small change in temperature can effect the hydrological balance of a watershed. Although global warming has been speculated to increase temperatures by as much as 5°C, the maximum increase in the temperature simulated here is a conservative value of 2°C. The higher temperature is implemented by simply adding the temperature increment to the current values of measured mean monthly temperatures. Two cases simulate temperature increases of 1°C and 2°C (Cases 1 and 2, respectively). The results of the simulations are compared to the reference case, which is the best-fit simulation previously discussed. In this way it is possible to highlight changes in the behaviour of the watershed caused by a change in temperature.

In both Cases 1 and 2, the higher temperatures did not significantly alter the elevation of the surface of Wabamun Lake, but did produce significant increases in the salinity of the lake. The seasonal and long-term trends in the lake-level fluctuations are essentially the same (Figure 6a) as the reference case. As temperature increases, the overall elevation of the lake decreased slightly by a maximum of 8-10 mm for Case 2 (Table 4). The salinity of Wabamun Lake continually increased during the 50 year simulation period to 1989 maximums of 650 µS/cm and 930 µS/cm, for Cases 1 and 2, respectively (Figure 6b), from a value of 490 µS/cm obtained with the reference case during 1989 (Table 4).

The relative annual amounts of water flowing into Wabamun Lake as groundwater, surface inflow and precipitation, and leaving the lake as groundwater, surface discharge and evaporation, calculated for a temperature increase of 1°C or 2°C are not significantly different from the reference case. For example, Figure 6 shows that for a temperature rise of 2°C, the median percentage of groundwater and surface water inflow are approximately 1-2% lower and the percentage of precipitation has increased by only 3-4% from the reference case. Groundwater and surface water outflow are only 1-2% lower and the percentage discharged as evaporation increase by 3%. Although the relative contribution to the hydrological balance of Wabamun Lake did not change significantly, the interquartile range was notably reduced, by as much as 7% for surface water discharge for Case 2. The results of the simulation Case 1 show similar trends; little change in the relative proportion of the balance components and reduced interquartile range. However, the changes for Case 1 are, as expected, less than those for the Case 2 simulation.

Although the relative contributions of the inflow and outflow components did not change significantly, the annual volume of water routed through each of the hydrological components did change from the reference case (Table 5). For example, with a temperature change of 2°C, surface water inflow and groundwater discharge to the lake exhibited a maximum annual decreased of 39% and 98%, with medians of 4% and 20% (Figure 7). The greatest annual change from the reference case in the volume of water discharging from the lake was evaporation which increased to a maximum of 18% (median of 9%). The annual change in groundwater discharge from the lake for this, and all subsequent cases, was negligible, and hence these values are not reported in Table 5. A maximum percentage change for surface water discharge is not reported in Table 5 because a percentage change could not be calculated when flow changed during the same year between the reference case and the a present simulation, from a previous value of no flow to a finite value and vice versa. However, the median change in surface water outflow is reported (Table 5). For Case 2, the amount of surface discharge decreased significantly from the reference case as indicated by the median value of 36%. The median values for Case 1, with a temperature increase of half of Case 2, is approximately half that of Case 2. The amount of precipitation and groundwater outflow did not change significantly in either Case 1 or 2.

As temperature increases, the change to the amount of groundwater flowing into the lake is considerably greater than the amounts of the other hydrological components, precipitation and surface inflow, that enter the lake (Table 5). The reduction in groundwater inflow to the lake is due to reduced groundwater recharge across the watershed because of increased evaporation. These results indicate that the increased evaporation would affect the groundwater flow system to a larger extent than the surface water system. This could lead to problems relating to groundwater supply. Because the amount of groundwater inflow to Wabamun Lake, relative to the precipitation and surface inflow, is very low, Wabamun Lake will not be significantly affected by a reduction in groundwater discharge to the lake. However, for lakes in which groundwater is the principle source of water contributing to the lake, the effects of a reduction of groundwater flow to a lake, due to increased temperatures, could be significant. The change in groundwater discharge from the lake, relative to the reference case, is negligible, and hence long-term increases in temperature will not affect discharge from a lake. Even though a reduction in the amount of groundwater discharging to a lake may not significantly affect the hydrology of the lake, the large reduction in groundwater discharge, shown in these simulations, is indicative of a substantial reduction in groundwater recharge throughout the watershed. Hence, groundwater resources within the watershed may become seriously depleted before any affect of this is noticed within a lake.

The results of these simulations indicate that while the volume of water in Wabamun Lake is not sensitive to small increases in temperature, the salinity of the lake will increase dramatically for temperature increase as small as 2°C. The cause of this small variation in the lake levels is that although more water is leaving the lake as evaporation, less water is entering the lake as groundwater or surface water inflow. This is due to increased evaporation occurring over the entire watershed, and hence, there is less water available for surface runoff and less groundwater recharge (and ultimately groundwater inflow to the lake). The salinity of the lake increases due to greater evaporation from the surface of the lake at the expense of surface water discharge via Wabamun Creek. Therefore, as water is lost through evaporation, it does not remove the salts that would have been flushed from Wabamun Lake as surface discharge.

Effects of Changes to the Total Monthly Precipitation

The simulations presented in this section discuss the results of a sensitivity analysis on the effects of a change in precipitation due to global warming. Although a change in precipitation will result from an increase in temperature, the simulations undertaken in this analysis were run without an accompanying temperature change in order provide insight into the behaviour of Wabamun Lake and its watershed to long-term changes in precipitation. Three cases are considered here. Cases 3 and 4 simulate a decrease in long-term precipitation by 5% and 10% respectively, from the 1940-1989 records. A third simulation (Case 5) was undertaken to examine how a 10% increase in precipitation would affect the hydrological budget of the watershed. The increase or decrease is simulated by multiplying the total monthly precipitation values by the corresponding percentages. All three cases are compared to the reference case (the best-fit simulation).

The effect of a long-term decline in precipitation are lower lake-surface elevations and greater lake salinity (Figure 8). Although the general trend of lake-surface fluctuations is the same, the elevation of the surface of Wabamun Lake declined by 7-10 mm and 12-15 mm for Cases 3 and 4, respectively, from the reference case (Table 4). In addition, the peak elevations of the lake surface, caused by spring runoff and major storms, are not as pronounced as in the reference case, and these peaks decrease as precipitation declines. The salinity of Wabamun lake increases as precipitation decrease. For example, with a 10% decrease in precipitation, the salinity reached a maximum of 910 μS/cm during 1989, which is a rise of 420 μS/cm from the value simulated during 1989 of the reference case (Table 4).

The relative proportion of groundwater, surface water and precipitation entering Wabamun Lake on an annual basis are essentially the same as the reference case (Figure 4). The relative amounts of groundwater and evaporation leaving the lake is essentially the same, but as precipitation declines, a noticeable decline in surface water outflow occurs to satisfy a slight increase in groundwater discharge and evaporation. Also, the ranges of annual proportions of these outflow components are much smaller than the reference case and the range decreases as precipitation decreases (from Case 3 to Case 4). For example, the interquartile range is 1%-3% for Case 4 (Figure 9) compared to a range of up to 15% in the reference case. As precipitation increases (Case 5) the relative proportions of the input parameters remains essentially the same, but surface water discharge increases with a corresponding slight decrease in groundwater outflow and evaporation.

As precipitation decreases, the actual amount of groundwater, surface water and precipitation entering the lake declines substantially from the reference case (Table 5). However, the relative amount of the inflow and outflow components, with the exception of surface water discharge, is essentially the same. The variation from the reference case becomes proportionally greater as the percent change in precipitation increases. For example, as the percent change in precipitation between Case 3 and Case 4 doubles from 5% to 10%, the volume of precipitation, groundwater and surface inflow to, and surface water outflow from, the lake, calculated in Case 4 (-37%, -10%, -15% and -59%, respectively) are approximately twice as high as those calculated for Case 3 (-14%, -5%, -7% and -31%, respectively). As illustrated by Case 5, a 10% rise in precipitation results in a much greater change in the volume of water discharging from the lake as surface outflow, than does a corresponding 10% decline in precipitation (Table 5). Although the median volumes of surface and groundwater inflow are relatively higher and lower, respectively, than the 10% decline case, the maximum values are much greater (Table 5).

Groundwater inflow to the lake was responsible for the greatest change in the volume of flow to the lake. Specifically, groundwater inflow decreased, in both Case 5 and 6, by 2 to 3 times the amount of decrease occurring by either surface water inflow and direct input of precipitation to the lake (Table 5). A decrease in precipitation results in a significant reduction in the amount of recharge to the groundwater flow system, which in turn reduces the availability of groundwater that can discharge to the lake. The change in groundwater discharge from the lake is negligible, and probably will not change significantly from the reference case until there is a major change in the elevation of the lake surface.

