APPLYING A CLIMATIC CHANGE SCENARIO TO A SEMI-DISTRIBUTED WATERSHED MODEL

by

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INTRODUCTION

There is increasing concern in the scientific community over the possibility of global warming due to increases in radiatively-active gases - the so-called greenhouse effect. Atmospheric general circulation models (GCMs) predict changes in temperature and in amounts and distribution of precipitation as a result of a doubling of CO_2 in the atmosphere. Such changes in climate would have an effect on water resources and water availability (Canadian Climate Centre, 1991). This concern is of some importance as, in many areas of the world, water usage is approaching the limits of water availability and any change in the availability or distribution of freshwater could have serious consequences (Falkenmark, 1989). There is therefore a strong incentive to develop hydrologic models able to simulate the effects of predicted climatic change on water resources.

Several researchers have used hydrological models of varying degrees of sophistication to investigate this issue. Kite and Waititu (1981) and Nemec and Schaake (1982) used the Sacramento model to study the effects of climatic change in East Africa and in the south-eastern U.S.A. respectively. The model was first calibrated under existing conditions and then rerun using a series of changes in precipitation and evapotranspiration (e.g., a 10% increase in precipitation and a 6% decrease in evapotranspiration). The resulting changes in runoff were expressed as percentage changes in the annual average. Similarly, Gleick (1987) developed a water-balance model to investigate the effects of climatic change on the water balance of the Sacramento Basin over the period 1931-1980.

Lettenmaier and Gan (1990) selected four study basins within the Sacramento-San Joaquin Basin and applied Anderson's (1973) snowmelt model and the soil moisture accounting model by Burnash et al. (1973). The models were calibrated over a four-year period and verified over at least 20 years of data. The monthly mean outputs from three GCMs (Geophysical Fluid Dynamics Laboratory, Goddard Institute for Space Studies and Oregon State University) running 2 x CO_2 scenarios were expressed as differences (for temperature) or as ratios (precipitation) to the base case scenario (1 x CO_2). The recorded climatic data and the Penman potential evapotranspiration were then adjusted using these differences or ratios and the models were run for both scenarios from all three GCMs. Results from Lettenmaier and Gan (1990) showed the typical back-shifting and reduction in peak flows as precipitation fell as rain rather than snow under the projected higher temperatures of the 2 x CO_2 scenarios.

Rango and van Katwijk (1990) described a step-by-step approach to modelling the effects of climatic change. At first they included only the effects of changes in temperature and precipitation but later included modifications to model parameters such as the snowmelt runoff coefficient, the rainfall-runoff coefficient and the winter snow accumulation. Troendle (1991) used a more detailed daily watershed model to examine the effects of increased temperature and precipitation on a subalpine hillslope. The model results showed an increased snowmelt and a peak flow that was, on average, 14 days earlier.

Precipitation and temperature would not be the only variables changing under a 2 x CO_2 scenario and Tsuang and Dracup (1991) investigated the impacts of changes in radiation, wind and humidity using a detailed energy-based snowmelt model for the Emerald Lake Basin, California. However, in order to use the alternative climate scenarios derived by Lettenmaier and Gan (1990) they were forced to assume that the wind and relative humidity would not change. Downward longwave radiation was increased by 15.5 w/m^2 and solar radiation was decreased by 0.5 w/m^2 in the snowmelt model. As expected from earlier studies, the snow accumulation was less under the 2 x CO_2 scenarios with more of the precipitation occurring as rain.

These analyses assumed that the watershed itself would remain constant; that, although the climate changed, the ecosystem would remain the same. However, climatic change will affect not only precipitation and temperature but also the distribution of land-types such as glaciers and permafrost zones; land-surface processes such as weathering, erosion and slope stability; soil processes such as drainage capacity and soil quality; vegetation characteristics such as

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biomass production (moisture-use) and shifts in vegetation zones and population diversity, migration and dispersal. Vegetation is known to exert a major influence over the micro-climate of a particular site. It regulates the temperature, moisture and wind regime and hence influences the quantity and quality of water available for infiltration and runoff. Changes in the vegetation can cause decreased evapotranspiration, increased erosion and degradation in water quality. The changed evapotranspiration rates then feed back into the altered precipitation and temperature regimes. A modified temperature and precipitation regime will also change the rate, location and timing of the snow accumulation and melt process with corresponding changes for the earth's albedo. The changes in albedo and the depth of the snow will change the heat budget at the surface and may displace the zones of continuous permafrost. This may then affect the infiltration and hydraulic conductivity rates within watersheds, in turn affecting the vegetation patterns.

