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NWRI Contribution No. 97-200

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MANAGEMENT PERSPECTIVE

Human activity over the last two centuries has altered the composition of Earth's atmosphere. Climate models based on the greenhouse theory suggest atmospheric accumulation of carbon dioxide and other "greenhouse gases" could increase temperature and change precipitation patterns and quantity. Concern over changes in climate caused by rising atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years as our understanding of atmospheric dynamics and climate systems has improved. Yet despite a better understanding of climatic processes, many of the effects of human-induced climatic changes are still poorly understood. The most profound effect of such climatic changes may be major alterations in hydrologic cycles and changes in water availability. Unfortunately, these are among the least well - understood impacts.

This paper approaches for evaluating the hydrologic impacts of climatic changes and presents a series of criteria for choosing among the different methods. One approach - the use of modified water-balance models - appears to offer significant advantages over other methods in terms of accuracy, flexibility and ease of use. Water-balance models are especially useful for identifying the hydrologic consequences of changes in temperature, precipitation, and other climatic variables. The ability of water-balance models to incorporate month-to-month or seasonal variations in climate, snowfall and snowmelt algorithms, groundwater fluctuations, soil moisture characteristics, and natural climatic variability makes them especially attractive for water-resource studies of climatic changes. Furthermore, such methods can be combined with state-of-the art information from general circulation models of the climate and with plausible hypothetical climate-change scenarios to generate information on the water-resource implications of future climatic changes.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Pendant les deux derniers siècles, l'activité humaine a altéré la composition de l'atmosphère de la terre. Les modèles climatiques, élaborés d'après la théorie des gaz à effet de serre, laissent supposer que l'accumulation de dioxyde de carbone et d'autres « gaz à effet de serre » pourrait augmenter la température et modifier la quantité et les caractéristiques des précipitations. Ces dernières années, les changements climatiques causés par des augmentations des concentrations atmosphériques de dioxyde de carbone et d'autres gaz traces ont suscité de plus en plus de craintes à mesure que nos connaissances de la dynamique atmosphérique et des systèmes climatiques s'amélioraient. Mais, en dépit d'une meilleure compréhension des processus climatiques, beaucoup des changements climatiques d'origine anthropogène restent encore mal connus. Les effets les plus marqués de ces changements pourraient être une altération majeure des cycles hydrologiques et des changements dans l'approvisionnement en eau. Malheureusement, il s'agit là des effets les plus mal connus.

Le présent document porte sur l'évaluation des effets hydrologiques des changements climatiques et présente une série de critères pour le choix entre les différentes méthodes. L'une des démarches - l'emploi de modèles modifiés d'équilibre hydrologique - semble offrir des avantages significatifs par rapport à d'autres méthodes quant à l'exactitude, la flexibilité et l'applicabilité. Les modèles d'équilibre hydrologique sont particulièrement utiles pour caractériser les conséquences hydrologiques des changements dans la température, les précipitations et d'autres variables climatiques. La capacité des modèles d'équilibre hydrologique à incorporer les variations saisonnières mensuelles dans les algorithmes climatiques, de précipitations nivales et de fonte des neiges, dans les fluctuations du niveau phréatique, dans les caractéristiques d'humidité du sol et dans la variabilité climatique naturelle les rend très intéressants pour l'étude des ressources en eau dans le cadre des changements climatiques. De plus, ces méthodes peuvent être combinées avec les données les plus récentes obtenues grâce aux modèles de circulation générale pour le climat et aux scénarios de changement climatique permettant d'obtenir de l'information sur les conséquences des futurs changements climatiques pour les ressources en eau.

ABSTRACT

Water-balance modelling techniques were developed and applied for assessing climatic impacts, and tested for a watershed in the Northeast Pond River basin using atmospheric-change scenarios from both state-of-the-art general circulation models and from a series of hypothetical scenarios. Results of this research strongly suggest that possible changes in temperature and precipitation caused by increases in atmospheric trace-gas concentrations could have major impacts on both the timing and magnitude of runoff and soil moisture in important natural resources areas. Of particular importance are predicted patterns of summer soil-moisture drying that are consistent across the entire range of tested scenarios. The decreases in summer soil moisture range from 10 to 50% for different scenarios. In addition, consistent changes were observed in the timing of runoff - specifically dramatic increases in winter runoff and decreases in summer runoff. These hydrologic results raise the possibility of major environmental and socioeconomic difficulties and they will have significant implications for future water-resource planning and management.

Key words: climate change, deterministic hydrological model, subarctic watershed, Canada

RÉSUMÉ

Des techniques de modélisation de l'équilibre hydrologique ont été mises au point et appliquées pour l'pour caractériser les conséquences hydrologiques des changements dans la température, les Northeast Pondcipitations et d'autres variables climatiques. La capacité des modèles d'équilibre hydrologique à incorporer les variations saisonnières mensuelles dans les algorithmes climatiques, de précipitations nivales et de fonte des neiges, dans les fluctuations du niveau phréatique, dans les caractéristiques d'humidité du sol et dans la variabilité climatique naturelle les rend très intéressants pour l'étude des ressources jeur aussi bien sur la chronologie que sur l'importance du ruissellement et de l'humidification du sol dans des régions importantes du point de vue des ressources naturelles. Les schémas prévus de séchage du sol en été, qui soient cohérents sur toute la plage de scénarios envisagés, sont particulièrement importants. La diminution de l'humidité du sol en été varie de 10 à 50 %, selon le scénario. De plus, on a observé des variations sensibles dans la chronologie du ruissellement - avec de très fortes augmentations du ruissellement en hiver, et des diminutions en été. Ces résultats hydrologiques font craindre le risque de difficultés environnementales et socio-économiques majeures, et joueront un rôle majeur dans la planification et la gestion futures des ressources en eau.

Mots clés : changement climatique, modèle hydrologique déterministique, bassin subarctique, Canada

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Abstract: Water-balance modelling techniques were developed and applied for assessing climatic impacts, and tested for a watershed in the Northeast Pond River basin using atmospheric-change scenarios from both state-of-the-art general circulation models and from a series of hypothetical scenarios. Results of this research strongly suggest that possible changes in temperature and precipitation caused by increases in atmospheric trace-gas concentrations could have major impacts on both the timing and magnitude of runoff and soil moisture in important natural resources areas. Of particular importance are predicted patterns of summer soil-moisture drying that are consistent across the entire range of tested scenarios. The decreases in summer soil moisture range from 10 to 50% for different scenarios. In addition, consistent changes were observed in the timing of runoff - specifically dramatic increases in winter runoff and decreases in summer runoff. These hydrologic results raise the possibility of major environmental and socioeconomic difficulties and they will have significant implications for future water-resource planning and management.

Key words: climate change, deterministic hydrological model, subarctic watershed, Canada

1. Introduction

For the past two centuries, atmospheric concentrations of carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs) have increased due to human activity. Potential effects of these changes on global climate are uncertain. Global atmospheric model scenarios based on the greenhouse theory project higher mean global temperatures, changes in amounts and distribution of precipitation, and increased frequency and intensity of disturbance events. The accuracy of these projections is unclear, due to questions about sources and sinks of greenhouse gases, variability among model projections, undefined atmospheric and biospheric interactions and feedbacks, and inconsistencies between characteristics of past climatic trends and the greenhouse theory. Particularly uncertain are regional atmospheric scenarios, which are most relevant to questions concerning potential ecosystem effects and management and policy responses. Watershed hydrological cycle responses to potential interacting effects of changing climatic regimes and atmospheric CO_2 concentrations are complex and difficult to predict.