In summary, the effect of a decrease in precipitation across the watershed is reflected in the lake by much greater salinity and lower lake-surface elevations, and in the groundwater flow system by much less recharge to the groundwater zone, and hence flow into the lake. The lowering of the surface elevation of the lake is due to a decrease in the amount of water that enters the lake, either directly as precipitation, originating as surface runoff and or groundwater. The salinity of the lake increases because a lower surface elevation of the lake causes a considerable reduction in the surface water discharge via Wabamun Creek, which acts to flush the dissolved salts from the lake, while evaporation continues to concentrate the salts in the lake. The reduction in precipitation across the watershed causes less recharge to the groundwater domain, and this in turn is reflected at the lake as a substantial reduction in groundwater discharge into the lake. From this it can be inferred that a long-term decrease in the amount of precipitation will cause a net reduction in the groundwater resources of the watershed. As previously noted, the large reduction in groundwater discharge may be indicative of a substantial reduction in the groundwater resources in the watershed although this reduction may not be observed as major hydrological changes within the lake.

Effects of Changes to Both Temperature and Precipitation

The two previous sections provided insight into the relative effects of changes to either precipitation or temperature on the hydrological behaviour of Wabamun Lake and the groundwater resources within its watershed. The simulations discussed here focus on the combined effects of small changes to temperature and precipitation. Again, the three cases presented here are compared to the reference case. The three cases are (1) an increase in temperature by 0.5°C and a decrease in precipitation by 5%, (2) an increase in temperature by 1.0°C and a decrease in precipitation by 5%, and (3) an increase in temperature by 1.0°C and a decrease in precipitation by 10% (Table 3).

As expected, as temperature increases and precipitation decreases together (Cases 6, 7 and 8), the change in salinity and the surface elevation of the lake will increase and decrease, respectively (Figure 10). However, in all cases the long-term and seasonal trends exhibited by the reference case are maintained. The net effect of increasing temperature and decreasing precipitation is a reduction in the amount of water that recharges the lake by both a reduction in precipitation and increased evaporation. Evaporation reduces recharge to the lake by reducing both water available for surface runoff and recharge to the groundwater regime (hence less groundwater discharge to the lake), and by increasing the loss of water directly from the surface of the lake. Decreased precipitation will also reduce surface runoff and groundwater recharge, as well as the addition of water directly to the lake surface.

The previous simulations showed that a relatively small change in temperature or precipitation over a long period of time can cause significant changes to the hydrological character of the lake and its watershed. The combined effects of increasing the mean monthly temperature by 1.0°C and decreasing the total monthly precipitation by 10% over 50 years results in a significant increase in lake salinity (Figure 10b) and decrease in lake-surface elevations (Figure 10a) from the reference case. In general, the relative proportions of the inflow and outflow components, with the exception of surface water discharge, are essentially the same as the reference case (Figure 4). Surface water discharge decrease substantially, and as shown by Figure 11, for a 10% reduction in precipitation and a 1.0°C increase in temperature from the reference case, there is essentially no surface water outflow during many years. Also, the interquartile range of evaporation, groundwater and surface water outflow are 1-2%.

The changes to the elevation of the lake surface and the lake salinity simulated by Case 8 are, in fact, greater than the combined effects of Case 1 and Case 4 where the temperature and precipitation changes are simulated independently. For example, the increased salinity caused by a 1.0°C rise in temperature, Case 1, and a 10% decline in precipitation, Case 4, are 160 µS/cm and 420 µS/cm, respectively, for 1989, (Table 4) for a total salinity change of 580 µS/cm. However, the change in salinity, as calculated by Case 8, is an increase of 840 µS/cm. Also, the maximum combined lake-surface elevation decrease as calculated by Cases 1 and 4 is approximately 18 mm, while that calculated by Case 8 is 25 mm (Table 4). The same pattern holds for Case 7, which is a temperature rise of 1.0°C and precipitation decline of 5%, where when the separate temperature increase (Case 1) and precipitation decrease (Case 3) are combined, the lake-surface elevation and salinity changes are less than when both changes are simulated simultaneously (Table 4).

The decrease in the amount of water recharging the lake can clearly be seen in Table 5. As the temperature increases and precipitation decreases from Case 6 to 7 to 8, the amount of groundwater inflow, precipitation and surface water inflow decrease relative to the reference case. In fact, these median values double as temperature and precipitation changes concurrently double. For example, between Case 6 and 8 (21% to 44% for groundwater, 5% to 11% for precipitation, 7% to 17% for surface water). The doubling trend is also evident with evaporation and surface water discharge which increases from 1.6% to 3.4% and 40% to 75%, respectively, (Table 5). Although the combined temperature and precipitation change affected both the salinity and surface elevation of the lake to a larger degree than the sum of individual changes (e.g. Case 8 vs Case 1 + Case 4), this was not evident in the mean annual percentages changes to the volume of the hydrological components. For example, the sum of the changes calculated by Cases 1 and 4, for groundwater inflow, precipitation, surface inflow, surface water discharge and evaporation, which are decrease of 45%, 11%, 18% and 74%, and an increase of 3.6%, respectively, are approximately the same as the results calculated by Case 8 (decreases of 44%, 11%, 17%, 75% and an increase of 3.4%, for groundwater inflow, precipitation, surface inflow, surface water outflow and evaporation, respectively).

As noted during the previously sets of simulations, the effects of increasing temperature and decreasing precipitation on the groundwater regime is a decrease in the amount of recharge to the groundwater system and hence a reduction in groundwater outflow to the lake. Also, the effects on the groundwater system are greater than on either precipitation or surface runoff. Because the change in the amount of groundwater entering the lake from the reference case is considerably larger than the sum of changes from the individual climatic effects (eg. Case 8 vs Case 1 + Case 4) it can be inferred that long-term climatic changes affecting both temperature and precipitation will have a significant impact on the groundwater resources of a watershed.

The results of these three simulations indicate that increasing temperature and decreasing precipitation together will increase the salinity and decrease the surface elevation of the lake because less water is able to recharge the lake (as surface runoff, groundwater inflow or precipitation) and more water is removed from the surface of the lake as evaporation. However, long-term and seasonal trends remain essentially unchanged. A combine temperature rise and precipitation decline causes the salinity and the surface elevation of the lake to increase and decrease, respectively, at a faster rate than if the corresponding individual changes to temperature and precipitation were summed. Although the effect on the lake due to a combined climatic change is greater than the sum of the individual changes, the actual relative changes to the volume of water associated with each hydrological components is approximately equal to the sum of the individual changes. The impact of a long-term combined temperature increase and precipitation decrease will have a significant impact on the groundwater flow system in terms of both a major reduction in recharge to the groundwater regime and available groundwater storage.

CONCLUSIONS

A lumped-parameter, lake-watershed model has been used to assess the groundwater contribution to the water budget of a lake-watershed system located in a Canadian prairie setting. The model successfully simulated the measured lake surface elevations over a period of 50 years, and lake water salinity for 2 years of Wabamun Lake, Alberta. The calibrated model was then used to simulate the effects of long-term climatic changes on a lake and its watershed. The simulations provided a basis for developing preliminary conclusions concerning the impact of climatic change on lake-watershed systems. These conclusions can be summarized as follows.

1. Groundwater outflow is the dominant factor maintaining a relatively low salinity for Wabamun Lake even though the 50-year median percentage of water loss through evaporation is approximately 60% of the total discharge from the lake. Good agreement could be obtained between the predicted and measured surface elevations of the lakes when the groundwater component was not considered, but the simulated salinity of the lake and discharge via Wabamun Creek differed dramatically from that measured. By simulating the routing of both water and solutes through all components in the watershed, a good agreement between the measured lake levels and salinity was obtained, thus quantifying the role of groundwater in the hydrological budget of a lake.
2. Long-term changes to temperature and precipitation have the potential to cause dramatic changes to the salinity of lakes in a prairie setting, even if these changes are very small (e.g. temperature increase of 1°C and a decline in precipitation by 5%). Because many of the lakes in western Canada and the United States are controlled by a fine balance between precipitation inflow and evaporative losses, a small increase in evaporation or reduction in precipitation will

cause a continual increase in the solute content of the lakes as long as the climatic changes are in affect. Also, small changes in temperature cause greater changes to the salinity of a lake than small changes in precipitation (e.g. temperature increase of 2°C and precipitation decrease of 10%), and as the relative change in temperature and precipitation increases, the increase in lake salinity becomes increasing greater.

3. The effect of climatic change on the volume of water in a lake (as reflected by its surface elevation) is not as substantial as the resultant changes in the salinity of the lake. However, increased evaporation and/or decreased precipitation over the watershed will cause some decline in the volume of the lake.
4. The climatic changes generally did not result in significant changes to the relative proportions of water entering the lake as groundwater inflow, surface water inflow and precipitation, or leaving the lake as groundwater discharge, surface outflow or evaporation. In fact, the simulated climatic changes resulted in a decrease in the range over which the 50-year median of the annual percentages varied.
5. Although the relative proportions of the hydrological inflow and outflow parameters did not change significantly, the actual volume of water entering and leaving the lake often exhibited very large differences from the reference case. In particular decreasing the amount of water in the watershed, reduced groundwater recharge and hence groundwater discharge from the lake to a significantly greater extent than other inflow components.
6. Because groundwater recharge is reduced throughout the watershed as temperature increases and/or precipitation decreases, the results of the simulations show less discharge to the lake, and hence, aquifer storage will be reduced. Although it is difficult to simulate the effects of long-term climatic changes within a groundwater flow system, the effects groundwater-lake interactions provide insight into these possible changes. The potential changes include (1) groundwater storage in the watershed will be reduced significantly, (2) if the quality and quantity of water is largely controlled by groundwater recharge, the reduction in groundwater storage will ultimately reduce the size of the lake and increase its salinity, (3) where groundwater flow systems are largely controlled by recharge from lakes, climatic change will have a negligible affect on the groundwater flow as long as there is not a major change in the elevation of the surface of the lake.

