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SENSITIVITY OF HYDROLOGICAL VARIABLES IN THE ARCTIC WATERSHED, COPPERMINE RIVER, NWT, CANADA DUE TO HYPOTHETICAL CLIMATE CHANGE

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The hydrological sensitivities to long-term climate change of the Coppermine River watershed in the Arctic region of Canada were analyzed using a watershed runoff model. This model describes an interdependent tank - cascade model that uses a mass balance coupled with linear reservoir concepts. It is physically based and uses climatological considerations not possible for watersheds. Mean annual and seasonal runoff resulting from a range of hypothetical climate changes were compared and evaluated. Water balance modelling techniques, modified for assessing climate effects, were developed and tested for a watershed using climate change Scenarios from state of the art general circulation models and a series of hypothetical Scenarios. In general, changes in precipitation had a larger effect on changes in runoff than changes in temperature. Changes in precipitation had significant effects on runoff during all seasons. Changes in temperature primarily affected the temporal distribution of runoff throughout the year. The changes in temperature affected the timing of snowmelt and the ratio of rain to snow. The effects of temperature were particularly significant during the spring and summer seasons. On an annual basis, increases in temperature led only to slight decreases in runoff. The effects of an increase in mean annual temperature of 1°C on annual runoff could be offset by an increase in annual precipitation of 10%. The magnitude of natural climatic variability was large and might mask the effects of long-term climate changes. These results raise the possibility of major environmental and socioeconomic difficulties, and have significant implications for future water resource planning and management.

INTRODUCTION

In recent years much attention has been focused on evaluating regional hydrologic implications of climatic change. For obtaining realistic estimates of actual changes in regional water availability that are valuable to water-resource planners, regional hydrologic assessments should be based on (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, soil characteristics, natural and artificial storage, and other regional complexities.

One of the most promising methods for assessing the regional hydrologic effects of global climatic changes is the use of water-balance models modified for use under conditions of changing climate (Gleick, 1986, Bobba et al. 1997). 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 wide ranging from annual (or longer) 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.

Since its introduction, the water-balance approach has become one of the most versatile and widely used tools for environmental and hydrologic analysis (Bobba and Lam, 1990; Bobba, 1992, Bobba et al. 1994). Numerous modifications and extensions to the original water-balance formulations have been developed and used in hydrologic research (Miller, 1977, Mather, 1978; U.S. Army Corps of Engineers, 1980). These modifications permit a systematic evaluation of flooding and drought probabilities, agricultural water demands, groundwater recharge rates, distribution of soils and vegetative cover, and a wide variety of other water-resource issues.

For climatic impact assessments, flexibility is an additional advantage of the water-balance approach. By integrating hydrologic advances with water balance techniques, new insights into hydrologic processes and environmental impacts can be gained. The evaluation of water balance methods has been presented earlier (Bobba et al., 1997). The objective of this study is to perform an assessment of the effects of a range of hypothetical climate changes on runoff in the Coppermine River watershed and to examination these effects in relation to natural variability.

THE WATERSHED DESCRIPTION

The Coppermine River watershed (Figure 1) is located in the north central region of the Canadian mainland Northwest Territories between latitudes 64°50’ and 67°50’ north and longitude 109°30’ and 118°20’ west. The watershed is approximately 520 km long and 100 km wide with a drainage area of about 50,800 km^2. The river flows generally northwest from its headwaters in the Ursula Lake/ Lac du Sauvage area at 460 m above sea level to its mouth at Coronation Gulf.

Mean monthly temperature, precipitation and runoff for the Coppermine River basin is illustrated in Figures 2a, 2b, and 2c. The maximum temperature is in July and minimum temperature is in January. Precipitation is fairly distributed throughout the year. The highest precipitation is observed in September. Runoff is relatively medium for most of the year, except during the spring when snowmelt occurs due to higher temperatures.

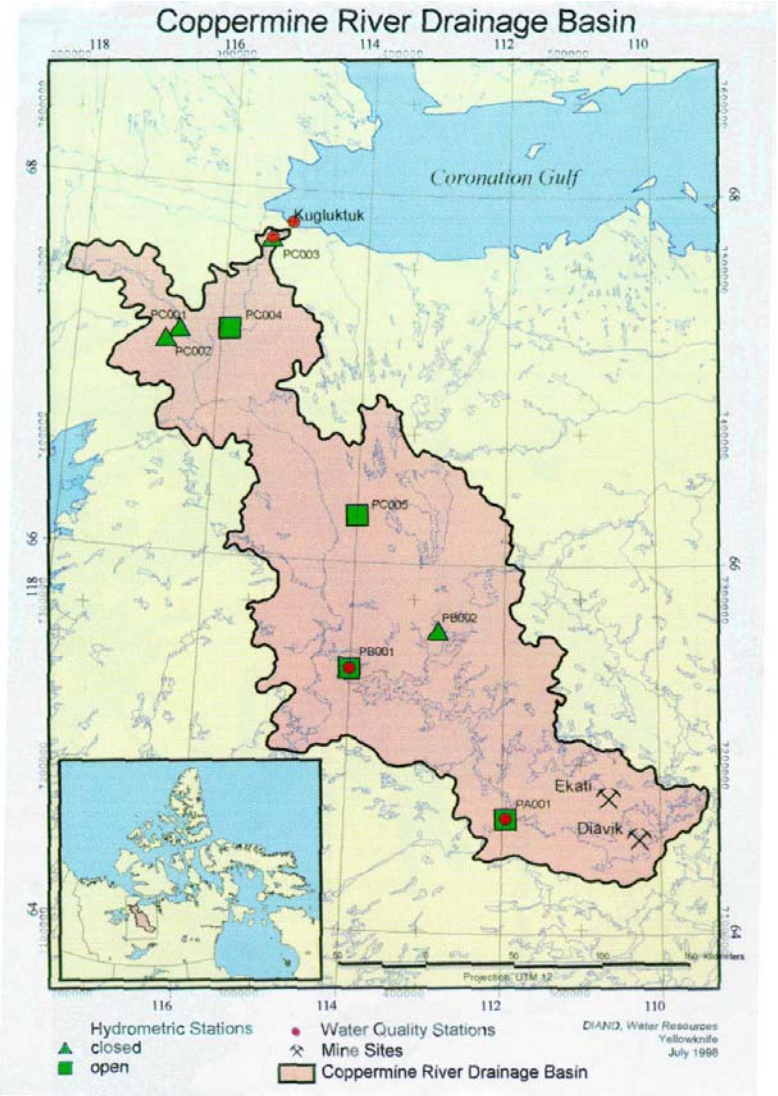

Figure 1. Location of Coppermine river basin in the Canadian Arctic.