Concern over global atmospheric changes caused by growing atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years as our understanding of atmospheric dynamics and global atmospheric systems has improved. Yet, despite a growing understanding of climatic processes, many of the effects of human-induced climatic changes are still poorly understood. Major alterations in regional hydrologic cycles and subsequent changes in regional water availability may be the most important effects of such climatic changes. Unfortunately, these are among the least understood impacts.

Many studies of the hydrological impacts of climate change have been carried out in different parts of the world (Manabe and Weatherald, 1987, Mitchell, 1989, Flaschka, 1984, Gleick, 1986). Studies on changes in annual and seasonal runoff have pointed to a great sensitivity of river basins even to insignificant changes in climatic characteristics, especially for basins located in arid and semiarid regions (Lins et al., 1988). The available evidence supports the view that the Sahelian drought is one aspect of climate variability.

Some of the possible impacts of climate change on the hydrological regime include: increase in summer evaporation, more rainstorms caused by increased convective precipitation in the summer months, increased intensity of tropical storms, and increased monsoon rainfall in the tropics (IPCC, 1990).

2. Analysis of Hydrological Studies due to Climate Change

There have been some serious efforts to evaluate the regional hydrologic implications of climatic changes (Schwarz, 1977, Stockton and Boggess, 1979, Nemec and Schaake, 1982; Revelle and Waggoner, 1983; Flaschka, 1984, U.S. Environmental Protection

Agency, 1984). These early works provided the first tentative evidence that relatively small changes in regional precipitation and temperature patterns might result in large changes in regional water availability. If realistic estimates of actual changes in regional water availability are to be calculated, however, a number of improvements over these earlier works need to be made. In order to be valuable to water-resource planners, regional hydrologic assessments should include (i) a focus on short time-scales such as months and seasons, rather than annual averages; (ii) the ability to incorporate both hypothetical climatic changes and the increasingly-detailed assessments of regional changes produced by Global Circulation Models (GCMS); (iii) the ability to produce information on hydrologically important variables, such as changes in runoff and available soil moisture, rather than just changes in temperature and precipitation; and (iv) the ability to incorporate snowfall and snowmelt, topography, soil characteristics, natural and artificial storage, and other regional complexities.

One of the most promising methods for assessing the regional hydrologic effects of climatic changes is the use of water-balance models modified for use under conditions of changing climate. Water-balance modelling was first developed in the 1940s and 1950s by C. W. Thornthwaite and J. R. Mather as a way of estimating evapotranspiration and of evaluating the importance of different hydrologic parameters under a variety of hydrometeorlogical conditions (Thornthwaite, 1948; Thornthwaite and Mather, 1955, 1957). The spatial resolution of water balances can range all the way from global assessments of the hydrologic cycle of the earth to microscale assessments of water balances on the surfaces of foliage or even animals. The temporal resolutions studied are equally large from annual balances to instantaneous continuous time, analyses. Almost all water-balance models evaluate the fate of specified water inputs, such as precipitation as those inputs are utilized, stored, or changed.

Water-balance models incorporate soil-moisture characteristics of regions, permit month-to-month, seasonal, and annual estimates of hydrologic parameters, and use readily-available data on meteorological phenomena and soil and vegetation characteristics. They can provide accurate estimates of surface runoff when compared to measured runoff, reliable evapotranspiration estimates under many climatic regimes, and estimates of groundwater discharge and recharge rates. Typical data requirements are monthly-average temperature and precipitation and information on the soil and vegetative characteristics of a region - often the only long-term hydroclimatological data that are available. In cold countries, snowmelt - a major source of runoff in many watersheds - can also be incorporated into such a model.

Since its introduction, the water-balance approach has become one of the most versatile and widely-used tools for environmental and hydrologic analyses. Moreover, numerous modifications and extensions to the original water-balance formulations have been developed and used in hydrologic research (Sokolov and Chapman, 1974; Miller, 1977, Mather, 1978; U.S.Army Corps of Engineers, 1980). These modifications permit the systematic evaluation of flooding and drought probabilities, agricultural water demands, groundwater recharge rates, the distribution of soils and vegetative cover, and a wide variety of other water-resource issues. Examples of the diverse applications of the water balance approach include the reconstruction of the hydrology of small, forested watersheds (Haan, 1972), estimation of Pleistocene-era climatic conditions and lake levels (Snyder and Langbein, 1962), and evaluation of the seasonal and geographical patterns of water supply and irrigation demand in a 785 000 km^2 basin in Northern Africa

(Al-Khashab, 1958).

For climatic impact assessments, the flexibility of water balances is an additional advantage: by integrating hydrologic advances with existing water balance techniques, new insights into hydrologic processes and environmental impacts can be gained. Furthermore, water-balance models are well suited to the current generation of micro-computer software and hardware.

Once a region has been characterized by water balances, the effects of climatic changes can be evaluated in three ways. First, after verifying model accuracy using long-term historical data, it is possible to use historical data to evaluate the effects of past fluctuations in precipitation and temperature on runoff, soil moisture, infiltration, recharge, surface flow, interflow and groundwater flow. Second, by determining the sensitivity of runoff, soil moisture, infiltration and recharge (deep percolation) to hypothetical changes in the magnitude and temporal distribution of precipitation and temperature, it is possible to assess the hydrologic effects of a wide range of climatic changes. Third, by incorporating even rough regionally desegregated changes in temperature and precipitation predicted by general circulation, climate changes on regional hydrology can be made.

All three approaches have advantages. In the first case, historical variations in temperature and precipitation can be used to determine the sensitivity of runoff and soil moisture in any given watershed. For example, an extended period of higher-than-average temperature may be accompanied by distinct reductions in runoff. Similarly, extended periods of high precipitation may change the timing of soil-moisture saturation and increase the vulnerability of watersheds to flooding. Second, the use of hypothetical data to test the sensitivity of watersheds to climatological variations offers the opportunity to evaluate possible transient climatic responses. While existing general circulation models are limited almost entirely to equilibrium response models, Schneider and Thompson (1981) have pointed out that the transient responses of the climate may be quite different. Despite the importance of this observation, there have been few attempts to incorporate non-equilibrium climatic states in climate impact assessments.

The third approach, linking regional models with general circulation model output, also has distinct advantages. Even in the absence of a consensus about the precise nature of changes in many hydrologic variables, regional models can be used both to evaluate the quality of regional information from GCMs and to begin to estimate realistic regional climate impacts. While the present quality of the regional information provided by GCMs is low, improvements in hydrologic parameterization and grid resolution of these models over the next several years will improve the quality of regional climate evaluations. Moreover, when information from non-equilibrium climate models becomes available, it can be used to investigate the transient responses of climate to anthropogenic perturbations. In the meantime, by linking GCM output with more accurate regional hydrologic models, regional evaluations may provide important insights.

3. A Hydrological Model for Climatic Impact Assessment

A hydrological model (Bobba et al. 1995) was modified to evaluate the advantages and limitations of water balance methods for the hydrologic assessment of climatic changes. Details of model formulation, testing, and validation are provided in Bobba et. al (1995), Bobba (1992), Bobba et.al (1992), and Bobba and Lam(1990). In order to determine the effects of changing climate on the water resources of the region, a series of climate-change scenarios (involving changes in temperature and precipitation) were used to drive the water balance model. They included both purely and hypothetical climate-change scenarios. The hypothetical scenarios of temperature and precipitation changes were chosen after reviewing state-of-the-art estimates of future changes in climatic conditions. These scenarios can be summarized as follows:

Three hypothetical scenarios involved combinations of plus 2 °C and plus and minus 0, 50, and 100% precipitation in different seasons. The data was used to produce different climate change scenarios.