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Table 1. Characteristics of Wabamun Lake and its watershed.

488 mm	:	mean total annual precipitation
534 mm	:	mean total annual potential evaporation
-15.3°C	:	mean minimum monthly temperature
16.6°C	:	mean maximum monthly temperature
418.2 km^2	:	area of the watershed (including the lake)
724.7 m amsl	:	mean lake surface elevation
77.7 km^2	:	surface area of Wabamun Lake
11.0 m	:	maximum depth of Wabamun Lake
6.5 m	:	mean depth of Wabamun Lake
503×10^6 m^3	:	lake volume
400 µS/cm	:	average specific conductance of the lake

Table 2. Groundwater storage elements for the Wabamun Lake watershed.

hydrostratigraphic unit	mean specific conductance (µS/cm)
till	880
alluvium	800
sandstone above coal (N of lake)	635
sandstone above coal (S of lake)	1120
coal (N and S of lake)	1075
sandstone/shale below coal (N of lake)	1370
sandstone/shale below coal (S of lake)	1370

Table 3. Simulations undertaken to examine the effects of climatic change.

Case	Temp. change	Precip. change
reference case	no change	no change
1	$T = T + 1.0^oC$	no change
2	$T = T + 2.0^oC$	no change
3	no change	$P = 95\% \cdot P$
4	no change	$P = 90\% \cdot P$
5	no change	$P = 110\% \cdot P$
6	$T = T + 0.5^oC$	$P = 95\% \cdot P$
7	$T = T + 1.0^oC$	$P = 95\% \cdot P$
8	$T = T + 1.0^oC$	$P = 90\% \cdot P$

Table 4. Simulated changes to the surface elevation and salinity of Wabamun Lake due to climatic change.

Case	simulated 1989 lake salinity (µS/cm)	change in salinity from 1989 of best fit (µS/cm)	change in surface elev. from 1989 of best fit (mm)
reference case	490	---	---
1	650	+160	-1 to -3
2	940	+450	-8 to -10
3	650	+160	-7 to -10
4	910	+420	-12 to -15
5	340	-150	+8 to +12
6	740	+250	-4 to -10
7	900	+410	-8 to -20
8	1330	+840	-8 to -25

Table 5. Percent changes to amount of water contributing to the hydrological balance of Wabamun Lake due to climatic change from the reference case (-ve and +ve refers to a decrease or increase from the best-fit simulation).

Case	% ΔGW_{in}		% ΔP		% ΔSW_{in}		% ΔE		% ΔSW_{out}	
	max.	median	max.	median	max.	median	max.	median	max.	median
1	-97.6	-7.5	-1.4	-0.3	-17.5	-2.6	+8.7	+4.2	*	-15.2
2	-98.0	-19.9	-0.9	-0.2	-39.2	-4.0	+14.0	+8.6	*	-36.2
3	-97.7	-13.9	-5.9	-5.3	-23.2	-7.2	+1.1	+0.4	*	-31.1
4	-99.6	-37.4	-11.5	-10.6	-33.9	-15.3	-1.4	-0.6	*	-59.2
5	+269.9	+29.5	+11.3	+10.6	+47.9	+18.9	-0.8	-0.3	*	+111.0
6	-99.6	-21.0	-6.2	-5.4	-30.4	-7.4	+2.3	+1.6	*	-39.6
7	-99.6	-29.8	-6.3	-5.4	-30.4	-10.4	+7.6	+3.8	*	-48.6
8	-99.9	-43.9	-12.0	-10.7	-36.4	-16.8	+7.0	+3.4	*	-74.8

* % change from SWOUT of the reference case to SWOUT of each case is undefined.

FIGURES

Fig. 1. Location of the Wabamun Lake watershed.

Fig. 2. Schematic illustration of the components and processes simulated by the lake-watershed model.

Fig. 3. Comparison between the measured and simulated values of (a) surface elevations and (b) the salinity, of Wabamun Lake from 1940 to 1989: best fit simulation.

Fig. 4. Annual relative amounts of inflow to, and outflow from, Wabamun Lake, and statistics on the long-term hydrological balance.

Fig. 5. Comparison between the measured and simulated values of (a) surface elevations and (b) the salinity, of Wabamun Lake from 1940 to 1989: without considering groundwater.

Fig. 6. Comparison between the measured and simulated values of (a) surface elevations and (b) the salinity, of Wabamun Lake: only a long-term temperature change.

Fig. 7. Annual relative amounts of inflow to, and outflow from, Wabamun Lake, and statistics on the long-term hydrological balance, effect of a 2°C rise in temperature.

Fig. 8. Comparison between the measured and simulated values of (a) surface elevations and (b) the salinity, of Wabamun Lake: only a long-term precipitation change.

Fig. 9. Annual relative amounts of inflow to, and outflow from, Wabamun Lake, and statistics on the long-term hydrological balance, effect of a 10% decline in precipitation.

Fig. 10. Comparison between the measured and simulated values of (a) surface elevations and (b) the salinity, of Wabamun Lake: both a long-term temperature and precipitation change.

Fig. 11. Annual relative amounts of inflow to, and outflow from, Wabamun Lake, and statistics on the long-term hydrological balance, effects of a 1°C increase in temperature and a 10% decline in precipitation.

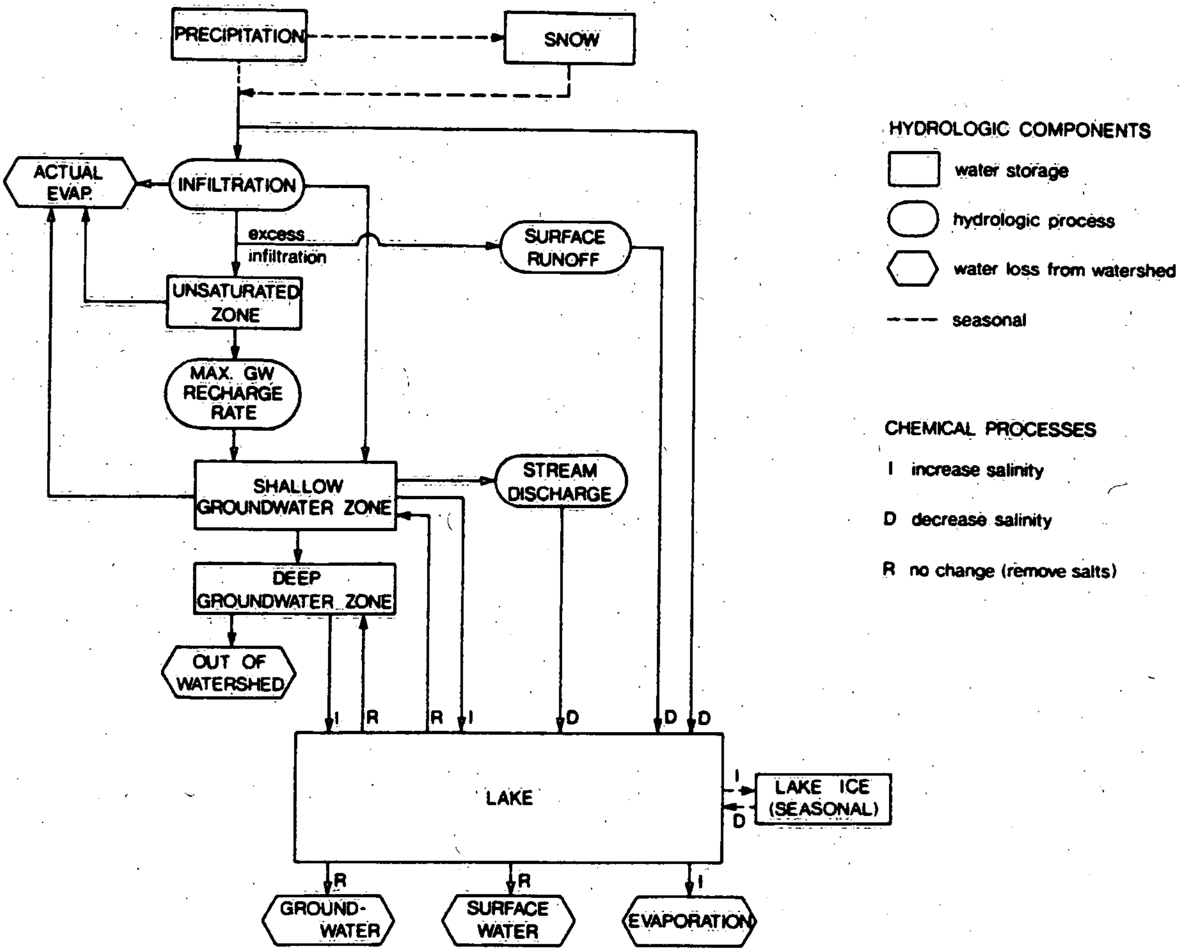
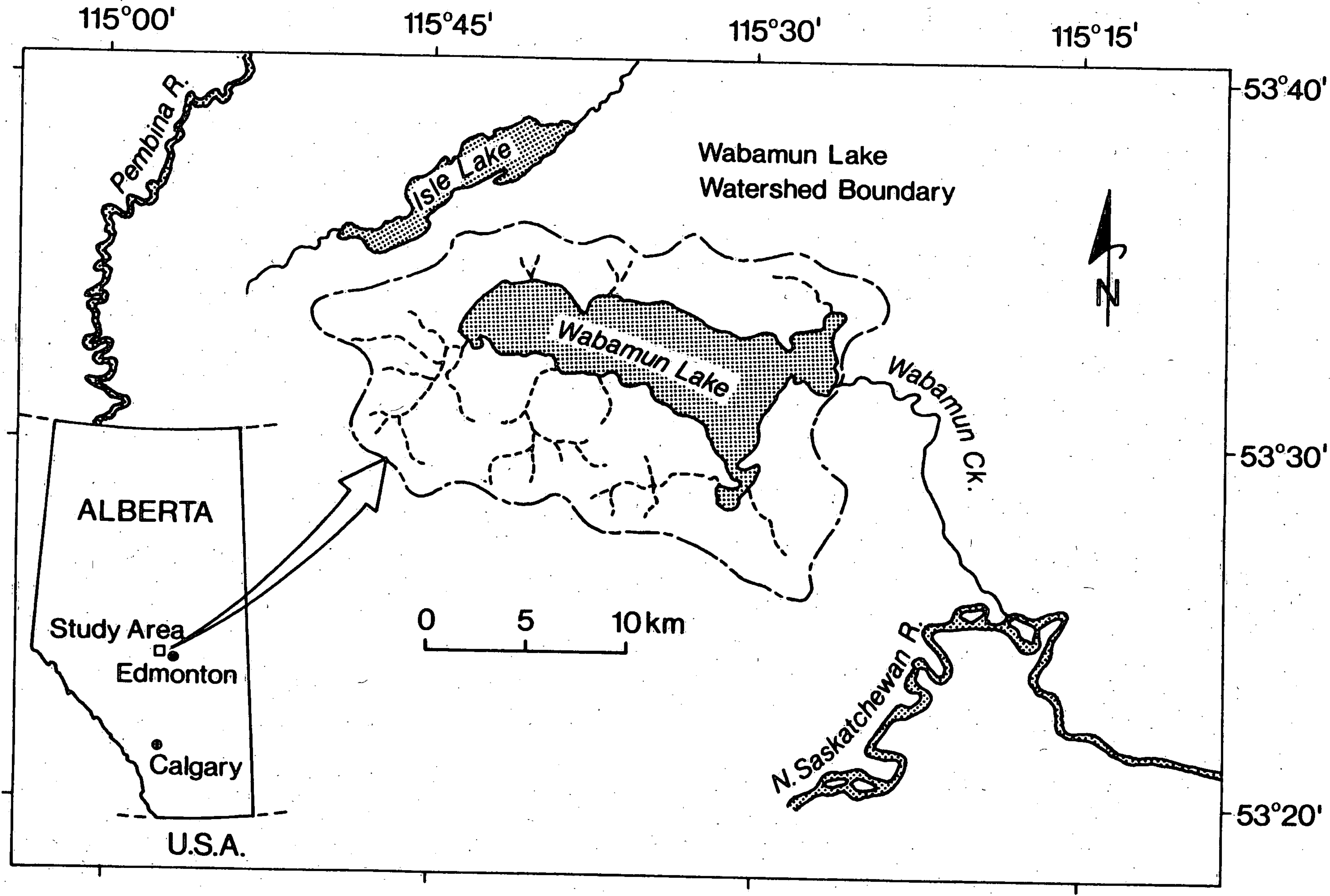