The direct effects of increasing CO_2 on the physiology of photosynthesis and transpiration of vegetation must also be considered. These include stomatal closure, decreasing transpiration rates, increasing plant efficiency and, hence, more water available for runoff. Idso and Brazel (1984) compared the effects of applying three scenarios of climatic change to Arizona watersheds both with and without considering the stomatal effects of increased CO_2. This work clearly showed that the anti-transpirant effect of the increase in atmospheric CO_2 reversed the climate change effect from a reduction in mean annual streamflow by 20- 40% to an increase of 40-70%. Wigley and Jones (1985) showed that, if Γ is the runoff ratio of the basin (runoff/precipitation), α is the change in precipitation due to climatic change and β is an evapotranspiration factor,

[1] $$\beta = 1 - 0.3a$$

where a is the fraction of the basin covered with vegetation, then the ratio of runoff after climatic change to runoff before climatic change is:

[2] $$\frac{R_1}{R_0} = \frac{\alpha - (1-\Gamma)\beta}{\Gamma}$$

Thus, for the basins studied by Idso and Brazel with runoff ratios of about 0.2 and a 10% decrease in precipitation (Γ=0.9), the change in runoff would vary between -50% for a basin with no vegetation to +70% for a basin completely vegetated.

Neither of these studies included the seasonal distribution of precipitation or temperature and both assumed that the percent of the basins covered by vegetation would not change despite the changed climate.

THE MODEL

A simple semi-distributed model (Kite, 1989) was used to investigate the uses of GCM data on a watershed in the Canadian Rocky Mountains. The watershed was first divided into a number of sub-basins and each sub-basin was classified by land-use (e.g., coniferous forest, grassland, crops, etc) using a Landsat image. The model was then applied to each land-use and each sub-basin.

The physical basin is represented in the model by three reservoirs or tanks, one for snowpack, one for a rapid response (which may be considered as a combined surface storage and top soil layer storage) and one for a slow response (which may be considered as groundwater). The three tanks have specified initial contents; there is a maximum depression storage and a maximum allowable depth for slow storage. The model has a total of 14 parameters and operates on a daily time interval.

Daily precipitation is converted from point data measured at climatic stations to areal averages for each land-use in each sub-basin. If the daily mean temperature is above a specified critical temperature then the precipitation is assumed to be rainfall and enters the rapid storage tank from where it may percolate to the slow storage tank at a rate governed by the Green-Ampt equation:

[3] $$\frac{dF}{dt} = P(7)\left[1 + \left[\frac{(m-m_0)\ (c+P(8))}{F}\right]\right]$$

where F is the total depth of infiltrated water in mm, t is the time in days, P(7) is the saturated conductivity in mm/day, m is the moisture content of the soil averaged over the depth to the wetting front, m_0 is the initial moisture content and C is the capillary potential at the wetting front in mm. In practice, the effective porosity is assumed to be 0.33 and the change in moisture content is calculated as:

[4] $$m - m_0 = 0.33 * [1 - D_s/P(9)]$$

where D_s is the depth of the slow tank so that the percolation is

[5] $$\frac{dF}{dt} = P(7)\left[1 + \left[0.33\,(1 - \frac{D_s}{P(9)})\right] * \frac{(D_r + \phi)}{D_s}\right]$$

where D_r is the depth of the rapid tank and ϕ is the potential (suction) head defined as