All three temperature and precipitation scenarios were then used to drive the deterministic hydrological model, and the effects on monthly average soil moisture, monthly average infiltration and recharge, daily-average different flows (e.g. surface flow, interflow, and groundwater flow), and total runoff were evaluated. For each average scenario, a 30 year record of daily maximum and minimum temperature and precipitation was used by applying the changes to the 30-year historical record of daily temperature and precipitation in the watershed. These data were used to drive the water-balance model, producing a daily (30-yr) record of predicted daily runoff, soil moisture, infiltration, recharge and different flows (surface flow, interflow and groundwater flow). The daily runoff, surface flow, interflow, groundwater flow, snowpack, infiltration, recharge, and soil moisture data were then averaged to produce long-term seasonal average values.

3.1. General description of the system

The main operating part of the watershed simulation and forecasting system consists of simulating the hydrological cycle using standard meteorological data. The hydrological model reads watershed data from the file, runs forecasts, and distributes results.

3.2. Watershed runoff modelling

The model has its own precipitation network from which data are available. These precipitation data are used in winter to increase the accuracy of the areal water equivalent simulation of snow. Snowmelt is the main source of runoff during spring, and one method for improving the snow simulation is to use all precipitation data available, as well as to check and update the simulated snow values against observed snow line and areal values. In summer or snow-free periods the precipitation data are used. Model operation is based on updating of the watershed model by changing areal precipitation according to observed water levels and discharge data.

The hydrological model is comprised of linked models: a soil moisture accounting model that calculates gains and losses of water in the soil through various processes (e.g. evapotranspiration, infiltration), and a snow accumulation and ablation model that calculates the accumulation of snow and the contribution of snowmelt to soil moisture and runoff. This model is widely used and generally accepted as one of the most reliable models in varied climatic conditions on different Canadian regions in Canada (Bobba and Lam, 1990). The model distributes soil moisture into upper, lower and deeper zones. The movement of water between zones is described by a percolation equation, the parameters of which are determined by the free-water content in the upper soil zone and the soil-moisture deficiency of the lower soil zone. The snowmelt model, described in detail by Bobba and Lam (1990), relies on air temperature as an index to energy exchange at the snow-air interface. The input to the model is areal temperature and precipitation data; the output is surface runoff, interflow, groundwater flow, infiltration, recharge, total surface runoff and moisture in different soil zones on a daily basis.

3.3. Snow model

The snow model simulates snow accumulation and snowmelt; the input is areal precipitation and daily maximum and minimum temperature (Bobba and Lam, 1985, 1990). Snowmelt is simulated by a degree-day model with increasing degree-day values during the melt period. Open and forest snowmelts are simulated separately, which is essential for correct simulation of long melt periods with cold and warm spells and to create appropriate distribution of areal snow cover (Bobba and Lam, 1985). The parameters of the snowmelt model are more or less specific for a basin and stations used. Other important processes in snow model simulation are liquid water retention in snowpack, refreezing of melted water, and simulation of snow-covered area and temporary surface storage during snow cover. Temporary storage causes delay in water outflow from the sub-basin due to snowdrifts and snowpack restricting water-flow through the terrain.

3.4. Soil moisture simulation

Soil moisture is simulated with a soil moisture storage model in which input includes rainfall and snowmelt, output terms are actual soil evaporation, which is simulated according to the degree of saturation of soil, and potential evaporation. When the soil becomes fully saturated, i.e. soil is wet, the actual evaporation approaches potential evaporation; outflow from soil moisture storage into the subsurface storage is an exponential function of the degree of saturation of soil. Soil moisture storage is active and changing during summer, when risk of flood and risk for long drought can be forecasted based on the state of soil moisture storage and precipitation forecast. When soil moisture storage is full abundant rainfall causes flooding, when empty, i.e. the soil surface is dry, rainfall creates little runoff and inflow into lakes and rivers remains low.

3.5. GROUNDWATER FLOW AND STORAGE

Water from soil moisture storage recharges the subsurface storage. Outflow from the subsurface storage mainly creates the runoff peaks during high flow. From the subsurface storage water goes into the groundwater storage whose outflow is the baseflow. The model structure is based on the old hydrological concept of runoff formation, where runoff is divided into interflow and groundwater flow. The use of many basins leads generally to a similar simulation of recharge/nonrecharge areas. The sub-basins near a river or lake usually have small soil, subsurface and groundwater storage and respond more quickly to rainfall and snowmelt. The upper sub-basins have larger storage and longer response times, and the outflow remains higher for longer periods; thus quantitatively, the old hydrological concept of runoff formation works well in runoff forecasting.

3.6. WATERSHED MODEL IMPLEMENTATION

The watershed model is built with the sub-models presented above. The model implementation begins by dividing a watershed into sub-basins according to the classification of geomorphological conditions (Bobba and Lam, 1990). The aim is to divide the watershed into small homogeneous sub-basins according to elevation, land use, snow distribution, and lakes and avoiding the combination of hydrologically different areas into one sub-basin (Bobba and Lam , 1988, 1990). This enables correct simulation of water levels and outflow in a lake and improves the simulation of areal runoff. The effects on runoff due to a lake not described in the model are taken into account mainly in the interflow, ground water and flood routing models. The accuracy of discharge simulation remains good, because lakes dampen the variation of runoff from the basin and damped catchments are easy to model. Finally the basic hydrological runoff and lake models are connected together to form the watershed model.

4. Application of Hydrological Model

The hydrological model was applied to Northeast Pond River watershed which is located approximately 20 km west of St. Johns', Newfoundland, Canada (Figure 1). It has an area of 3.90 km^2 and its geomorphological description is given in Bobba et al. (1995, 1994). The bedrock in the watershed consists of mafic and volcanic rocks. The bedrock is overlain by surficial unconsolidated deposits a meter or more in thickness. The overburden consists of olive firm, very stoney, sandy loam till derived mainly from grey slate. The top soil in the swamp area consists of fibrous and partly decomposed peat moss mainly sphagnum mosses.

4.1. CLIMATE AND RUNOFF

Mean monthly temperatures, precipitation, and runoff for the Northeast Pond River basin are illustrated in Figure 2 (average values for years 1954-1983). Daily temperature and precipitation data were obtained from St.John's meteorological station and runoff data were obtained from the gauge at the watershed outlet (Figure 1). Mean monthly temperature and precipitation were calculated from daily data. The climate of the study area is dominated by the Labrador current which consists primarily of arctic waters. This current introduces relatively cold water to the area in spring and summer but by comparison fairly warm water in winter. Hence, the study area has a marine climate, characterized by short but pleasant summers and mild winters. The average temperature for the warmest month (July) varies from 13.5°C to 16.5°C over the study area, with the central part of the area being warmest and the coastal area coolest. February is the coldest month with an average temperature ranging from 4.5°C to 2.0°C. Precipitation, while fairly evenly distributed throughout the year, is heaviest during the winter months, April to September being the months with lowest precipitation. Because the mean monthly temperatures are below or just above freezing from October to May, potential evapotranspiration (PET) is low and precipitation exceeds PET during these months, producing a surplus of water that is available to fill soils to their moisture holding capacities and to generate runoff. During summer months, PET exceeds precipitation and little of the summer precipitation becomes runoff (Bobba 1992). Because of the freezing temperatures during winter months, the majority of the precipitation during the winter season falls as snow and accumulates throughout the winter. Thus the surplus of precipitation in excess of PET that occurs during the cold months is stored as snowpack accumulations. The snow accumulations melt as temperatures increase to above freezing point during spring. The effects of snowmelt are evident in the mean monthly values of runoff. Runoff is relatively medium for most of the year, except during the spring when snowmelt occurs. The majority of the annual runoff in the watershed occurs during the months of March to April, with the peak occurring during April. Because the snowmelt accounts for such a large proportion of the annual runoff, snowpack accumulations measured on or about March can be used to estimate annual runoff in the watershed. A regression of annual runoff measured at the stream gauge for the years 1954 -1983 with the March snowpack measurements in the watershed indicates that 70% of the variability of annual runoff in the watershed can be explained by variations in the March snowpack accumulations (Bobba et al., 1995).