PRECIPITATION
SNOW
ACTUAL EVAP.
INFILTRATION
excess infiltration
SURFACE RUNOFF
UNSATURATED ZONE
MAX. GW RECHARGE RATE
SHALLOW GROUNDWATER ZONE
STREAM DISCHARGE
DEEP GROUNDWATER ZONE
OUT OF WATERSHED
I
R
R
I
D
D
D
LAKE
I
LAKE ICE (SEASONAL)
D
R
R
I
GROUND-WATER
SURFACE WATER
EVAPORATION
HYDROLOGIC COMPONENTS
water storage
hydrologic process
water loss from watershed
seasonal
CHEMICAL PROCESSES
I increase salinity
D decrease salinity
R no change (remove salts)

Fig 1


115°00'
115°45'
115°30'
115°15'
53°40'
53°30'
53°20'
Pembina R.
Isle Lake
Wabamun Lake
Watershed Boundary
N
Wabamun Lake
Wabamun Ck.
ALBERTA
Study Area
Edmonton
Calgary
U.S.A.
0
5
10km
N.Saskatchewan R.

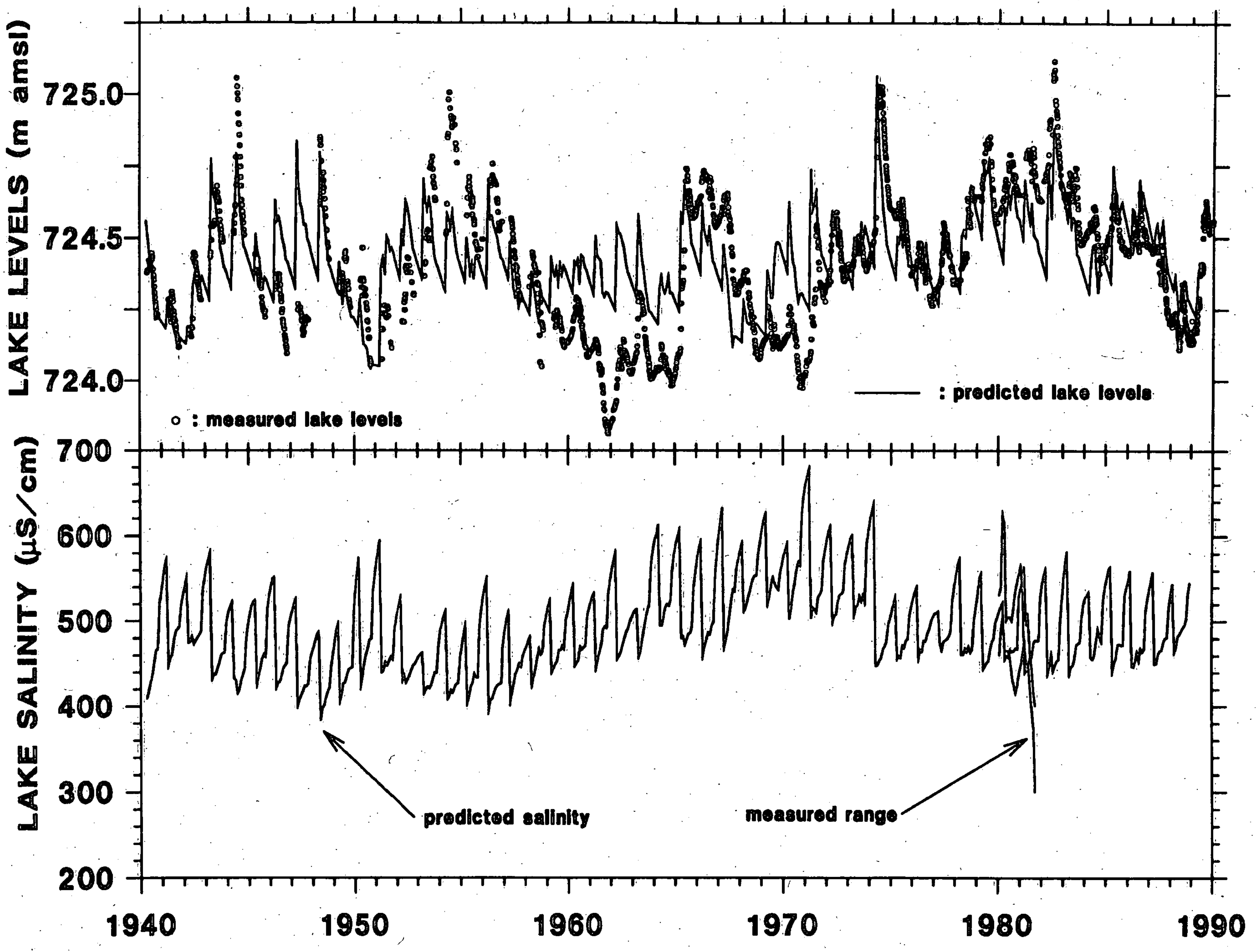

LAKE LEVELS (m amsl)
725.0
724.5
724.0
○ : measured lake levels
: predicted lake levels
LAKE SALINITY (µS/cm)
700
600
500
400
300
200
predicted salinity
measured range
1940
1950
1960
1970
1980
1990