[6] $$\phi = 250\,[\,-\log(\,P(7)/86400)\,] + 100$$

If the contents of the rapid storage tank are greater than the depression storage then they may also be depleted to runoff, Q_s, at a rate based on the Manning equation:

[7] $$Q_s = (D_r - P(8))^{1.67}\sqrt{S_0}\;A/n$$

where S_0 is the average overland slope, A is the area of the land-use and n is a roughness parameter for overland flow. At the same time, any snowpack is depleted to snowmelt depending on the specified snowmelt rate and the daily air temperature. Snowmelt is proportioned between the rapid storage tank and the slow storage tank. Snowmelt may, optionally, be modified by the areal extent of snowcover observed from NOAA satellite (Kite, 1989).

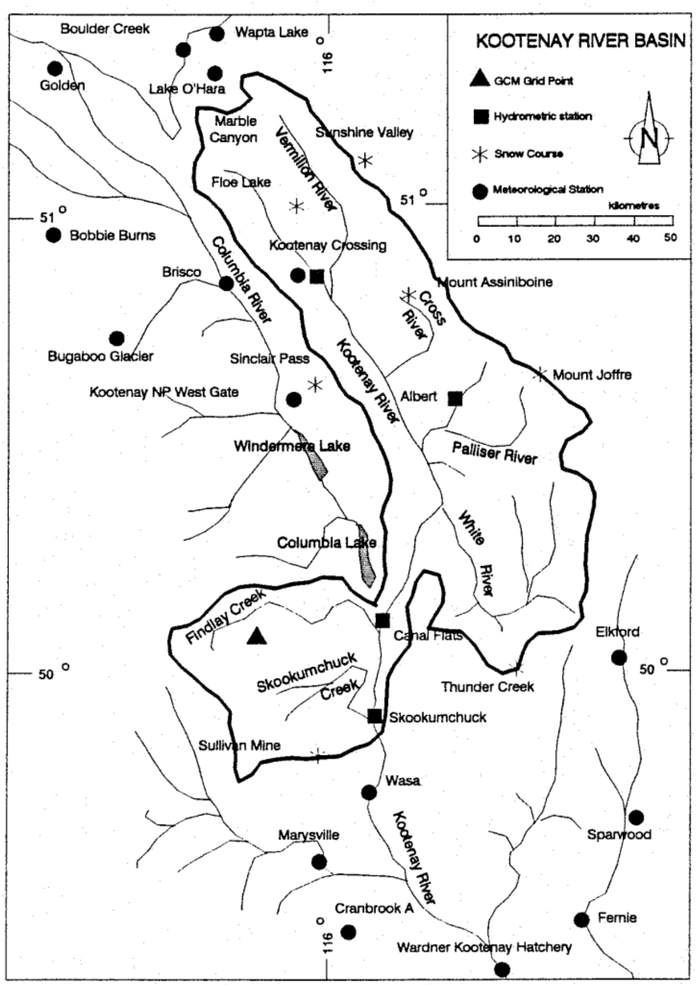

Figure 1. Kootenay Basin showing station locations.

If, on the other hand, the daily mean temperature is below the critical value, then the precipitation is assumed to be snowfall and is added to any existing snowpack. There would be no snowmelt in this case, but the rapid storage would be allowed to infiltrate and to runoff as before. Slow storage contributes to streamflow at a rate depending on the contents of the tank, and on the temperature and is passed through a moving average filter of variable length. Evapotranspiration is satisfied, if possible, first from the snowpack and then from rapid storage and, finally, from slow storage.

THE DATA

The basic data needed by the model are daily mean temperature, precipitation and areal evapotranspiration. Optional data include daily streamflow and long-term mean daily streamflow (used for calibration), daily cloud and snow cover data from NOAA satellite and daily snow water equivalent from DMSP satellite.