GENERATION OF METEOROLOGICAL DATA

The watershed is within the zone of continuous permafrost. Even though there are currently four hydrometric gauges in operation there is hardly any extensive historical hydrometeorological data available (Coulombe-Pontbriand et al., 1998). Hence the need for data augmentation using generated data based on the statistical characteristics of the limited observed data. The theory of the generation of the data is explained earlier (Diiwu et al. 2002).

The observed data for each of the hydrological and meteorological variables (maximum temperature, minimum temperature, streamflow, and precipitation) were analyzed. The statistical parameters of mean, standard deviation, skew, first quartile, and second quartile were computed for the observed data. The probability distribution which best describes the particular variable was determined by means of probability plots. The selected probability distribution was then used to generate a set of random numbers.

Generation of Maximum Temperature, Minimum Temperature and Precipitation

For generation of maximum temperature, minimum temperature and precipitation, the cumulative distribution F(x) corresponding to the best fit probability distribution was obtained. Since 1 ³ F(x)

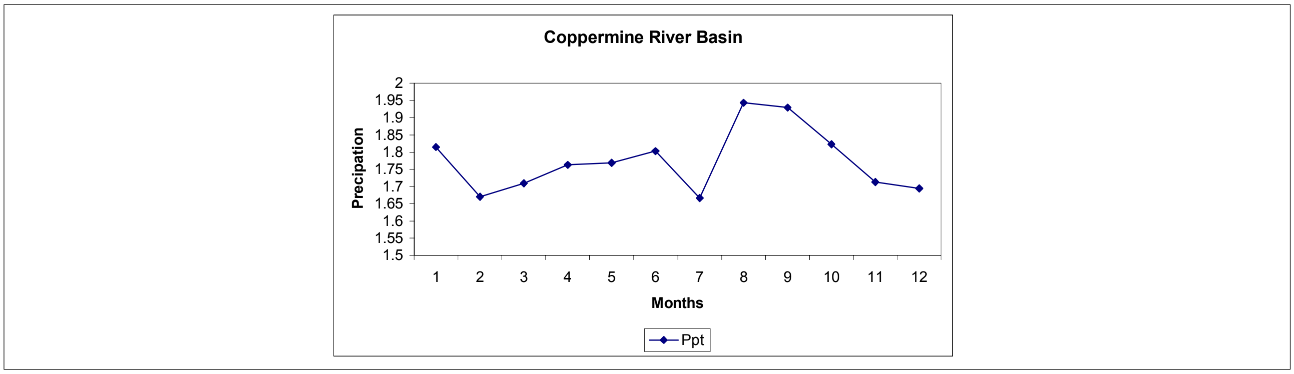

Figure 2a. Mean monthly precipitation (cm) of Coppermine River watershed.

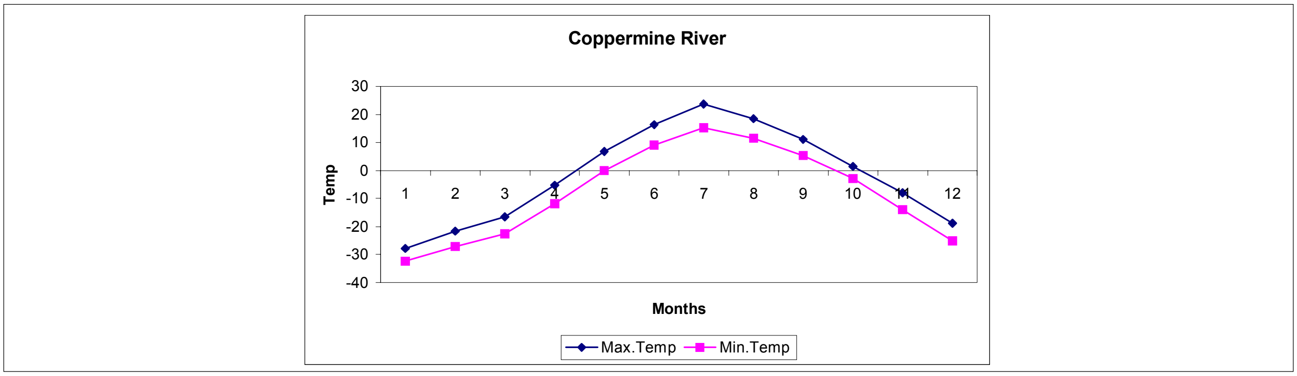

Figure 2b. Mean monthly maximum and minimum temperature (^{o}C) of Coppermine River watershed.

