EFFECTS OF CLIMATE CHANGE ON WATER SUPPLIES IN MOUNTAINOUS SNOWMELT REGIONS

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SUMMARY

Snowmelt runoff comprises a surprisingly large part of the world's water supply, especially in mountainous regions where it is depended upon for irrigation and hydropower. The Snowmelt Runoff Model (SRM) was used on three mountain basins in North America under conditions of climate change in order to simulate the hydrological response to expect in the future. The focus was on increases in temperature and decreases in snow cover, although the effects of changes in precipitation and transpiration were considered briefly. It was found that in response to a 4-5°C warming, the beginning of the snowmelt season advances by about a month, snow cover disappears from the basin as much as a month earlier, and runoff is shifted from the summer half year to the winter half year with winter runoff sometimes doubling. It was further found that runoff in April and May (when water demands are low) is increased greatly at the expense of large decreases in June and July (when water demands are high). In extreme years the hydrological effects of climate change are intensified. The effects on water management will include changes in reservoir operating rules, increased maintenance for existing water control structures and replacement or construction of new facilities, reviews of water law in relation to climate change, and reassessment of existing interstate and international water compacts. The continually mounting demand for water will increase the need to know the climate change effects on water supply and the appropriate water management responses.

INTRODUCTION

The projected increase in the concentration of CO_2 and other greenhouse gases in the atmosphere is likely to result in a global temperature increase as well as other changes in climate. Any change in climate, particularly a temperature increase or global warming, will have a resultant effect on snow accumulation, snow cover extent, and snowmelt runoff and water supply. Snow, which may cover up to 53% of the land surface in the Northern Hemisphere (Foster and Rango, 1982) and up to 44% of the world's land areas at any one time, supplies at least one-third of the water that is used for irrigation and the growth of crops (Gray and Male, 1981). In high mountain snowmelt basins of the Rocky Mountains, as much as 75% of the total annual precipitation is in the form of snow (Storr, 1967), and 90% of the annual runoff is from snowmelt (Goodell, 1966). In other parts of the world, these percentages may be even higher. In southern Asia, snowmelt from the Himalayas and adjacent mountain ranges supplies virtually all of the water to irrigate the arid valley bottoms which produce high-value crops such as cotton, alfalfa, sugar beets, wheat, fruits, and vegetables (Steppuhn, 1981).

In addition to irrigation applications, snowmelt is a major source of runoff for generation of electric power in mountainous regions. Hydropower companies will be significantly affected if global warming causes a shift in the snowmelt runoff patterns that they have relied upon for many years. Effects of global warming will also extend to the recreation industry through changes in the duration and areal extent of snow cover in ski resort regions. In areas near mountain regions, domestic water supplies also depend on snowmelt runoff and could be directly affected.

BACKGROUND

As with most other applications, assessment of climate change effects on snowmelt cannot wait until the climate has changed. Planning for a response to climate change has to start now rather than 50 years in the future. Fortunately, much work has been done on snowmelt runoff modelling for forecasting. This allows us to attempt an evaluation of the effects of climate change on snowmelt now so that appropriate information on future scenarios can be supplied to water resources planners.

Snowmelt runoff models are mathematical representations of the melting of snow and delivery of the meltwater to the stream channel. The melting of snow is commonly represented using the "degree-day approach" which uses observed temperature as an index of the environmental factors that cause snow to melt. More complex models sometimes try to include more of the factors that directly cause melt, such as, net radiation, clouds, humidity, wind, and albedo, in an "energy balance approach." In addition, the snowmelt models variously need to consider in some way snow accumulation, snow cover depletion, precipitation distribution, evapotranspiration, soil moisture, and land cover in attempting to come up with an accurate simulation of observed snowmelt runoff.

These attempts have generally been successful as has been documented by the World Meteorological Organization (WMO, 1986; 1992). As a result, a number of these successful snowmelt runoff models have been adapted to generating snowmelt runoff scenarios under conditions of climate change (Cooley, 1990; Gleick, 1987a; Gleick, 1987b; Gleick, 1989; Kite, 1993; Lettenmaier and Gan, 1990; McCabe and Ayers, 1989; Nash and Gleick, 1991; Pangoulia, 1991; Rango and van Katwijk, 1990a; Roos, 1990; Troendle, 1991; van Katwijk, et al., 1993; Martinec, et al., 1994a; Martinec and Rango, 1989). Most snowmelt runoff models employ the degree-day approach because of simplicity and availability of data. The model employed in this paper is the Snowmelt Runoff Model (SRM) which is a simple degree-day model with a unique aspect -- it requires input of satellite-derived snow cover extent data. SRM is easy to use, has been widely applied and validated internationally, and is well documented (Martinec, et al., 1994b).