Fig 3

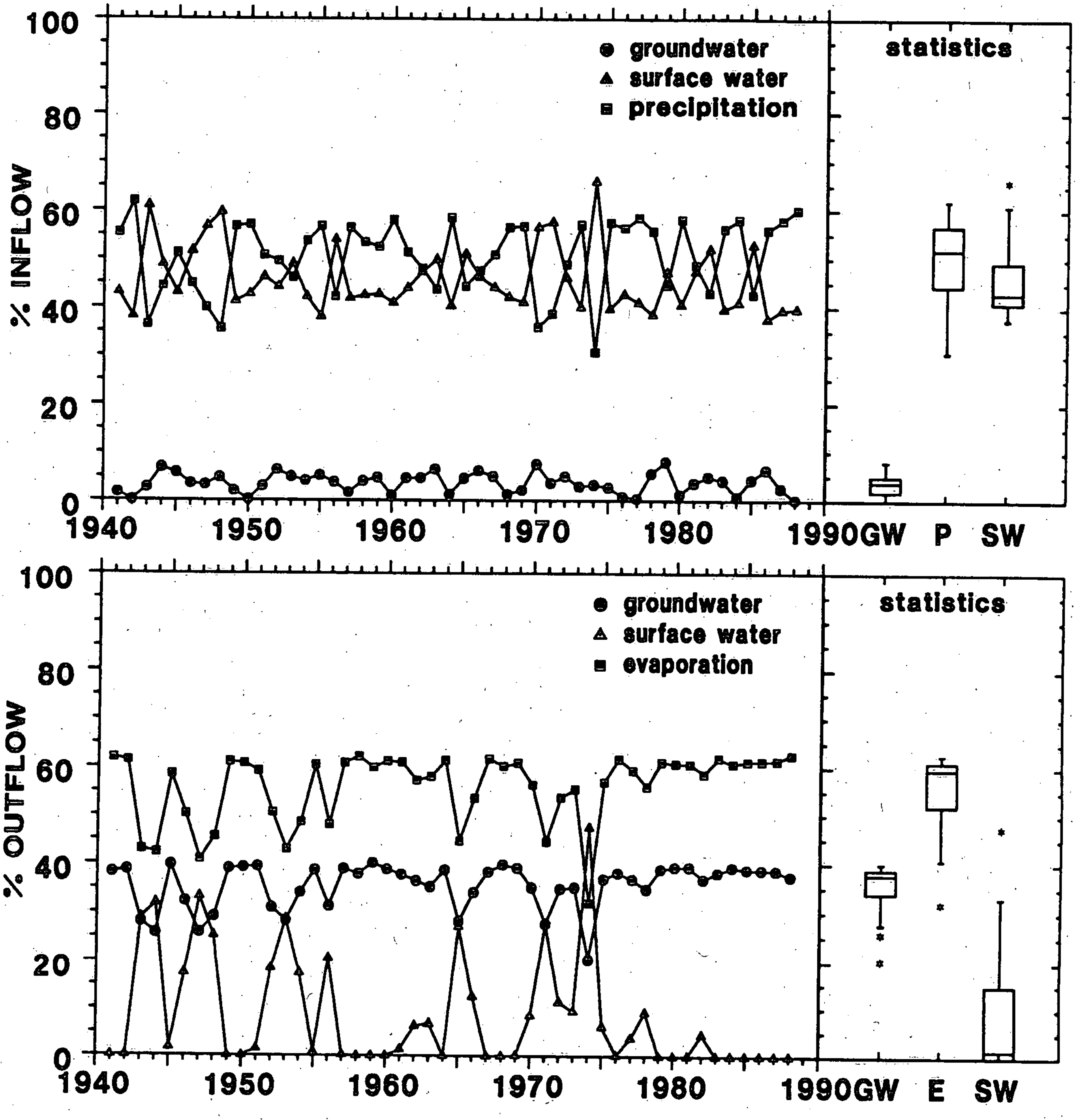

100
80
60
40
20
0
% INFLOW
● groundwater
▲ surface water
■ precipitation
statistics
1940
1950
1960
1970
1980
1990
GW
P
SW
100
80
60
40
20
0
% OUTFLOW
● groundwater
△ surface water
■ evaporation
statistics
1940
1950
1960
1970
1980
1990
GW
E
SW

Fig 4

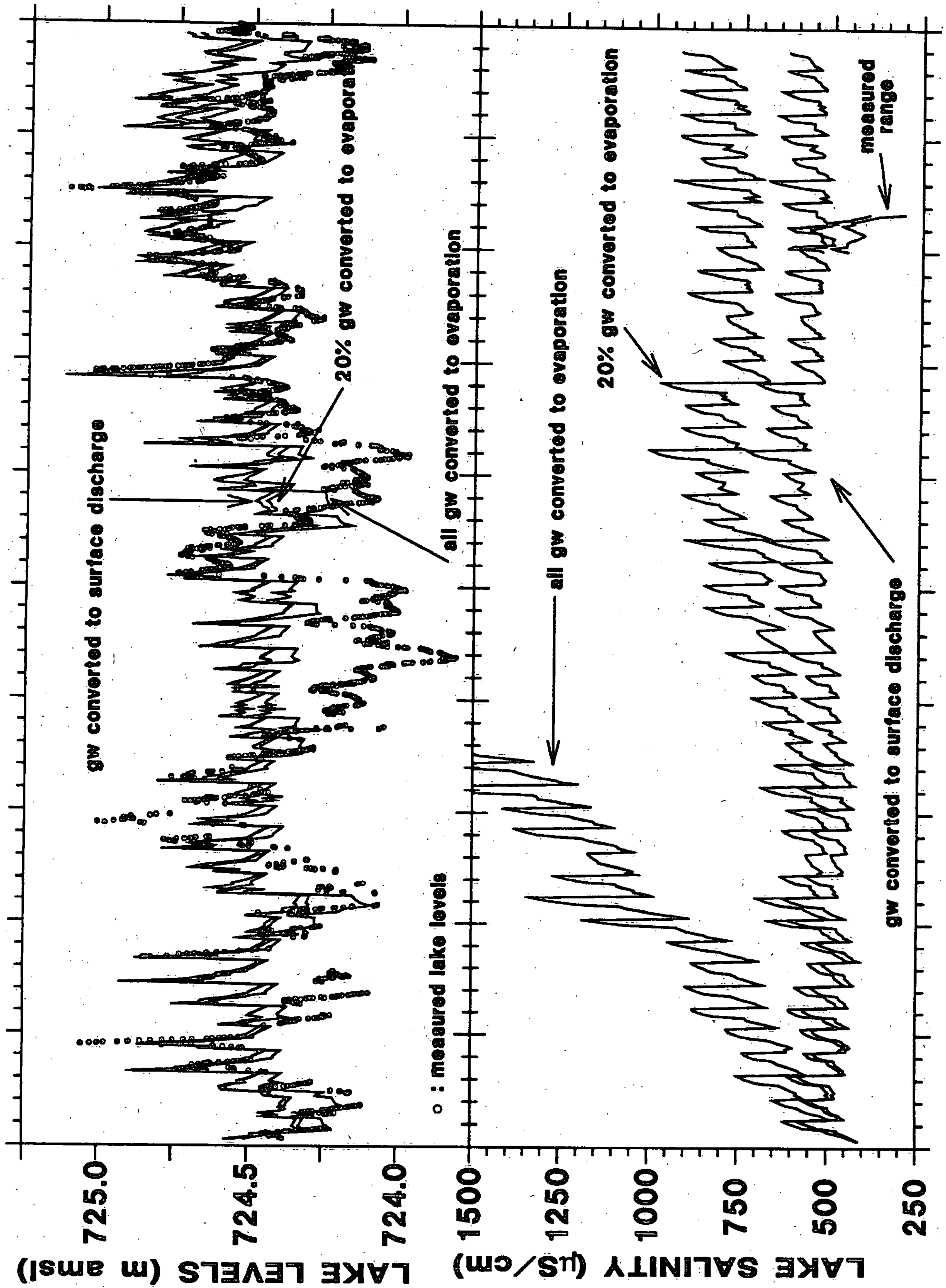

LAKE LEVELS (m amsl)
725.0
724.5
724.0
o : measured lake levels
gw converted to surface discharge
20% gw converted to evaporation
all gw converted to evaporation
LAKE SALINITY (µS/cm)
1500
1250
1000
750
500
250
all gw converted to evaporation
20% gw converted to evaporation
gw converted to surface discharge
measured range
1940
1950
1960
1970
1980
1990