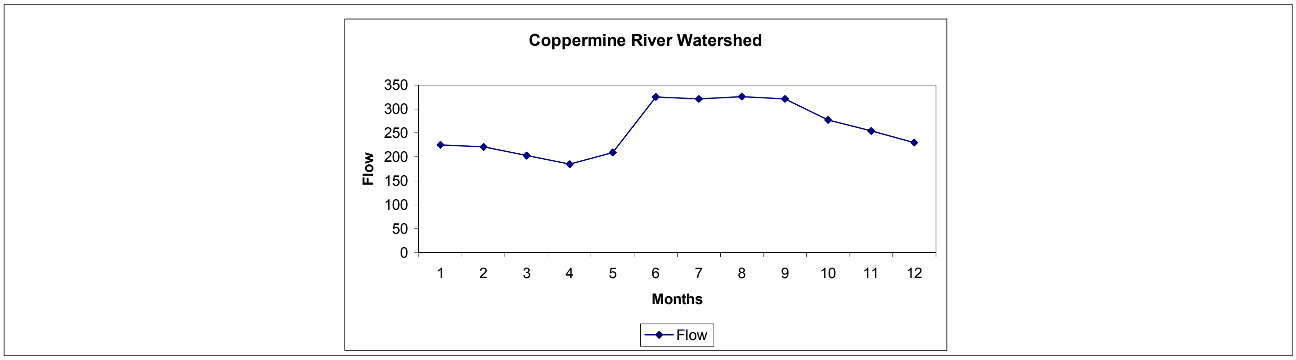

Figure 2c. Mean monthly runoff (mm) of Coppermine River watershed.

^{3}0, the cumulative distribution function is used to generate uniform random numbers ***u*** from the interval (0, 1). That is,

$$u = F(x) \tag{1}$$

The corresponding random variable x is then obtained by inversion (Maidment, 1993):

$$x = F^{-1}(u) \tag{2}$$

This yields sets of purely random numbers; moreover, the equation can be used for both forward and backward extension of the data.

Streamflow

In the case of streamflow, since the inherent memory in the observed flows is to be retained in the generated flows, the generated data must retain the correlation structure of the observed data. To ensure this, the following equations were used for the generation of data (Linsley and Crawford, 1960).

For forward extension:

$$q_{i+1} = q'_{j+1} + b_j(q_i - q'_j) + t_i\sigma_{j+1}(1 - r_j^{\,2})^{1/2}$$

(3)

and for backward extension:

$$q_{i-1} = q'_{j-1} + b_j(q_i - q'_j) + t_i\sigma_{j-1}(1 - r_j^{\,2})^{1/2}$$

(4)

where q_i, q_{i+1}, q_{i-1} are the flows in the ith, (i+1)th and (i-1)th months from the start of the synthetic sequence, q'_j, q'_{j+1}, q'_{j-1} are the mean monthly flows in the jth, (j+1)th, and (j-1)th month of the annual cycle; b_j is the regression coefficient for estimating flows in the (j+1)th or (j-1)th month as the case may be from the flows in the jth month. The coefficient t_i is a random variable with zero mean and unit variance, s_{j+1} (or s_{j-1}) is the standard deviation of the flows for the (j+1)th (or (j-1)th) month, and r_j is the correlation coefficient between flows in the jth and (j+1)th months or between jth and (j-1)th months.

The data generation was implemented on an Excel spreadsheet using the above equations and the probability distributions, which were determined as best describing the hydrological and meteorological variables. For maximum temperature, minimum temperature and precipitation the normal distribution was the probability distribution that best describes these variables. In the case of streamflow, it was the lognormal distribution.

As an example, the generated data was checked (Figures 3 and 4). The generated data for each of the variables were checked against the observed data to ensure that not only do the synthetic data and observed data have similar statistical characteristics but that the synthetic data were also physically realistic, bearing in mind the hydrology of the zone of continuous permafrost within which the Coppermine River Watershed is located. The monthly means (for January to December) for the observed and synthetic data were computed and used as monthly data for further analysis. The statistical parameters (mean, standard deviation, skew, first quartile, and second quartile) for the

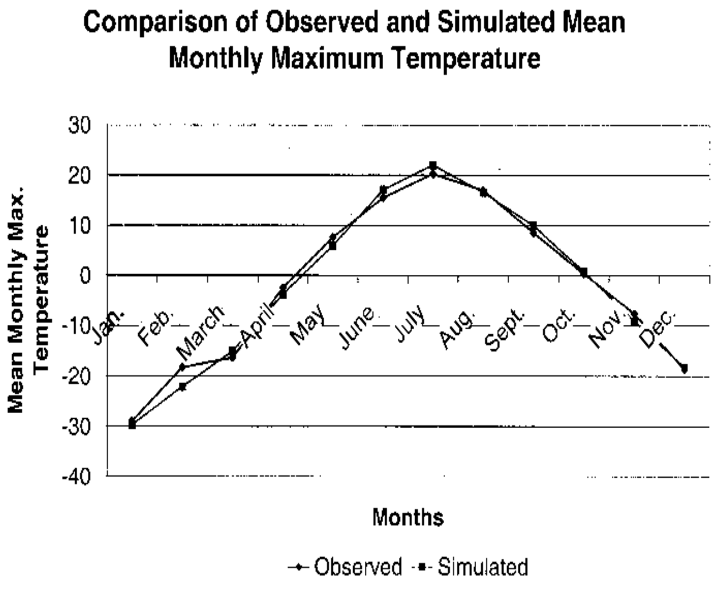

Figure 3. Comparison of observed and simulated monthly mean maximum temperature (°C).

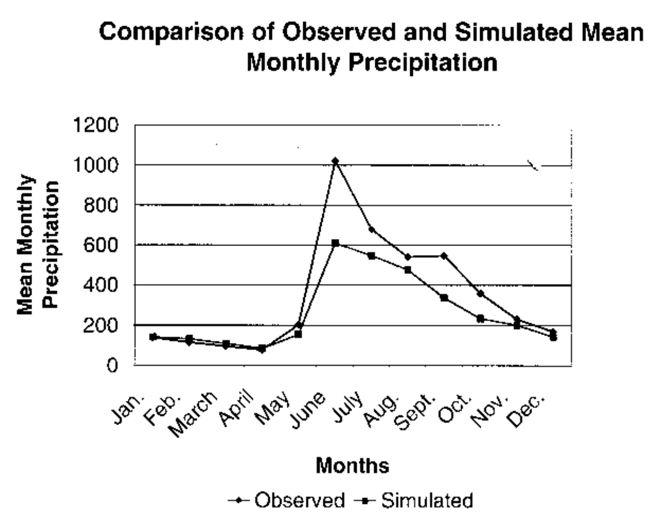

Figure 4. Comparison of observed and simulated monthly mean precipitation (mm).

monthly data were then computed for the synthetic data and compared with those for the observed data. Two-sample Student t-tests of hypothesis were carried out to compare the means of the monthly data. Plotting the observed monthly time series alongside the generated monthly time series was also carried out to compare the time series graphs (Figures 3 and 4) (Diiwu et al. 2002).