Daily temperature, precipitation and evapotranspiration are averages over land-use classes of sub-basins. The complementary relationship areal evapotranspiration (CRAE) model (Morton, 1983) is used with dewpoint temperatures, air temperatures and hours of bright sunshine to estimate monthly values of areal evapotranspiration. The monthly evapotranspirations are then interpolated to daily values using the daily hours of bright sunshine and daily wind-run. Daily data for the period 1987-1991 are available. Fig. 1 shows the locations of the streamflow gauging stations, the snow courses and the climatological stations for the Kootenay Basin, 7100 km², situated in south-eastern British Columbia. Climatic change data were obtained from the outputs of the second generation Canadian Climate Centre general circulation model (GCMII), (Boer et al., 1990). This model uses a grid of 3.75° x 3.75°, has full diurnal and annual cycles, uses a simple ocean and sea-ice model and includes cloud optical properties feedback. When used with the 'standard' greenhouse gas experiment, the output from this model shows a globally-averaged surface temperature increase of 3.5° and a 4% increase in precipitation and evaporation. Mean monthly values of 21 variables were obtained from a 10-year control run (1 x CO_2) and a 10-year experiment run (2 x CO_2) for a grid point (116.25°W, 50.10°N) within the Kootenay Basin. The data at this grid point represent averages over an area of approximately 280 km W x 420 km N or 118,00 km².

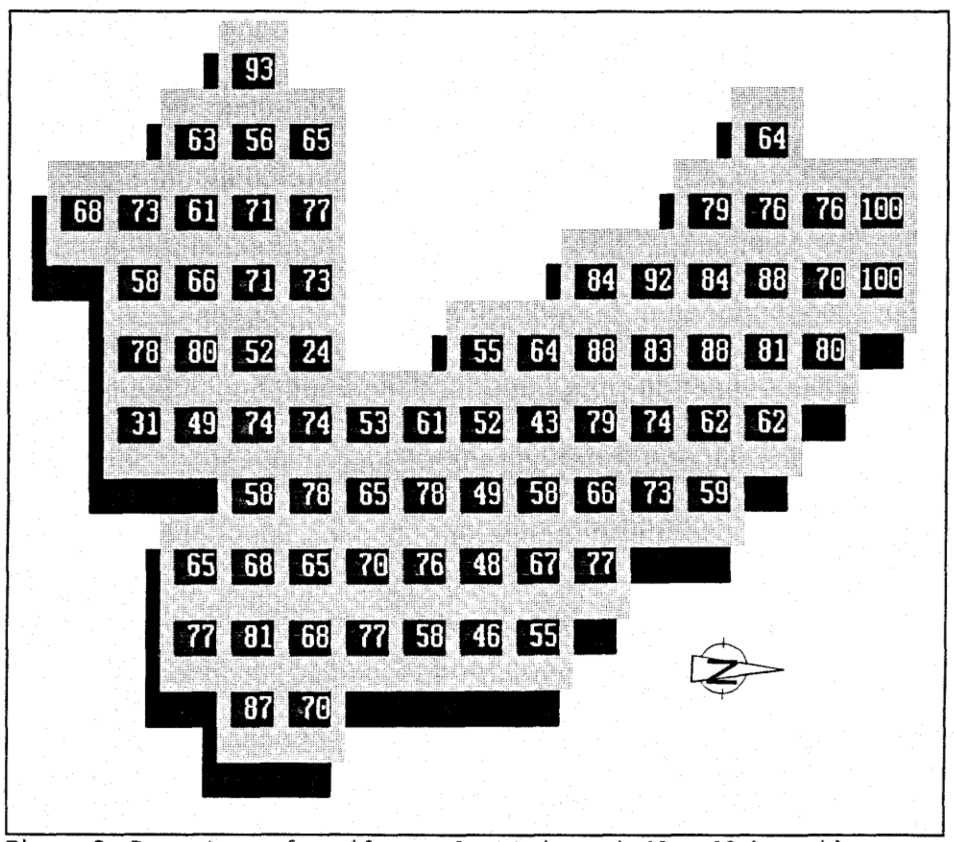

Figure 2. Percentage of coniferous forest in each 12 x 12 km grid square, Kootenay Basin.