Fig 5

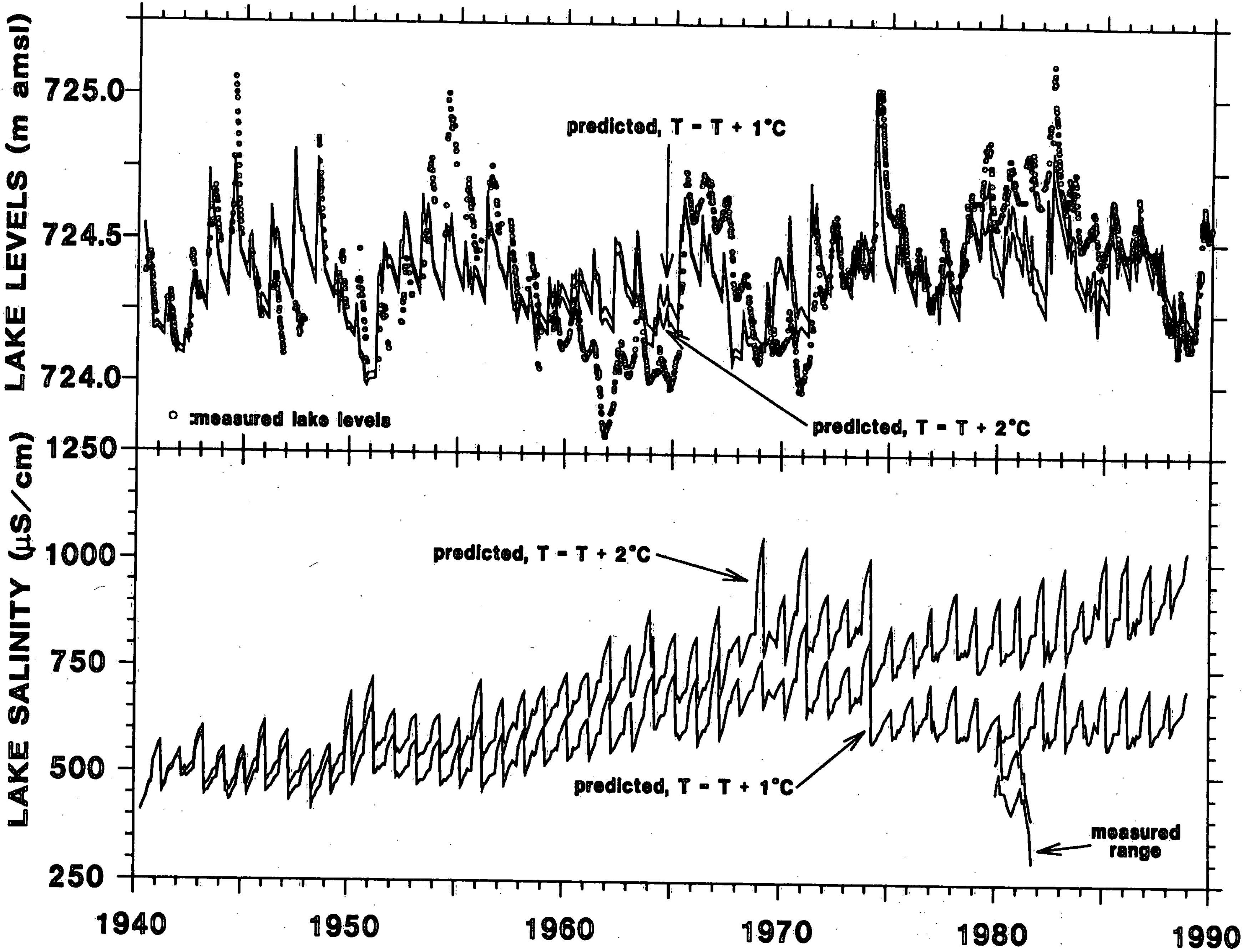

LAKE LEVELS (m amsl)
725.0
724.5
724.0
predicted, T = T + 1°C
predicted, T = T + 2°C
○ :measured lake levels
LAKE SALINITY (μS/cm)
1250
1000
750
500
250
predicted, T = T + 2°C
predicted, T = T + 1°C
measured range
1940
1950
1960
1970
1980
1990

Fig 6

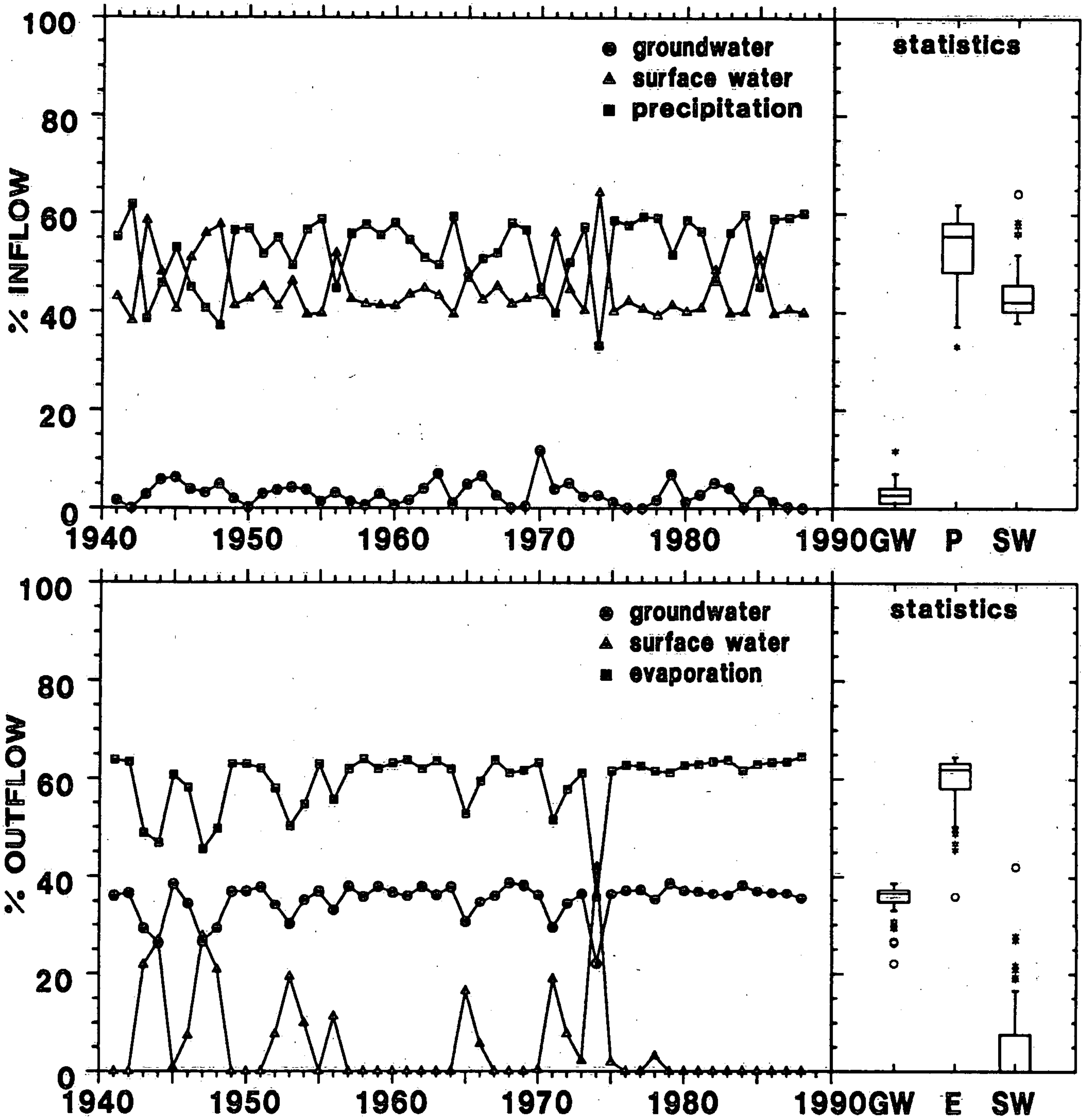

% INFLOW
groundwater
surface water
precipitation
statistics
0
20
40
60
80
100
1940
1950
1960
1970
1980
1990
GW
P
SW
% OUTFLOW
groundwater
surface water
evaporation
statistics
0
20
40
60
80
100
1940
1950
1960
1970
1980
1990
GW
E
SW