METHODS

In this study, a runoff model was used to simulate runoff in the basin for current climatic conditions and for prescribed hypothetical climatic conditions that represent a range of possible climate changes. The hypothetical changes in climate included changes in mean seasonal and annual temperatures of 0° C, and +1°C and changes in precipitation of 0%, and +10% (a total of four Scenarios). These changes in climate were computed by uniformly changing current values of daily temperature and precipitation by the specified amounts for all months of the year. By altering the current time series, the natural temporal variability in temperature and precipitation were preserved. The observed and altered time series of daily temperature and precipitation were input to a watershed runoff model to simulate time series of daily runoff. The resulting time series of runoff were then compared on a seasonal and annual basis to evaluate the effects of changes in temperature and precipitation on the watershed runoff. Annual analyses were performed on a yearly basis and seasonal analyses were performed for winter, spring, summer, and for autumn.

CLIMATIC SCENARIOS

To assess the potential impacts of climatic change on runoff in the basin, Scenarios of changes in temperature and precipitation (Table 1) were used as inputs to the 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 (Table 1) were used in the watershed runoff model.

The values chosen for hypothetical Scenarios typically reflect best estimates of changes in important climatic variables, although extreme 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 for Scenarios 3 and 4 reflects the consensus that greenhouse warming will

Table 1. Climatic Scenarios for Climate Change Effects in Coppermine River Basin

Scenarios	Change in Temperature (^oC)	Change in Precipitation (%)
SCE–1 (Sim. Flow)	No Change	No Change
SCE - 2	No Change	+10
SCE - 3	+ 1	No change
SCE - 4	+ 1	+10

produce temperature rises in this range, given an equivalent doubling of atmospheric CO_2. The study considers only temperature and precipitation increases due to climate change. Recently this Scenario has been observed in the Arctic.

THE WATERSHED RUNOFF MODEL

A runoff model (Bobba et al. 1997) 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. (1997), and Bobba and Lam (1990).

The model runs on a daily basis. The calibrated model parameters are shown in Table 2. Figure 5a shows the comparison of the average monthly observed and computed average flow and Figure 5b shows the scatter diagram of observed and computed flow. In all cases, the model has a fairly good fit (Figure 5a).

RESULTS

Changes in mean seasonal and annual runoff for each of the hypothetical climate change Scenarios were expressed as a difference from current conditions (Scenario 1), and as a

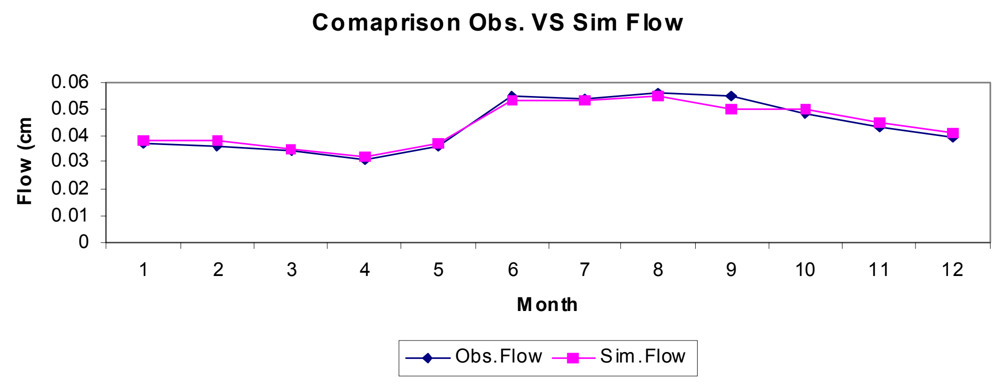

Figure 5a. Comparison of computed and observed monthly flow (cm) data for Coppermine River.

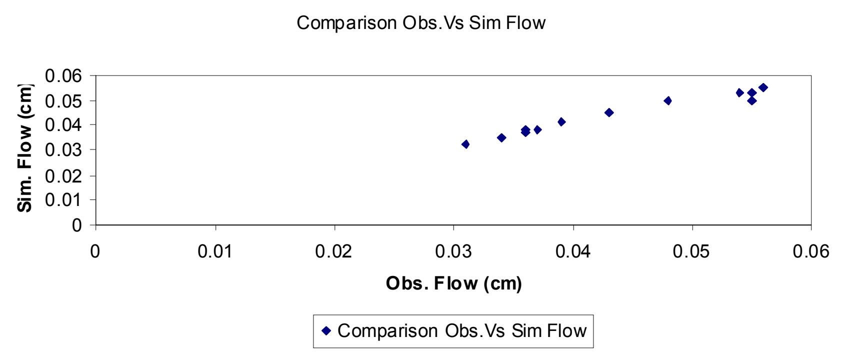

Figure 5b. Scatter diagram of computed and observed average monthly flows (cm).

Table 2. Hydrological Model Parameters for Runoff Model

Infiltration (AB)	0.40
Deep Infiltration (BC)	0.035
Surface Flow(A)	1.400
Inter Flow (B)	0.400
Groundwater Flow	0.25

percentage change from current conditions. Figure 6 shows the average snow pack for three different Scenarios. If the temperature and precipitation increased, the trend of the snow pack was equal to regular snow pack (Scenario 4). If the temperature did not increase but precipitation increases, the snow pack increased (Scenario 2). If the temperature increased but precipitation was not (Scenario 3), the snow pack was less than normal but the snow pack was disappeared by May in the watershed.