4.2. MODEL CALIBRATION

The optimization criteria in the calibration are the sum of the square of the difference between the observed and simulated water equivalents of snow, discharge, and water level. All available observations are used in the calibration. Further details are provided in Bobba and Lam (1985, 1990). The hydrological model was calibrated for the period 1954-1959 and verified for the period 1960-1983, reported earlier (Bobba, 1992., Bobba et al. 1994, 1995). Conventional techniques were used to develop the model parameters.Three statistical techniques were used as indicators of the accuracy of the simulation. The computed hydrograph produced a satisfactory fit with the observed data. In particular, the episodic events during snowmelt for many years were accurately simulated as well as other episodes due to heavy rainfall. The magnitudes of these peaks were also predicted reasonably well (Bobba et al. 1994, 1995).

4.3. CLIMATIC SCENARIOS

To assess the potential impacts of climatic change on runoff in the basin, scenarios of changes in temperature and precipitation were used as inputs to a watershed runoff model. Currently, we lack the ability to estimate the regional scale details of climatic change. Thus, for this study we relied on purely hypothetical scenarios as well as scenarios derived from the outputs of general circulation models. Climate change scenarios used in the watershed runoff model were:

Scenarios	Change in temperature	Change in precipitation
Scenario 1	T plus 2°C	Precip * 2.00 (Jan to Apr) Precip * 0.50 (May to Sept) Precip * 1.50 (Oct to Dec)
Scenario 2	No change	Same as above
Scenario 3	T plus 2°C	No change

The values chosen for hypothetical scenarios typically reflect best estimates of changes in important climatic variables, although extremes values are occasionally chosen to explore where a system might fail to perform as expected or designed. Thus, the practice of using hypothetical temperature increases of 1,2,3,or 4°C reflects the consensus that greenhouse warming will produce temperature rises in this range, given an equivalent doubling of atmospheric CO_2 (Hengeveld, 1995). Because much greater uncertainty surrounds estimates of change in regional precipitation, both increases and decreases in average temperature and precipitation are modeled in this study.

5. Model Results

5.1. SNOW PACK

Figure 3(a,b,c) shows the percentage change of snow pack, net supply and total flows in different seasons of the average of thirty years data. The computed thirty years of data were separated in different seasons of winter, spring, summer and fall for the analysis. Each season average was compared with the thirty year average of the season data without scenario and showed change in percentage. Due to the projected higher temperature (2 °C), the snowpack was less (20 - 60%) in winter and fall, even due to mild temperatures. Also, the net supply and flows were higher for all the scenarios in winter and spring. Due to higher temperature and less precipitation (50% less) in summer, the summer net supply and flows were less than average net supply and flow of that season except scenario 2.

Figure 3a shows the snowpack thickness in the watershed for different seasons. If the temperature goes up 2°C, the snowpack thickness reduces in the watershed from more than 100% to 10% for all the scenarios in all seasons except scenario 2. Snowpack thickness was higher in winter and spring months due to higher precipitation. Snowpack thickness was less for all the scenarios in the fall.

5.2. NET SUPPLY

The net supply was higher (40-170%) higher in winter months than normal supply due to higher precipitation and temperature (Figure 3b). Surprisingly, the net supply was 40% higher than normal in spring and summer except for fall scenario 2 due to higher precipitation without temperature changing. The net supply was less for the summer to fall season for scenario 1. This may be due to the higher temperature by 2°C with 50 % less precipitation in that season.

5.3. TOTAL FLOWS

Figure (3c) shows the total flows (combined surface, interflow and groundwater flows) of the watershed in different seasons for the average of thirty years of data. The total flow was 125% higher than normal flow for scenario 1 due to higher temperature and higher precipitation, 50% higher flow than observed flow for scenario three. In the spring months, the total flow was higher (25 - 50%) than the normal flow for all scenarios. The flows were 50% to 10% lesser in summer and fall for scenario one. Surprisingly, the scenario 2 and scenario 3 acted differently for summer and fall seasons.

The percentage change in stream total flows followed the net supply. The flows were higher in winter months than spring months. Scenario 1 showed higher flows in winter months than spring months. Summer flows were less (negative) than other scenarios in summer months. The groundwater discharge might be less than thirty year average groundwater flow in summer months due to less precipitation and high temperatures for evaporation in scenario 1.

5.4. UPPER SOIL ZONE, INFILTRATION AND SURFACE FLOW

The upper soil zone moisture (Figure 4) is influenced by net supply and follows the same pattern. The upper soil moisture (75%), infiltration (125%) and surface runoff (100%) were higher for scenario 1 than scenarios 2 and 3 in winter season. Scenarios 1 and 3 experienced less change during the summer season. The upper soil moisture influenced infiltration to the lower soil zone moisture and surface flow. The upper soil moisture, infiltration, and surface flow were less in summer months except for scenario 2. Even if precipitation was less (50%), the temperature did not change for scenario 2 and as a result, the soil moisture, infiltration and surface flow did not change in the system. Scenario 2 showed higher flow parameters (interflow and groundwater flow) except surface flow in summer months.

5.5. LOWER SOIL ZONE, DEEP PERCOLATION AND INTER FLOW

The lower soil zone moisture followed the same pattern as infiltration from the upper soil zone moisture. The higher percentages (125%) were observed for winter months. Similarly higher percentages were observed for deep percolation and interflow in winter months. The summer month lower soil moisture, deep percolation and interflow percent changes were similar to those of net supply, and upper soil zone moisture. The temperature influenced the soil system more than precipitation.

5.6. DEEPER SOIL ZONE AND GROUNDWATER FLOW

The deeper soil zone moisture, and groundwater flow followed the pattern of change as deep percolation (recharge). Surprisingly, the deeper soil moisture changes for scenarios 1 and 2 were higher than for the above systems in the spring season and that influenced the groundwater flow in spring season. Similarly, the summer deeper soil moisture and groundwater higher percentages for scenario 2.

6. Discussion and Conclusions

This study evaluated watershed impacts resulting from changes in global climate - changes in water availability. Widely-varying climate-change scenarios were used to drive a water-balance model designed to evaluate the impacts of global climatic changes on runoff, soil moisture, surface flow, interflow, groundwater flow, infiltration, and recharge in the watershed. The scenarios studied include three scenarios with hypothetical temperature and precipitation changes.

Major changes in runoff, soil moisture, infiltration, deep percolation and different flows (surface flow, interflow and groundwater flow) were observed in all scenarios, including certain changes that were consistent in their direction in every scenario despite wide differences in the original precipitation and temperature inputs. The most important changes were persistent decreases in soil moisture, decreases in the magnitude of summer runoff, and increases in the magnitude of winter runoff. These results suggest important hydrologic sensitivities.