TEST BASINS

SRM has been utilized under conditions of climate change in numerous basins and three in western North America have been chosen for this paper. The first basin is the upper Rio Grande basin in the Rocky Mountains of Colorado, the headwaters of the Rio Grande which flows into New Mexico and along the border between Texas and Mexico. The upper portion of this basin that was studied is 3419 km^2 in area, and the mountain snowpack in it supplies most of the runoff to the Rio Grande flow. The second basin is the Kings River basin located in the Sierra Nevada Mountains of California. This basin is 4000 km^2 in area, and it provides a large amount of water for irrigation in the Central Valley of California, most of it originating as snowmelt. The third basin is the Illecillewaet River basin of British Columbia which is a tributary to the upper Columbia River. It is 1155 km^2 in area and is different than the other two basins because it has a number of glaciers and permanent snow fields in the upper elevation zones, and it is located in a more humid environment. It is interesting to note that both the Rio Grande and Illecillewaet River are transboundary basins in the downstream reaches which adds to the importance of considering the climate change effects.

RESULTS OF CLIMATE CHANGE HYDROGRAPH SIMULATIONS

In order to use SRM to produce a snowmelt runoff scenario under conditions of a future climate change, several steps are necessary. First, SRM must be applied to the test basin in the simulation or forecast mode for a series of years to be assured that accurate hydrographs are produced. For example, on the Rio Grande basin several prior studies focused on SRM forecasting of spring runoff, and the model parameters and variables were established for 14 years (Rango and van Katwijk, 1990b). It was also fortunate that in those 14 years both a very low and a very high runoff year occurred. Second, a change in climate has to be decided upon. The magnitude of the change is usually obtained from General Circulation Model (GCM) runs over the region. The appropriate increase in temperature is used to modify the temperature input variable in SRM. In some runs, precipitation is also changed and other times it is kept the same. Third, the new temperature and precipitation input variables are used by SRM for a particular year to create a new snow cover indicative of the new climate. The three variables needed for input to SRM are now ready for use in the climate change year. Fourth, the effect of the proposed climate change on the SRM parameters, such as, the degree-day coefficient, the snow runoff coefficient, and the date of snowpack priming, must be considered. At a minimum, a certain number of the parameters must be shifted forward in time to simulate the effect of an earlier Spring in a warmer climate. It has been found that a 1°, 3°, and 5°C increase in temperature corresponds to a 5, 20, and 35 day advancement of the beginning of the Spring melt period (van Katwijk, et al., 1993). Finally, with the development of a new set of variables and parameters for a particular year, SRM is ready to be run to simulate the effects of climate change on a particular year's runoff. Additionally, a method has been developed with SRM that allows the shifting of accumulated snow, snowmelt, and runoff from the summer half year (April to September) to the winter half year (October to March) when the global warming occurs during all months (Martinec, et al., 1994a). These techniques have been perfected on the Rio Grande, Kings River, and Illecillewaet River.

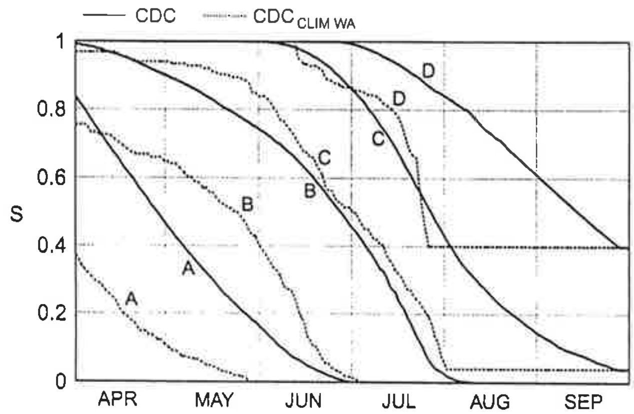

Figure 1 Depletion curves of snow coverage(S) for four elevation zones of the Illecillewaet basin from 1984 satellite data and for a temperature increase of +4°C

Figure 1 shows the change in snow cover as a result of a +4°C increase in temperature in 1984 for the Illecillewaet River basin. The conventional snow cover depletion curves (CDC-solid line) are obtained from satellite monitoring in 1984, and the climate change affected depletion curves ($CDC_{CLIM\ WA}$- dashed line) are generated by SRM to reflect the changed climate. The $CDC_{CLIM\ WA}$ curves also take into account the shifting of runoff from summer to winter and a resultant decrease of snow water equivalent at the beginning of the melt season. In Figure 1, it is apparent that the snow completely leaves an elevation zone a month or more earlier than in the unchanged climate. Such information should be an interest for the winter recreation industry in mountain areas. Figure 1 also shows minimum snow cover in zones C and D greater than zero which is a result of glaciers being present in the basin.