Figure 7 illustrates the computed average net supply for the watershed. Net supply was equal normal in early spring months for higher temperature and precipitation (Scenario 4). Due to higher temperature snow melted earlier than regular period (Scenario 3). Similarly if the temperature did not increase but due to higher precipitation the peak of net supply is higher than the regular period. If only the temperature only increased without increasing precipitation then the net supply was less (Scenario 3) than regular net supply in early spring months but it was equal up to that in autumn months like Northeast Pond River (Bobba et al. 1997).

Surface flow from the upper reservoir is shown in Figure 8. Computed surface flow was higher for all the Scenarios (2,3, and 4) than normal surface flow (Scenario 1). Most of the flows were flat in winter months. Surface flow was higher than normal in summer months (May to June), but it reduced in autumn months. This may be affected due to higher temperatures in late spring months; melted snow became runoff in late spring and summer months. Peak of the surface flow was shifted to later month (June) than that it would occur regularly.

Figure 9 shows interflow from the lower reservoir of the watershed runoff. It followed the same pattern of net supply. As expected, inter flow was higher from late spring months and continued for all months. Interflow was higher for Scenarios (2,3, and 4) in winter months due to high temperatures.

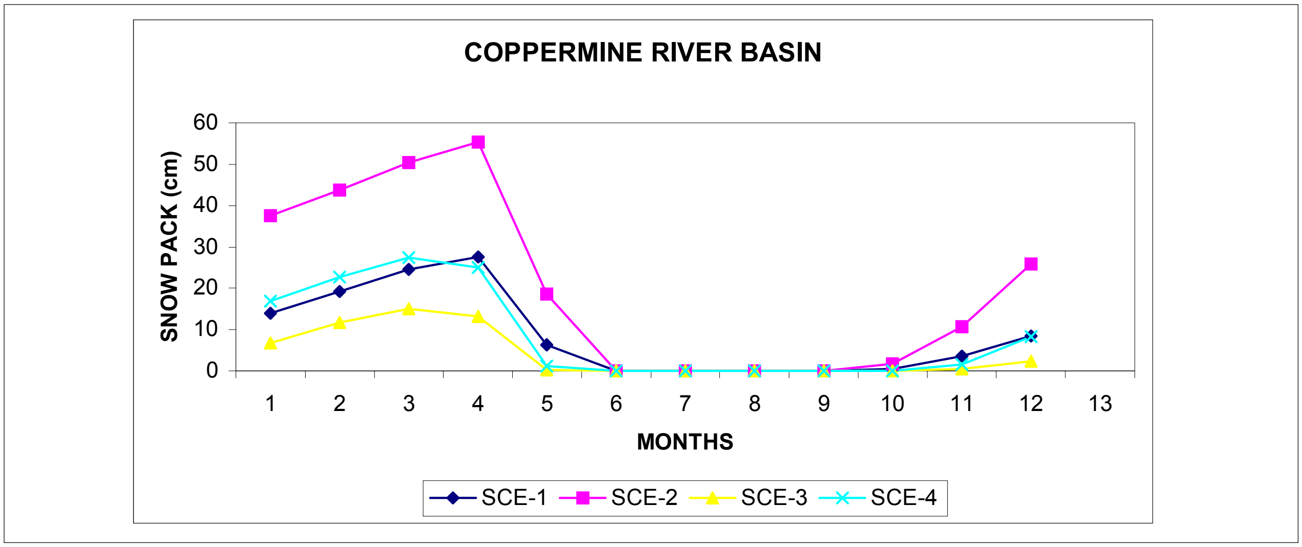