Fig 7

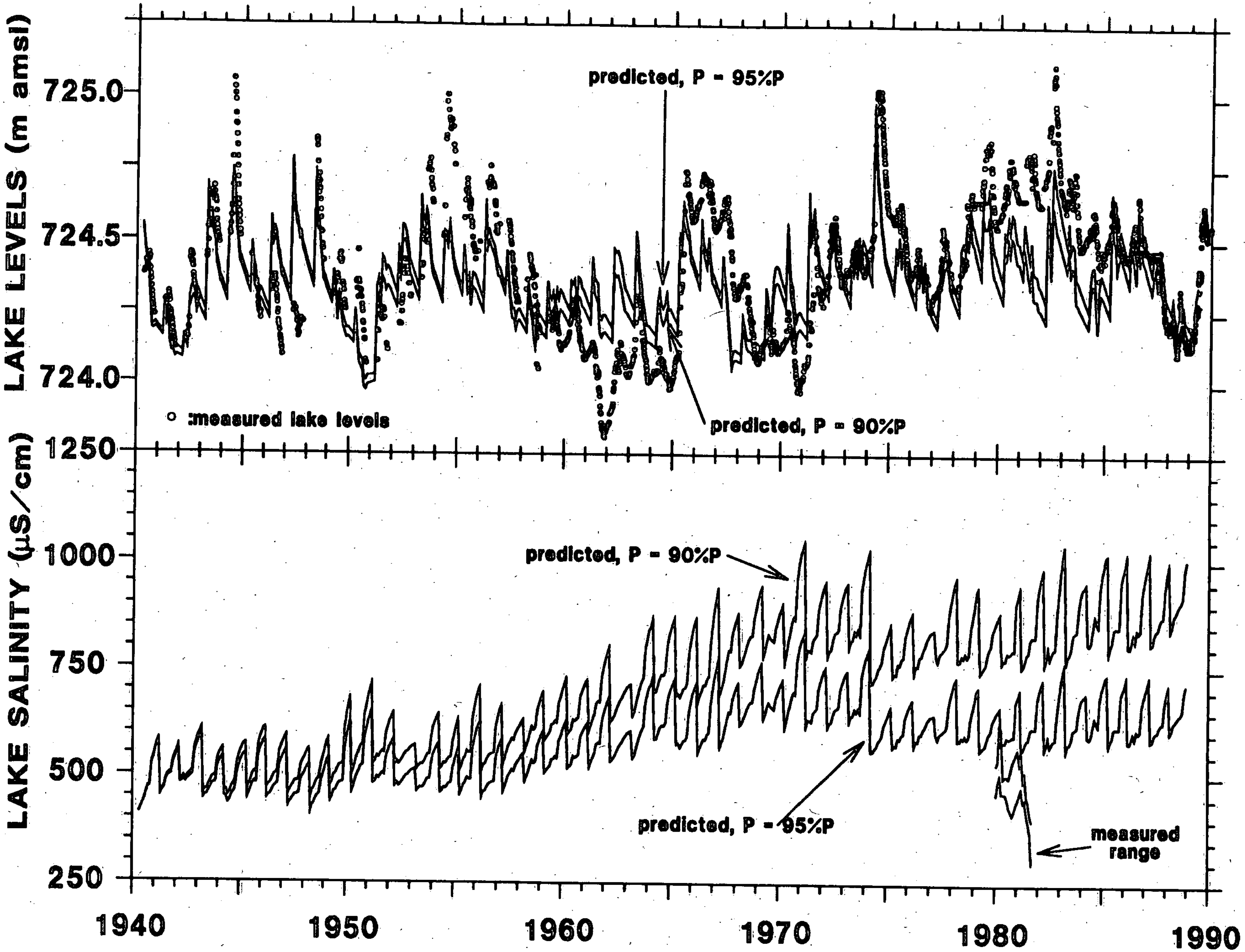
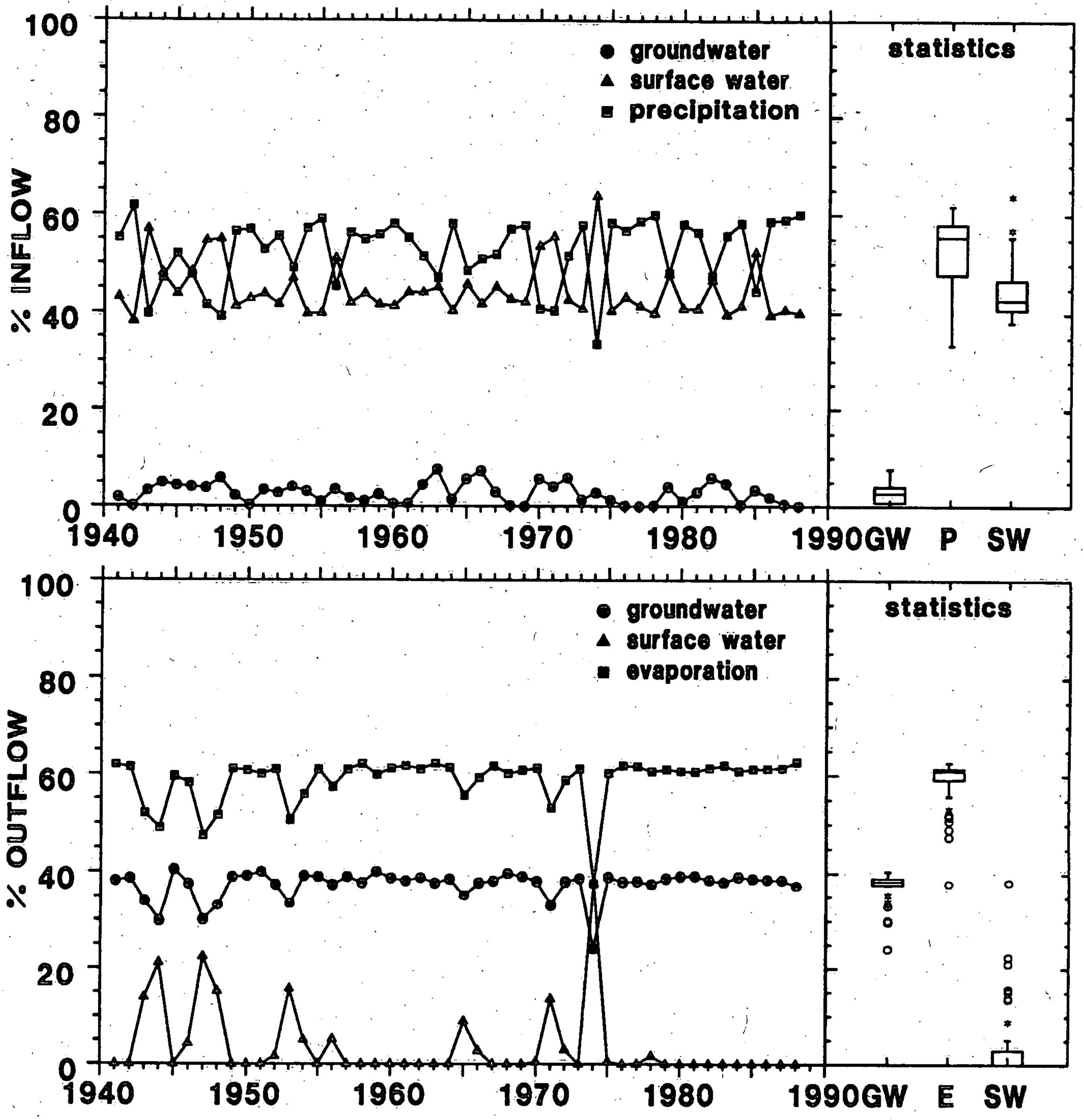

LAKE LEVELS (m amsl)
725.0
724.5
724.0
predicted, P = 95%P
predicted, P = 90%P
○ :measured lake levels
LAKE SALINITY (µS/cm)
1250
1000
750
500
250
predicted, P = 90%P
predicted, P = 95%P
measured range
1940
1950
1960
1970
1980
1990

Fig 8


100
80
60
40
20
0
% INFLOW
groundwater
surface water
precipitation
statistics
1940
1950
1960
1970
1980
1990
GW
P
SW
100
80
60
40
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0
% OUTFLOW
groundwater
surface water
evaporation
statistics
1940
1950
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1980
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GW
E
SW