Land-use data for the SLURP model were obtained by classifying a Landsat image of the basin into three classes for each 12 x 12 km grid square; bare-ground (including fresh clear-cut), coniferous forest, crop and grassland (including reforested areas, lake, river, marsh). Fig. 2 shows an example of the land-use data.

METHOD

The SLURP model was calibrated using recorded streamflow for three sub-catchments of the Kootenay Basin for the period 1986-1990. Fig. 3 compares the recorded and the simulated hydrographs. The original climatological data for the sub-catchments were then modified to simulate the climatic change scenario by applying the differences between the two GCMII runs (as percentages or as absolute values) to the recorded 1986-1990 temperature, precipitation and evapotranspiration data. This provided a second set of input data for the hydrological model.

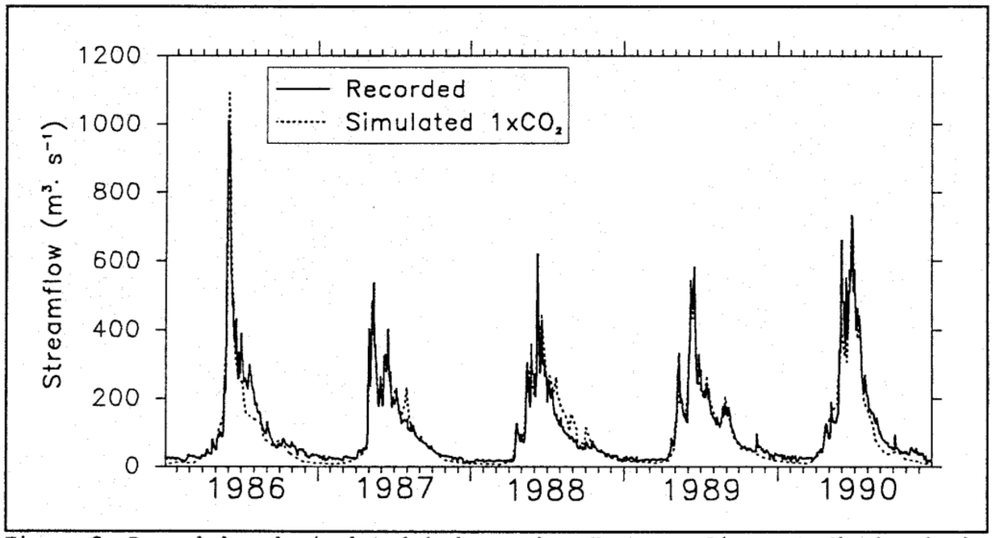

Figure 3. Recorded and simulated hydrographs, Kootenay River at Skookumchuck, 1986-1990.

The original land-use distribution data were modified by considering the effects of climatic change on ecoclimatic zones. Changes in the Canadian Cordilleran ecoclimatic province are likely (Zoltai, 1988) to be restricted to an altitudinal expansion of the conditions already present at lower elevations, e.g., an expansion in the grass/cropland land class at the expense of the coniferous forest class. Ozenda and Borel (1990) found that, for the European Alps, a 1° C rise in temperature would cause an upward shift of vegetation zones by about 180 m. Table 1 lists the recorded percentages of land-use in the Kootenay Basin and those estimated as applying under a 2 x CO_2 scenario.

Table 1 Land-Use by Sub-basin

	Kootenay Crossing	Kootenay at Canal Flats	Kootenay at Skookumchuck
Area, km²	420	4970	1730
Present conditions:			
Bare-ground, %	10	9	9
Forest, %	74	70	62
Grass/crop, %	16	21	29
2 x CO_2 scenario:			
Bare-ground, %	0	0	0
Forest, %	16	6	44
Grass/crop, %	84	94	56

The model was run again using the modified climatic data and the changed land-use percentages, but retaining the original parameter set. The daily areal evapotranspirations were then modified to reflect the changed stomatal activity. Since the basins are said to be 100% covered with vegetation under the 2 x CO_2 scenario, evapotranspirations were multiplied by 0.7 (Wigley and Jones, 1985) and the model was run a third time using the modified evapotranspiration data.