Both seasonal and monthly impacts were studied because short-term hydrologic changes are often of greater interest and value to water-resource planners than annual-average changes. Four 'seasons' were evaluated - winter (January, February and March), spring (April, May and June), summer (July, August, and September) and fall (October, November and December) . These assumptions are consistent with most climatic analyses of seasonal climatic variables. They also correspond well to actual seasonal conditions in the basin, which receives much of its precipitation during winter months and is dry during summer months.

6.1. CHANGES IN RUNOFF: HYPOTHETICAL SCENARIOS

Dramatic changes in runoff patterns were observed in all hypothetical scenarios. Summer runoff for all hypothetical scenarios was reduced compared to base summer runoff. Figure 3 plots the percent changes in average runoff for the hypothetical scenarios in different seasons. The reduction in summer runoff was most pronounced in those runs where temperature was increased and precipitation was reduced, although reductions in summer runoff occurred even with large increases in precipitation from winter to spring. The most dramatic example of this was a reduction in summer runoff of nearly 50% when temperature increased 2 °C and precipitation reduced 50%.

Winter runoff increased over the base in case of all the scenarios. The percent changes in the average winter runoff are plotted in Figure 3. Increases in temperature alone caused increases in the average winter runoff due to an increase in the proportion of snow to rain and hence a decrease in the storage of water in the snowpack during winter months. For the T + 2 °C run with no change in precipitation, winter runoff increased 50%. When precipitation changes were imposed on the temperature increases, winter runoff results became mixed - for T+ 2 °C runs, increases in precipitation caused increases in winter runoff, and decreases in precipitation caused decreases in winter runoff. For the T+ 2 °C runs, the winter runoff changes were mostly positive: winter runoff increased for all the runs, Figure 3. Some of the changes in average winter runoff were extremely large, particularly in the runs with increases in precipitation. Increases in precipitation of only hundred percent led to increases in the average winter runoff of between 125% and 45 % for the T+ 2 °C and the runs. Such dramatic increases in runoff must raise concern about flooding possibilities, especially in basins with flood-control systems designed for different hydrologic conditions, or in basins without major reservoirs. Temperature increases alone increased the variability of runoff during the winter months by increasing the proportion of rain to snow and thus increasing the amount of prompt runoff.

For all hypothetical scenarios evaluated, major shifts in the timing of monthly runoff were seen. While an increase in the average temperature was a principal driving force for these shifts, the changes in precipitation contributed to and amplified the effects. Even in those cases where overall precipitation decreased, the distribution of runoff over the year changed so that spring and summer runoff decreased while runoff during winter months increased (Bobba et al., 1995).

The changes in the timing of runoff occurred primarily because of the increase in the average temperatures, which has two effects: (i) A large increase in the proportion of winter precipitation that falls as snow, and (ii) an earlier, faster, and shorter spring snowmelt. The first effect causes greater winter rainfall and winter runoff and less overall precipitation to be stored in the snowpack and held over until spring snowmelt. The second effect intensifies the magnitude of peak flows in spring and shortens the duration of spring runoff, which leads to decreases in summer runoff levels and depressed soil-moisture levels throughout the spring and summer.

6.2. CHANGES IN SOIL MOISTURE: HYPOTHETICAL SCENARIOS

Temperature increases alone increased winter soil moisture by 20 and 125% as a result of increased snowmelt rates. Of greater interest is the fact that the increases in soil moisture for the three scenarios were relatively high - soil moisture even decreased slightly when the temperature increased by 2 °C and precipitation not increased. It should be noted that the change in soil moisture noted for this run was extremely highly statistically significant. During winter months, the percentage increase in precipitation had a larger effect on absolute precipitation than the percentage decrease in summer months simply because the overall precipitation levels were higher. Yet these increases in precipitation did not manifest themselves as proportional increases in winter soil moisture. During winter months, soils tend to be near or at saturation and surplus moisture that falls as rain tends to run off, while the rest falls as snow and is stored in the snowpack. Thus greater winter precipitation tends to result in either more prompt storm runoff (and hence, total surface runoff) or an increase in the snowpack. Decreases in precipitation have the opposite effect, which can be seen by the larger proportional decrease in average summer soil moisture values. Figure 4 shows the percent changes in average winter soil moisture values for the runs using hypothetical inputs.

The average summer soil moisture values in the agricultural portion of the basin showed large, consistent decreases from the base case for all hypothetical scenarios.The percent changes in the average summer soil moisture are shown in Figure 4 for three hypothetical temperature and precipitation scenarios. These decreases range from eight percent to 44%. The minimum decrease of 8% resulted from a temperature increase of 2 °C combined with no increase in the average precipitation. The maximum decrease in the average summer soil moisture of 44% resulted from a 2 °C increase in temperature combined with a 50% decrease in the average precipitation. Winter soil-moisture values also showed increases in the basin, the scenarios resulted in increased average winter soil moisture.

Monthly soil-moisture availability in the watershed using the hypothetical temperature and precipitation scenarios was also reduced consistently from its base level, with the greatest percentage reductions occurring during summer months. For hypothetical cases, soil-moisture values were reduced in every month of the year. For some runs, which involve increases in precipitation, only increases in the soil moisture during winter months were observed.

The water-balance model results using three scenarios showed large reductions from the base summer soil-moisture values in the basin despite the widely varying precipitation inputs. These reductions ranged from 20 to 50%. The average winter soil-moisture results showed modest changes in all scenarios.

The decreases in the average summer soil moisture in the watershed were remarkably consistent regardless of which scenario was used to drive the water-balance model. The magnitude and the consistency of the average soil moisture drying signified a major hydrologic impact, especially given that these results are consistent with the summer soil-moisture results from the hypothetical temperature and precipitation scenarios discussed earlier. All climate-change scenarios led to decreases in summer soil moisture.

In addition to the seasonal results described above, there was a consistent seasonal depression of soil-moisture availability for the runs. The only increases occurred during some winter months for the highest precipitation scenarios of the model. The water-balance model results using three scenarios showed decreases in monthly soil moisture after March continuing through December. The other two scenarios - using the hypothetical relative and absolute precipitation data, showed increases in soil moisture beginning again in November.

Figure 5 shows the percentage change in average snowpack, net supply, etc, for three scenarios. All the hydrological variables were affected for scenario 1. Specifically, snowpack was effected due to higher temperature. The thickness of snowpack was 40 to 60% less than for normal weather conditions. This condition was affected by higher precipitation and temperature condition for scenario 1. All other variables were higher than normal conditions except for scenario 3. Higher temperature influenced scenario 3.