Fig. 9

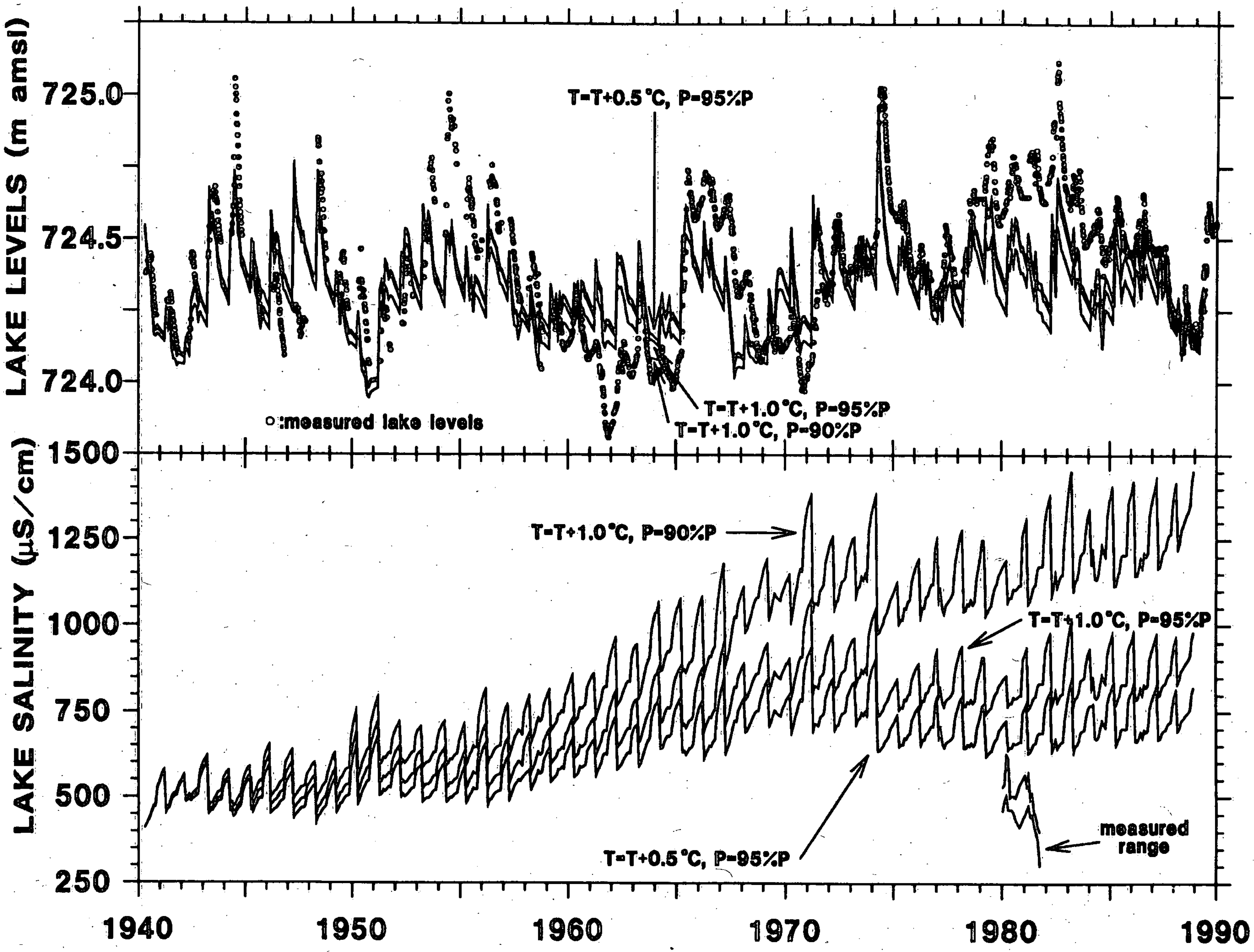
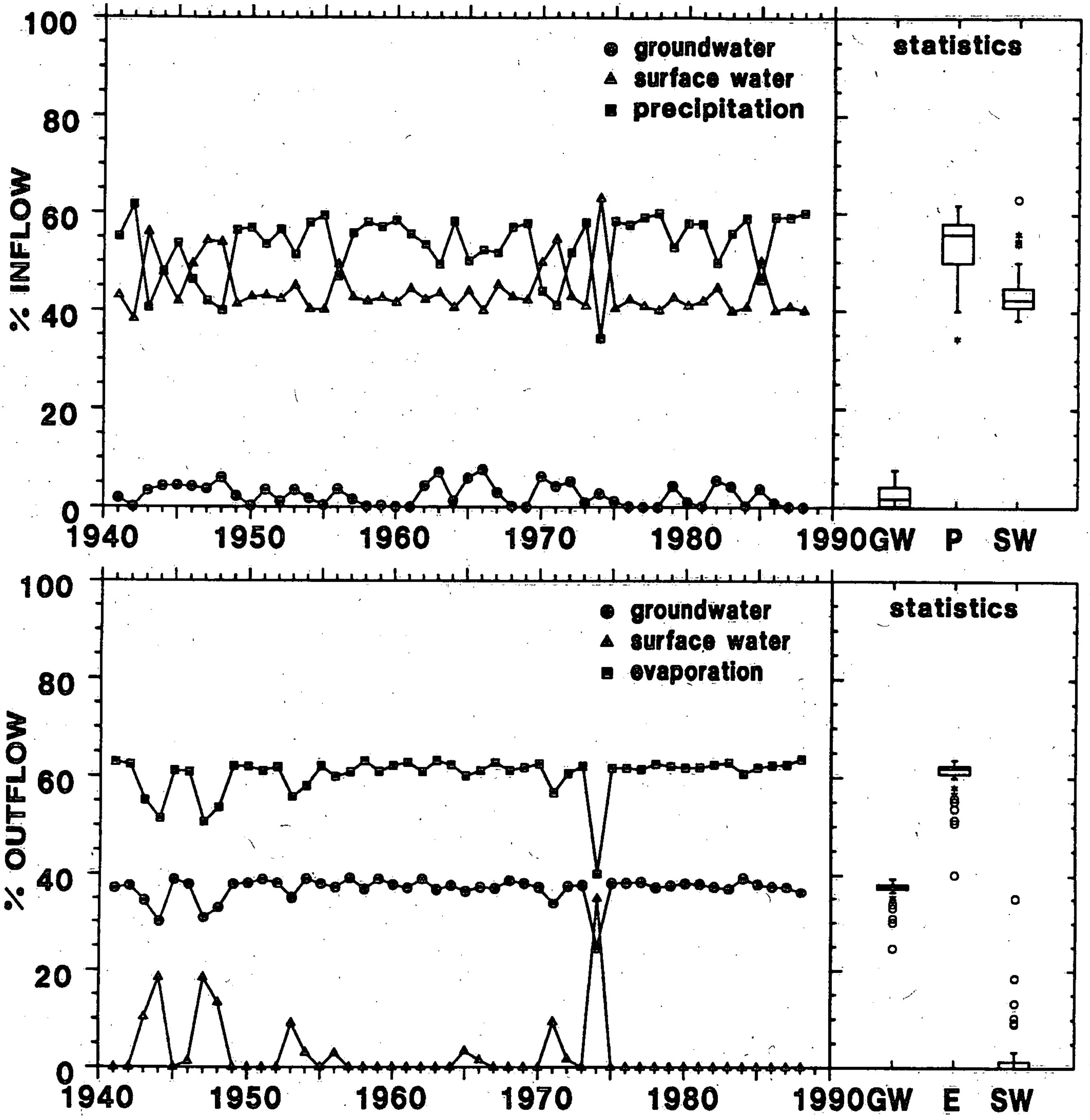

LAKE LEVELS (m amsl)
725.0
724.5
724.0
T=T+0.5°C, P=95%P
T=T+1.0°C, P=95%P
T=T+1.0°C, P=90%P
o :measured lake levels
LAKE SALINITY (µS/cm)
1500
1250
1000
750
500
250
T=T+1.0°C, P=90%P
T=T+1.0°C, P=95%P
T=T+0.5°C, P=95%P
measured range
1940
1950
1960
1970
1980
1990

Fig 10


% INFLOW
100
80
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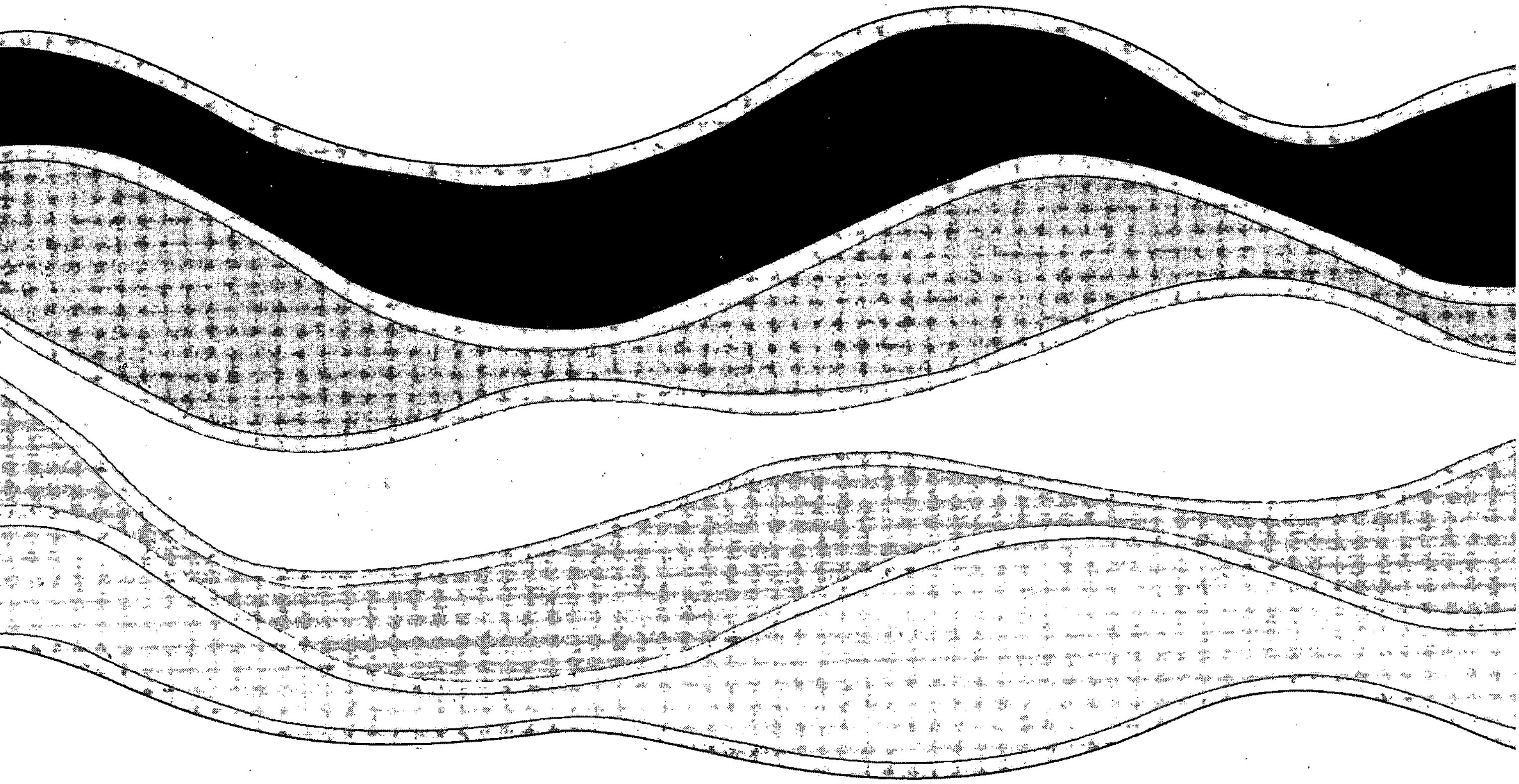
1950
1960
1970
1980
1990
groundwater
surface water
precipitation
statistics
GW
P
SW
% OUTFLOW
100
80
60
40
20
0
1940
1950
1960
1970
1980
1990
groundwater
surface water
evaporation
statistics
GW
E
SW

Fig 11



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