Figure 6: Simulated average Snowpack depth (cm) for different Scenarios

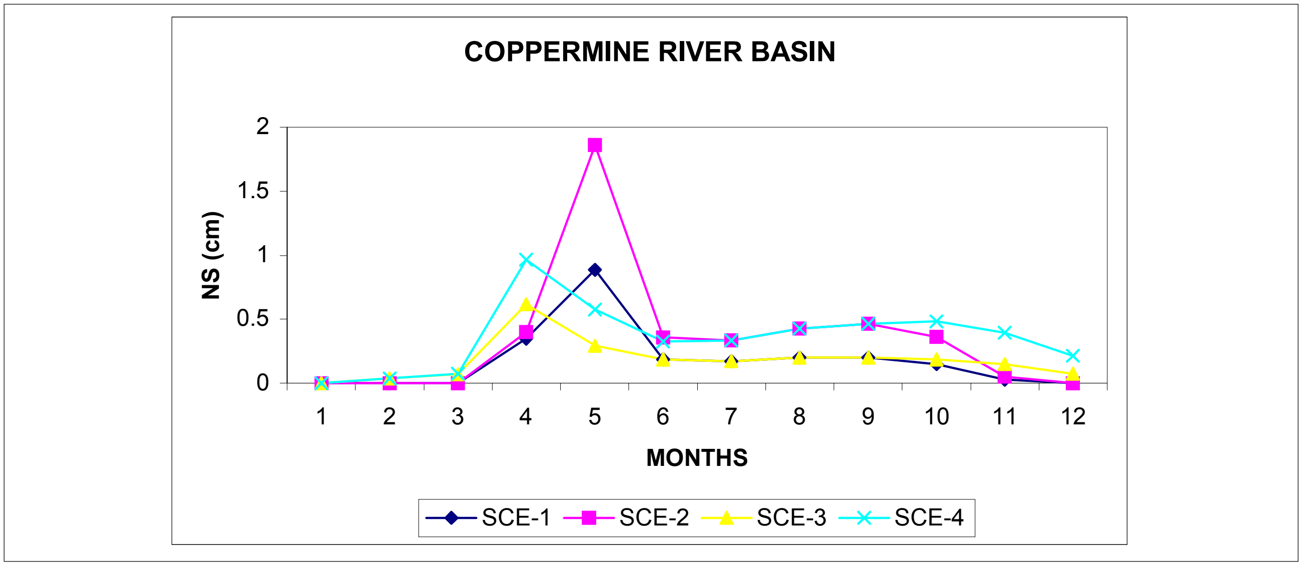

Figure 7: Simulated average net supply (cm) for different Scenarios

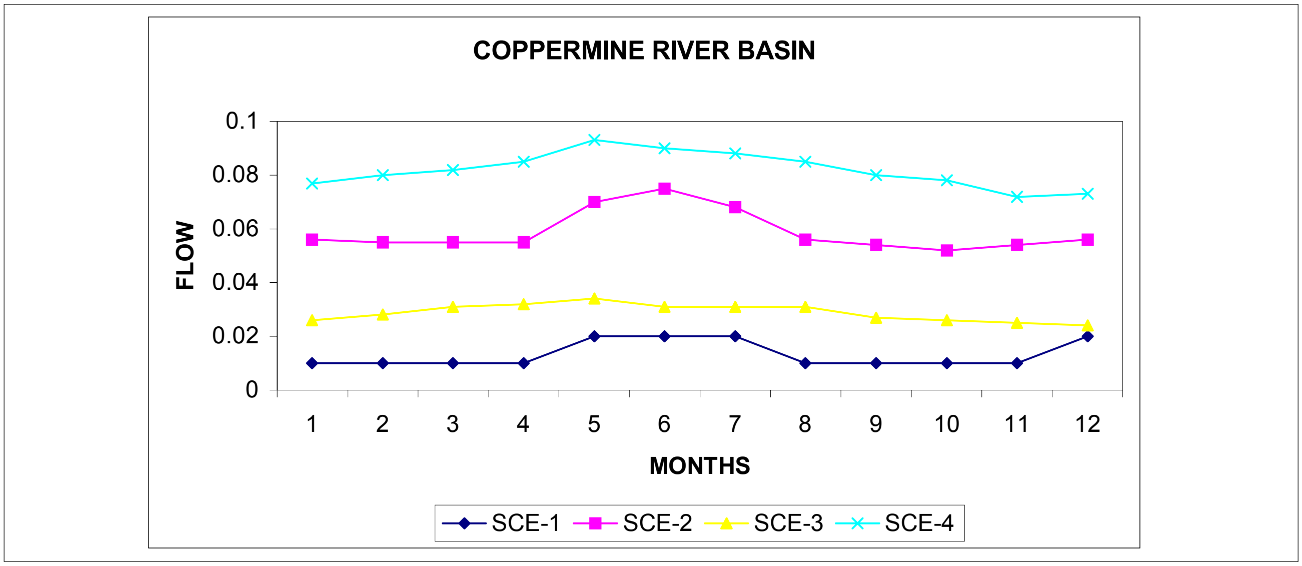

Figure 8: Simulated average surface flow (cm) for different Scenarios

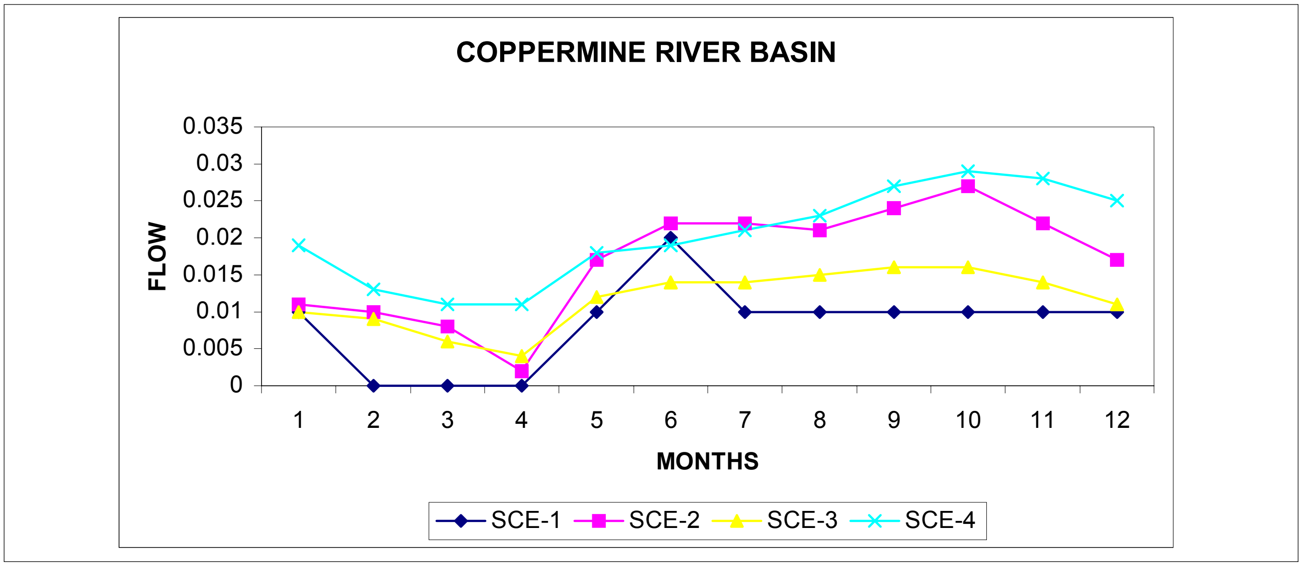

Figure 9: Simulated average interflow (cm) for different Scenarios

Figure 10 shows that groundwater flow increased more in later spring and summer due to higher net supply and temperature but groundwater flow was less or equal autumn months for Scenario 2 . Higher recharge water increased hydraulic heads and higher gradients pushed more groundwater in those months. Due to high temperature and precipitation, the snow melted and more water recharged from surface reservoirs to groundwater reservoir.

Observed and computed flows (Figure 5a) and simulated total flows for different Scenarios are shown in Figure 11. Peak of the observed, computed (Figure 5a) flow were in the same month. The flows in all the Scenarios were higher from later spring to summer months (May to August). The flows were all flat in other months for Scenarios 2,3, and 4. Scenario 4 (Figure 11) showed higher flow in all seasons except in the summer season. Analysis of the effects of changes in temperature on changes in annual runoff indicated that changes in temperature had only a minor effect on the magnitude of annual runoff. The effects of changes in precipitation on changes in annual runoff were about three to seven times as great as the effects of changes in temperature.