RESULTS

The second column of data in Table 2 presents the calibration results for the semi-distributed model for the years 1986-1990 using 1 x CO_2 data. The three criteria (Kite, 1991) and the flow data indicate that the model simulates the recorded streamflow well.

Table 2: Model results, Kootenay Basin above Skookumchuck.

Statistic	1 x CO_2	2 x CO_2	2 x CO_2 (stomatal effect)
Total precipitation, mm	3289	4313	4313
Total evapotranspiration, mm	961	864	660
Total recorded runoff, mm	2412		
Total computed runoff, mm	2206	3314	3523
Mean computed flow, m^3/s	100	150	159
Mean recorded flow, m^3/s	109		
Maximum computed flow, m^3/s	1092	982	1025
Maximum recorded flow, m^3/s	1010		
Standard error, m^3/s	32		
Nash/Sutcliffe criterion	0.94		
Garrick et al. criterion	0.79		
Previous-day criterion	-1.38		

The third and fourth columns of data in Table 2 present comparable data using the 2 x CO_2 inputs and the 2 x CO_2 inputs with stomatal effect included. The results show an increase in precipitation and a corresponding increase in mean streamflow, but a slight reduction in the maximum daily flows. The incorporation of the stomatal effect decreased the evapotranspiration and slightly increased the mean and maximum streamflows. A comparison of the 1 x CO_2 and the 2 x CO_2 hydrographs shows that, although the peak streamflow has decreased, the frequency of high flows has increased significantly. For example, mean daily flows above 300 m^3/s occur only six times in the period 1986-1990, but 16 times under the 2 x CO_2 scenario.

The inter-annual distribution of hydrological variables is also affected by the climatological changes. Figs. 4 and 5 show the changes between recorded data and the 2 x CO_2 scenario for mean monthly snowpack and mean monthly streamflow respectively.

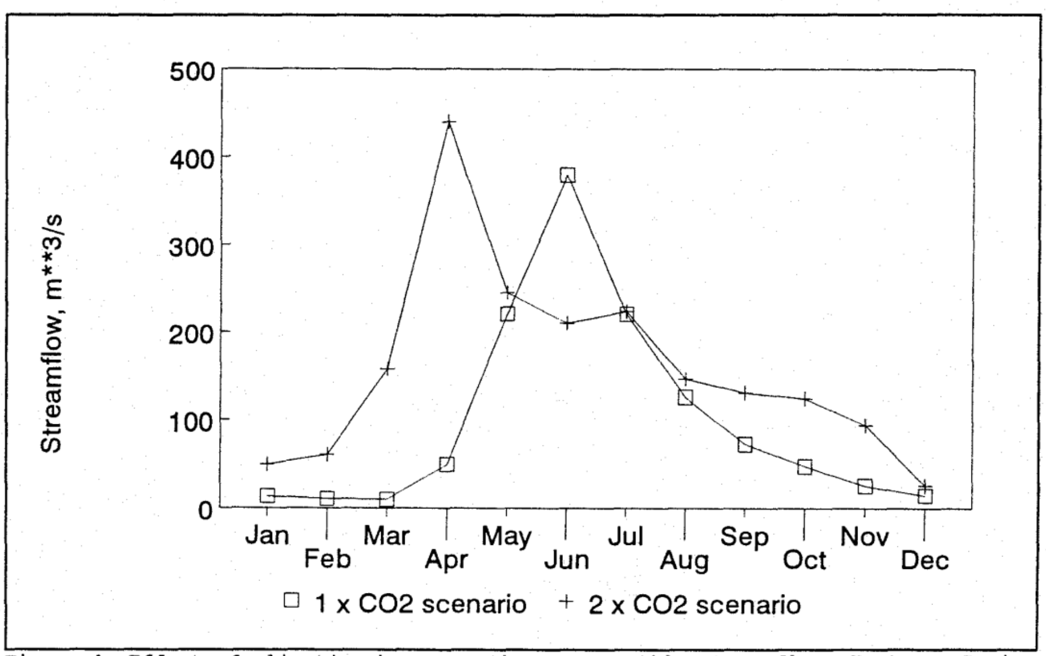

Figure 4. Effect of climatic change on the mean monthly streamflow, Kootenay Basin.