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Figure Captions

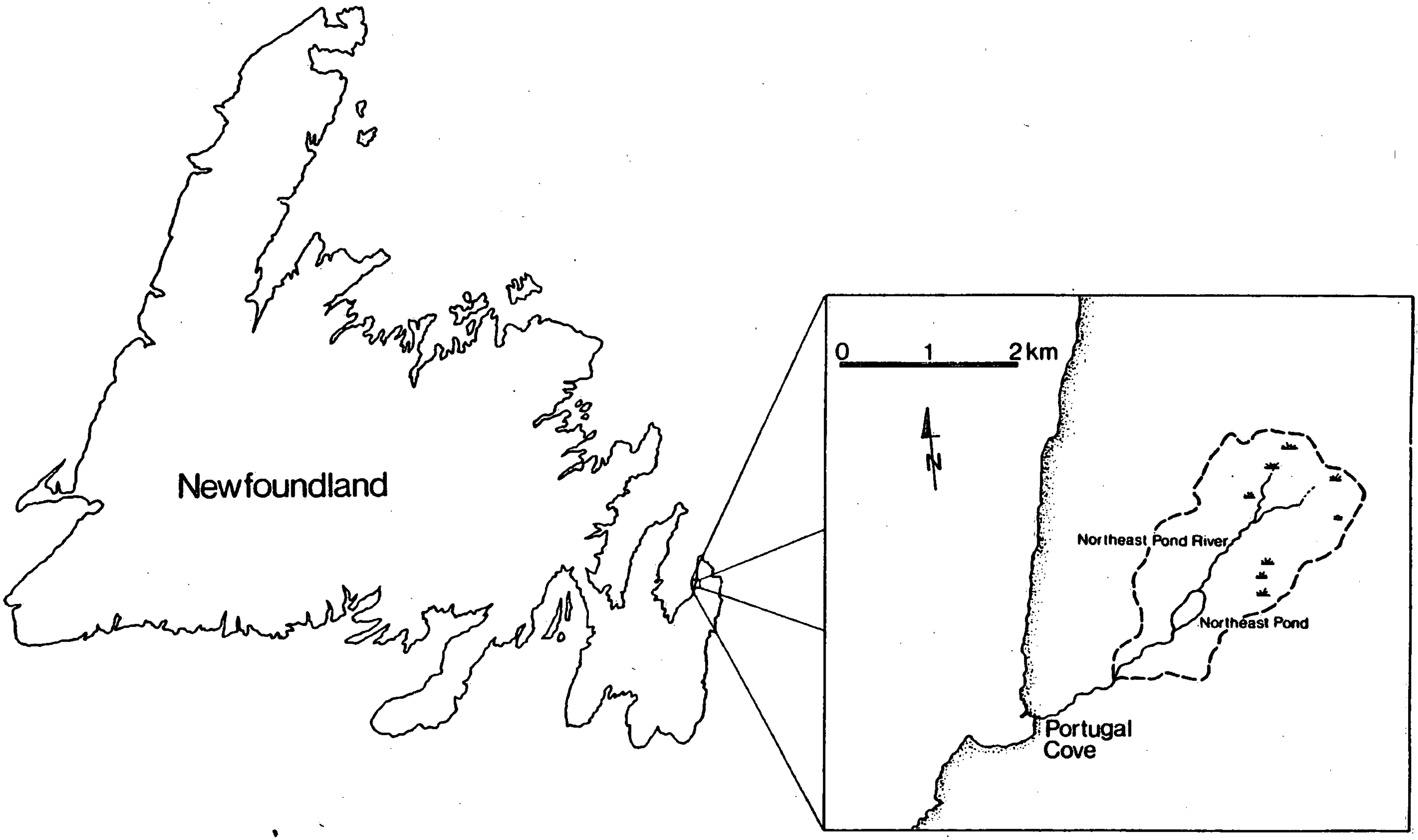
Figure 1: Location of Northeast Pond River watershed.

Figure 2: Mean monthly temperature, precipitation and runoff of watershed.

Figure 3: Percentage change of snow pack, net supply, and flows in different seasons for different scenarios.

Figure 4: Percentage change of upper soil zone moisture, infiltration, surface flow, lower soil zone moisture, deep percolation, inter flow, deeper soil zone moisture, and groundwater flow in different seasons for different scenarios.

Figure 5: Percentage change of different watershed variables for different scenarios.