Hypothetical changes in precipitation and temperature influenced on total runoff indicated that changes in precipitation had a large effect on changes in seasonal and annual runoff. This is not

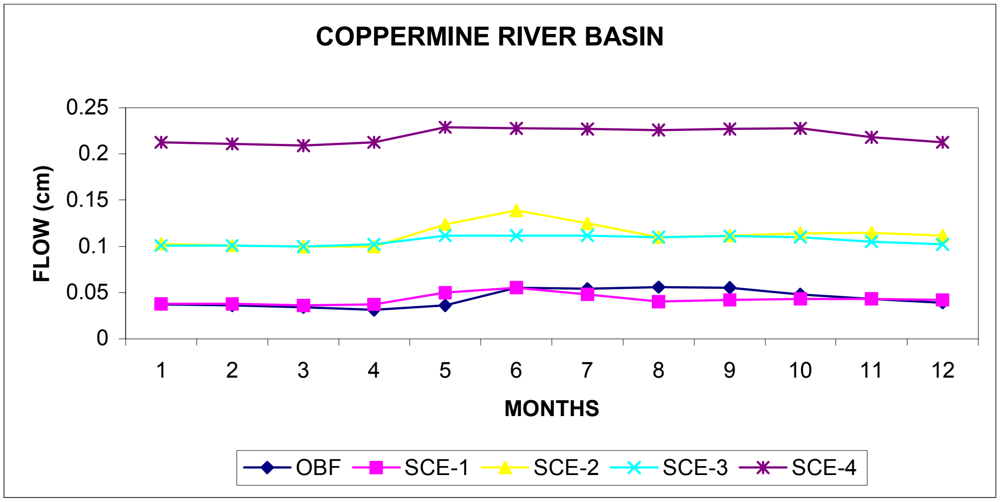

Figure 10. Simulated average groundwater flows (cm) for different Scenarios

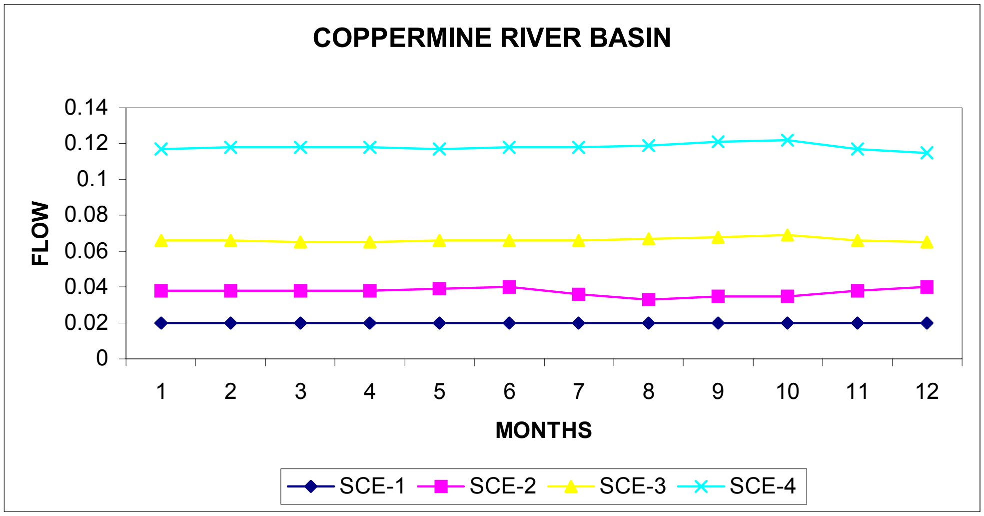

Figure 11: Simulated total flow (cm) for different Scenarios

surprising because precipitation represented the input of water that ultimately became runoff. Changes in temperature and changes in runoff indicated that changes in temperature only had effects on runoff comparable to those of changes in precipitation during the spring and summer seasons. During the spring, changes in temperature had an effect on the ratio of rain to snow which affected spring runoff, and during both the spring and summer seasons, changes in temperature affected the timing of snowmelt runoff. As temperatures increased, peak runoff shifted to earlier months in the year, generally causing decreases in summer runoff and increases in late spring runoff.

Changes in monthly and seasonal runoff volumes are as important to managers as changes in annual totals and these changes will be controlled by geological as well as climatic conditions of watershed. In Figure 12 Scenario 1 is compared between observed and computed flow (Figure 5a). Figure 12 shows the percentage change in average snow pack, net supply and so on for three Scenarios. Due to Scenario 1 (in Figure 12, Scenario 2) all the variables were affected in the watershed. Specifically snow pack was affected due to temperature. Thickness of snow pack reduced to 40 to 60% less than normal weather conditions. This condition affected due to higher precipitation and temperature condition for Scenario 1 (in Figure 12, Scenario 2). All other variables were higher than normal conditions except Scenario 3 (in Figure 12, Scenario 4). The higher temperature was influenced for the Scenario 3.