Despite the increased precipitation, the monthly snowpacks were reduced because of the higher temperatures. Accordingly, the mean monthly streamflows are increased and the peak is shifted from June to April.

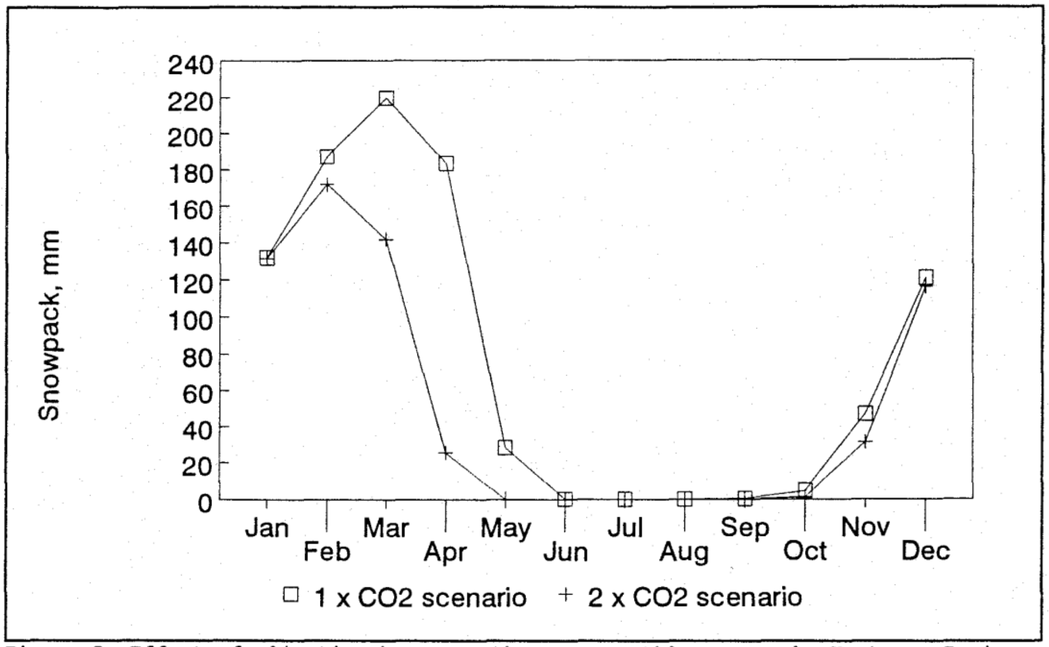

Figure 5. Effect of climatic change on the mean monthly snowpack, Kootenay Basin.

The runoff ratio for the Kootenay Basin above Skookumchuck is 0.73 and the increase in mean annual precipitation from 1 x CO_2 to 2 x CO_2 is 31%. The 60% increase in annual runoff simulated in the hydrologic model agrees very well with that predicted by Equation [2] above (Wigley and Jones,1985).

CONCLUSIONS

A semi-distributed watershed model has been developed that is based on land-use characteristics obtained from Landsat. The model is also able to use snow and cloud cover from NOAA satellites and snow water equivalent data from the DMSP satellite. Relating the model parameters to land-use means that the model can be moved from watershed to watershed without major recalibration and can be used to investigate changes in land-use.

The output from a GCM simulating a 2 x CO_2 scenario was used to investigate the use of the model under different climatic conditions. The effects of the GCM scenario are interesting but the important result is the linking of the GCM output with the hydrological model and the incorporation of the anticipated changes in land-use. The linking, at the moment, is crude; changes in temperature, precipitation and evapotranspiration are lifted directly from the GCM, the land-use is assumed to vary only with temperature and the increase in stomata efficiency is assumed to vary linearly with CO_2 concentration. Further research will make the linking more interactive, with the hydrological model replacing the simple land-phase component of the GCM, and with more physically-based changes in vegetation.

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