Newfoundland
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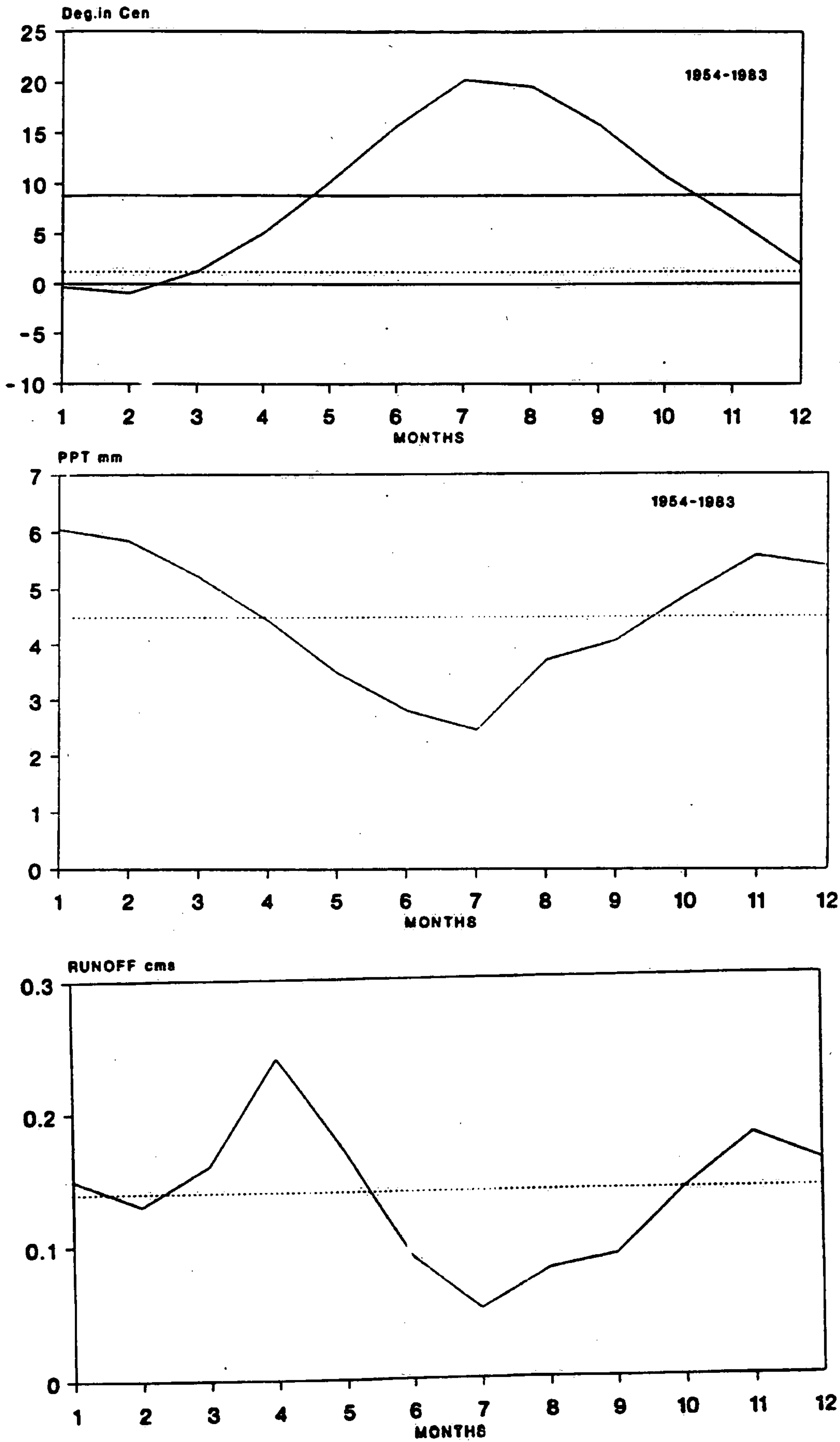
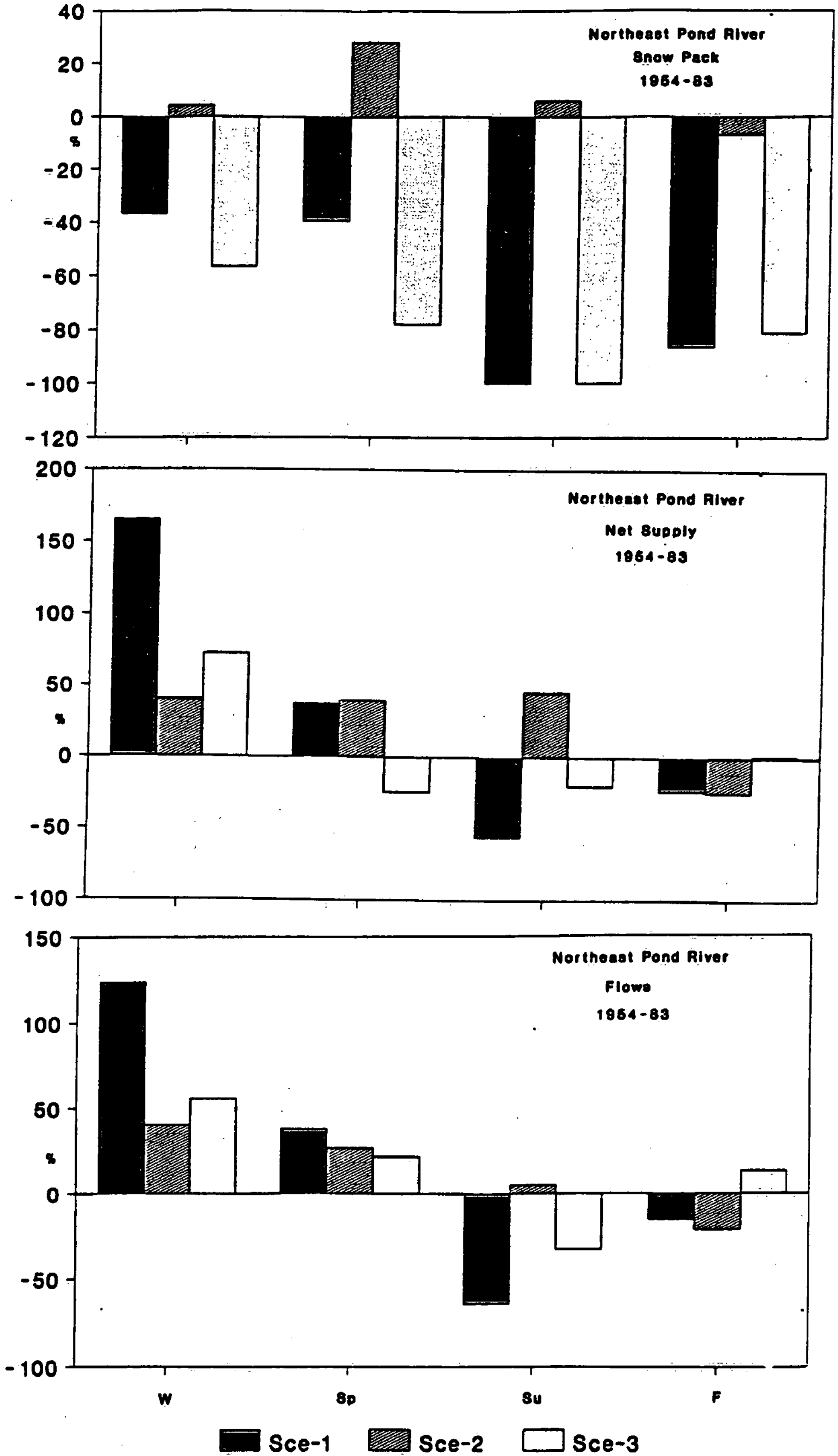
Northeast Pond River
Northeast Pond
Portugal
Cove

NORTH EAST POND RIVER

1954-1983




Northeast Pond River
Snow Pack
1954-83
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-20
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-80
-100
-120
Northeast Pond River
Net Supply
1954-83
200
150
100
50
%
0
-50
-100
Northeast Pond River
Flows
1954-83
150
100
50
%
0
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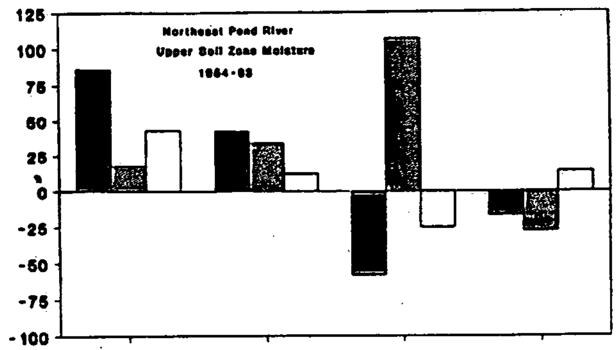
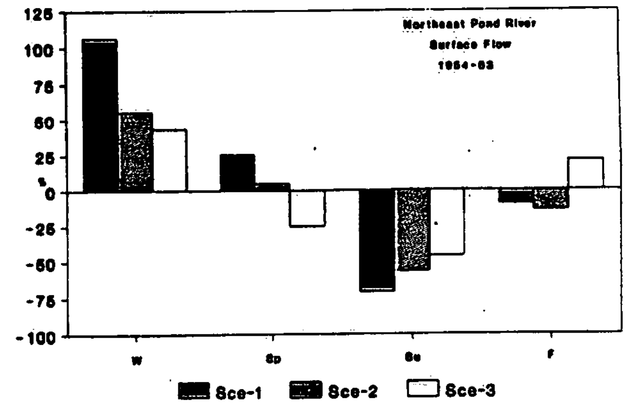
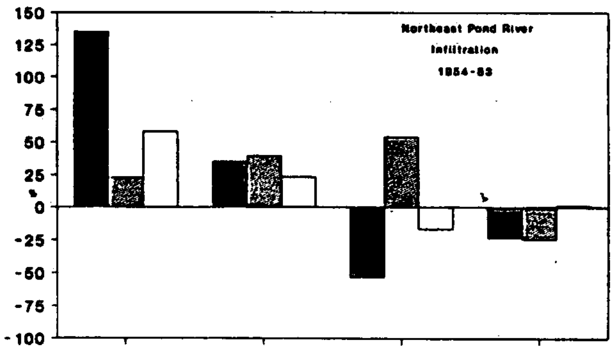
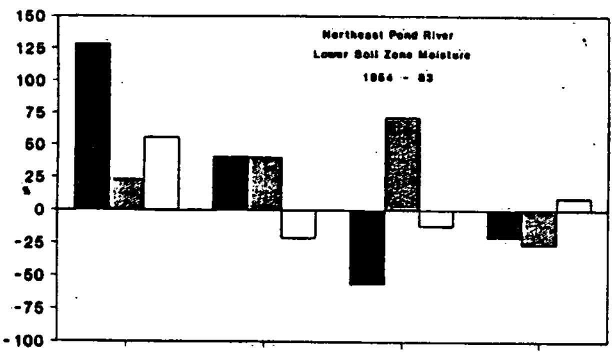
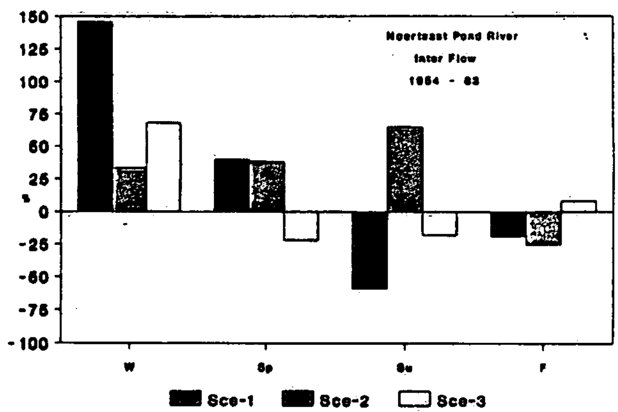
NORTHEAST POND RIVER, NEWFOUNDLAND, CANADA