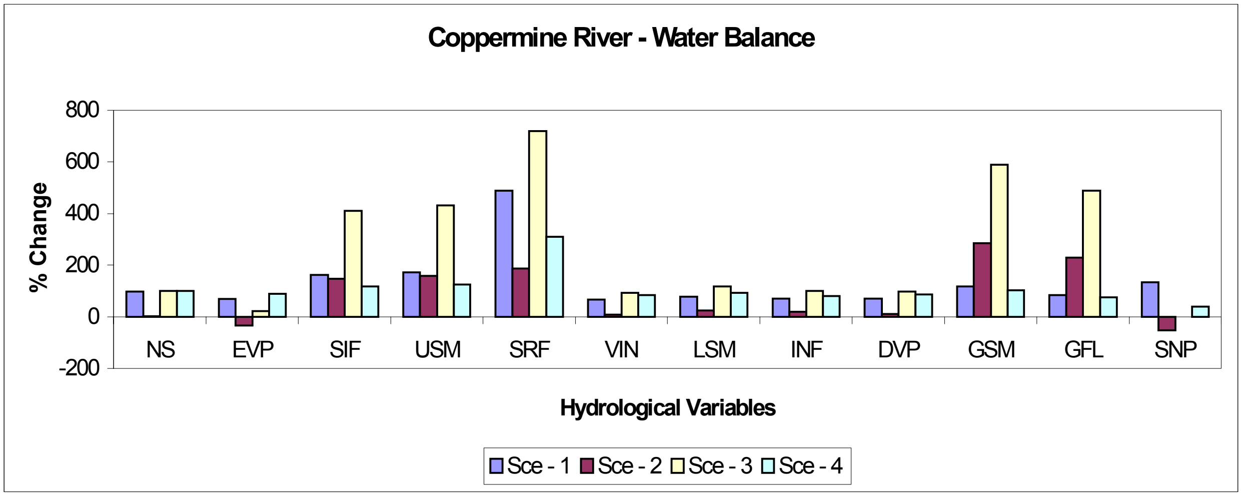

Figure 12. Percentage change of different hydrological variables for different scenarios

SUMMARY AND DISCUSSION

This study evaluated one of the most important regional impacts that may result 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 and soil moisture in the watershed. The Scenarios studied include four Scenarios with hypothetical temperature and precipitation changes.

Despite the uncertainties that surround the nature and timing of future climatic changes and their subsequent impacts, the results presented here raise serious concerns about regional water availability. In particular the seasonal variability did not observe for all Scenarios. Higher total flows were observed for higher temperature and precipitation (Scenario 3). This consistency suggests strongly that hydrologic vulnerabilities will make the impacts of climatic changes on ecological effects an issue of major concern in many regions of the Arctic. Three particularly important and consistent changes were observed: (1) decreases in summer runoff volumes for all climate-change Scenarios, (2) major shifts in the timing of average-monthly runoff throughout the year, and (3) large increases in runoff volumes for the climate change Scenarios.

The principal physical mechanisms involved the decrease in snow as a proportion of total winter precipitation, an earlier and faster disappearance of winter snowpack due to higher average temperatures, and a more severe evapotranspiration demand during the warmer summer months are both physically plausible and consistent with the hydrologic mechanisms that lead to summer soil moisture depletion. While other, countervailing hydrometeorologic features may well exist such as cloud cover/evapotranspiration feedbacks, the consistency of soil moisture and runoff results observed here must be considered a first warning of possible important changes in regional availability. As more information on these other factors develops, it can be incorporated into water-balance models to provide more detailed regional assessments.

The hydrologic changes described above will, if they materialize, have serious implications for many aspects of water resources, including water supply, flooding and drought probabilities, groundwater use and recharge rates, the price and quality of water, and reservoir design and operation to mention only a few. Yet information on these changes, by itself, is unlikely to lead to major policy changes. Only by looking at the specific characteristics of ecological problems and their vulnerability to the types of changes in runoff and soil moisture identified above can details of future societal impacts be evaluated. Such evaluations must begin now in diverse hydrologic basins so that policies for mitigating or preventing the most serious hydrologic impacts of climatic changes can be developed and implemented. Watershed runoff modelling of the Coppermine River suggests that variations in mean annual flow of 30% as a result of climatic change are not unrealistic, with even greater changes possible in most watersheds. The relationship between changes in precipitation and changes in annual runoff are nearly linear for the Scenarios.

A 10% increase in precipitation causes an increase in runoff of approximately 10%, assuming increases in temperature and evapotranspiration. The changes in annual flow could be aggravated or mitigated by changes in seasonal flow. Should precipitation increase in some regions, spring flooding is a possible consequence. Decreases in mean annual runoff may, however, decrease seasonal variability. Overall, seasonal changes in runoff patterns are likely to be greater than annual changes and may be more sensitive indicator of climatic change.

In general, watershed runoff models suggest that streamflow and soil moisture is sensitive to climate change. Impacts of this magnitude on the Coppermine River could have enormous ecological repercussions. This study also points out the difficulty of observing climatic impacts. Most hydrologic records are quite short and have been subject to other complicating effects. The robustness of the results presented here is constrained by the reliability of the model. Although providing more detailed information than simple statistical relationships, current watershed runoff models have substantial limitations and their applicability under altered climatic conditions has not been established. Future research in this area would benefit from the collection of additional hydrologic data, the development and testing of regional hydrologic models specifically for climate impact studies, and the standardization of the statistical techniques for evaluating simulation data.

The magnitude of changes in annual flow induced by hypothetical Scenarios ranged from decreases in mean annual runoff of 25% to increases of 15%. The greatest decrease in runoff was seen in the basin for a 1° C increase in temperature in conjunction with a 10% increase in precipitation. A 100% increase in precipitation caused runoff to increase 100%. All relationships between runoff and precipitation are nearly linear for the range of Scenarios studied. Runoff increases more slowly than precipitation. Model biases undoubtedly affect this relationship. Percentage changes in runoff are dominated by low flow years.

CONCLUSIONS

A calibrated physically based watershed runoff model was used to simulate runoff for a range of hypothetical climate change Scenarios. The results indicated that changes in temperature had an effect on the magnitude of annual runoff, but strongly affected the distribution of runoff by affecting the ratio of rain to snow during the winter and spring seasons, and by affecting the timing of snowmelt during the spring and summer seasons. In contrast, changes in precipitation had a large effect on the magnitude of seasonal and annual runoff. In addition, the magnitude of natural climatic variability is large and may mask the effects of long term climate changes.

Major changes in runoff and soil moisture can be observed in all Scenarios, including certain changes that are consistent in their direction in every Scenario despite wide differences in the original precipitation and temperature inputs. The most important changes are 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 and influence on Arctic ecological conditions.

Both seasonal and monthly impacts were studied because short-term hydrologic changes are often of greater interest and value to water-resource and ecological planners than annual-average changes. Two seasons were evaluated: winter and summer. These assumptions are consistent with most 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 normally dry during the summer months.

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