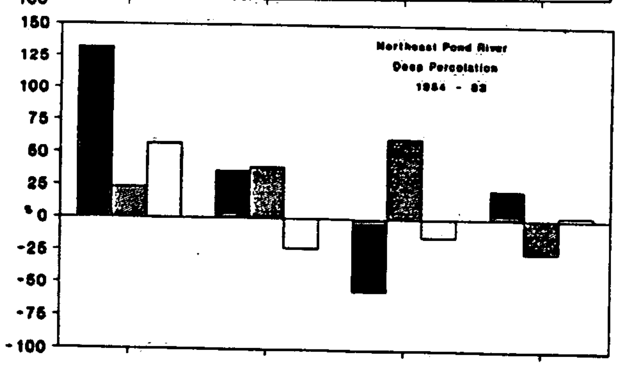


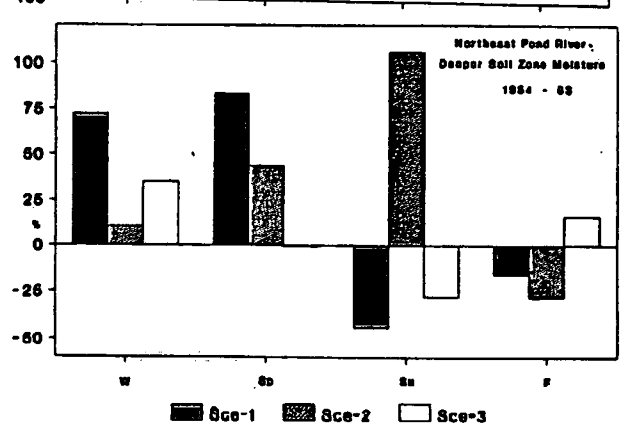


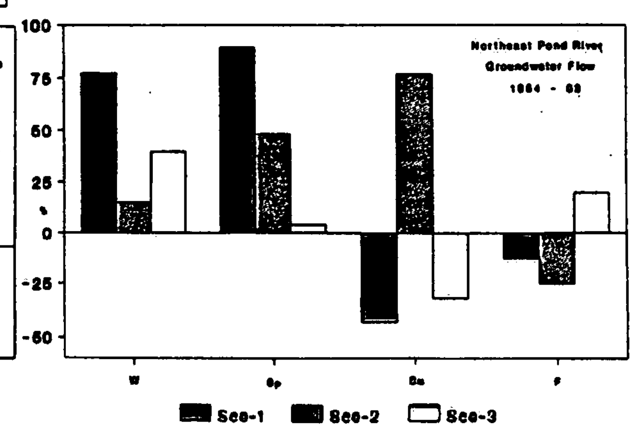


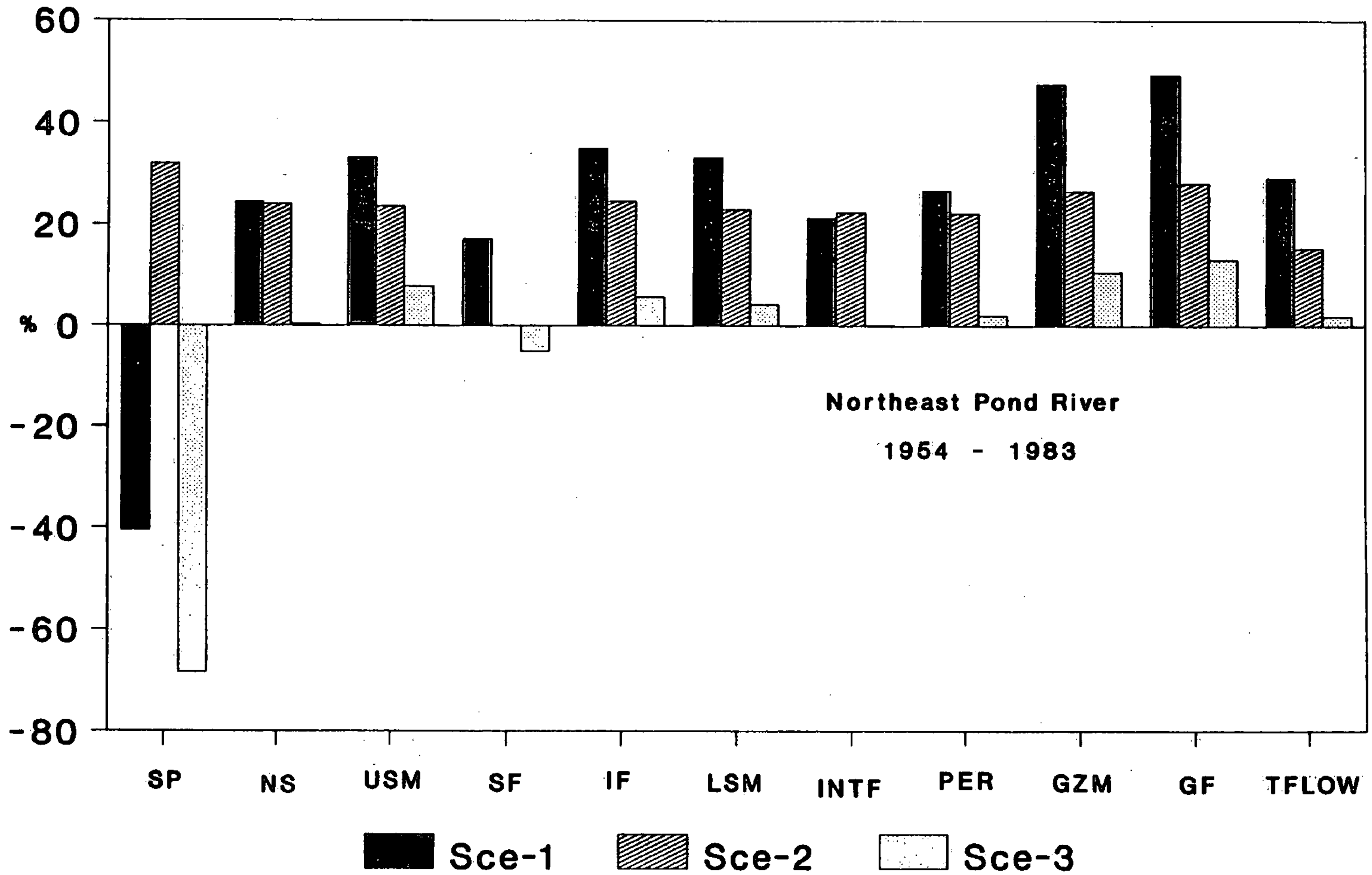












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Northeast Pond River
1954 - 1983
SP
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USM
SF
IF
LSM
INTF
PER
GZM
GF
TFLOW
Sce-1
Sce-2
Sce-3

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