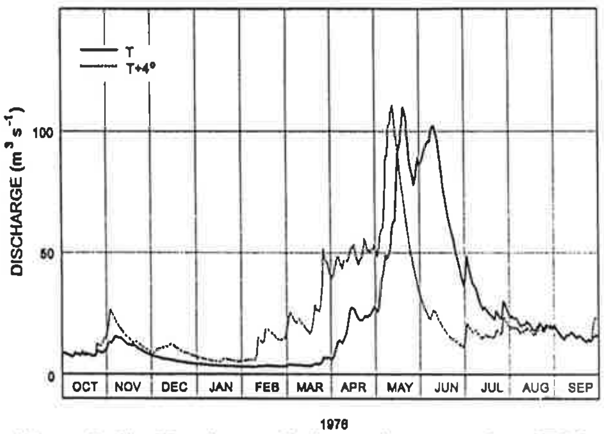

Figure 2 Rio Grande basin hydrographs generated by SRM for existing temperatures (1976) and for a temperature increase of +4°C

As a result of this change in snow cover, temperature, and possibly precipitation, snowmelt runoff can also be expected to change. Figure 2 shows the hydrograph resulting from a +4°C warming for the entire year 1976 in the Rio Grande basin. The solid line, which is the SRM simulated hydrograph for actual climate in 1976, is considered as the base for comparison. The dotted line is the 1976 hydrograph under conditions of climate change. Under normal conditions, only 14%, of the yearly natural runoff flows off in the winter half year (October to March) and 86% flows off during the summer half year (April to September). Under a +4°C warming, the percentages change considerably to 30% (winter) and 70% (summer). The runoff is shifted forward in time by about one month.

Figure 3 shows a representative year, 1973, on the Kings River basin. Under normal conditions, 22% of the yearly natural runoff flows off in the winter half year and 78% in the summer half year. Under conditions of a +4°C warming, the percentages are 39% (winter) and 61% (summer). Large decreases in runoff are noted in the summer months of June and July.

Figure 4 presents the hydrographs for 1984 on the Illecillewaet River basin. Under normal conditions, 10% of the annual runoff occurs in the winter half year and 90% in the summer half year. Under conditions of a +4°C warming, the percentages are 17% (winter) and 83% (summer). Again a shift forward of runoff by about a month is observed. April and May experience big increases, and July and August show large decreases.

Of the three basins, the Illecillewaet River is the only one to experience an increase in summer runoff volume. Recalling Figure 1, this additional runoff appears to be produced late in the summer in part by the constant values of snow cover which result from permanent snowfields and glaciers in zones C and D. The presence of the glaciers could tend to mitigate the hydrological effects of climate change, but only temporarily until the glaciers themselves disappear.

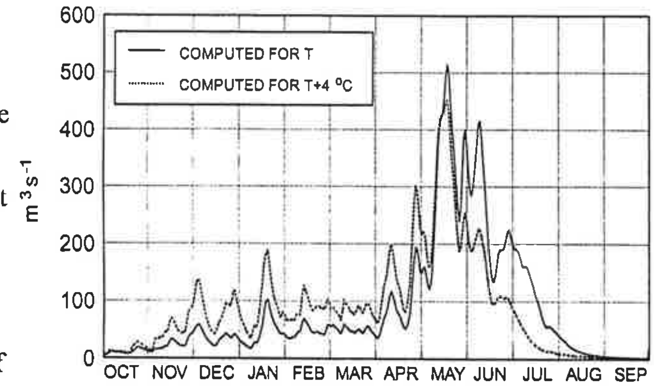

Figure 3 Rio Grande basin hydrographs generated by SRM for existing temperatures (1976) and for a temperature increase of +4°C

In a study that looked only at runoff during the spring and summer months on the Rio Grande and Kings River basins (van Katwijk, et al., 1993), a 5°C warming increased April and May flows by 185% and 26%, respectively. June and July experienced 61% decreases in flow each month. Such a reconfiguration of the runoff pattern will cause a major effect on downstream water users. As would be expected, there are some complicating factors. The rise in atmospheric CO_2, which is in large part responsible for the increase of temperature, will also increase plant efficiencies and promote a reduction in transpiration-based water losses from vegetated areas in the basins. The magnitude of these transpiration reductions is a question that still needs to be answered by research. If some of the maximum reductions reported in prior research studies (Cure and Acock, 1986; Carlson and Bunce, 1991; and Kutchment and Startseva, 1991) occur, a 12% decline in transpiration would result from a doubling of CO_2. This would be translated to a conservation of water which would appear as increased runoff. Figure 5 shows the effect on monthly and total seasonal flows from a maximum transpiration reduction (van

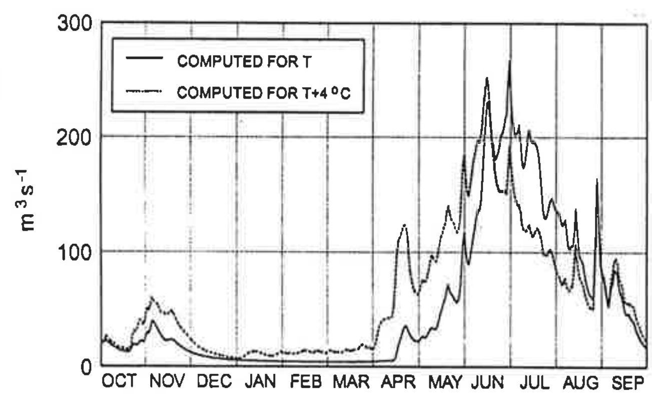

Figure 4 Illecillewaet River basin hydrographs generated by SRM for existing temperatures (1984) and for a temperature increase of +4°C

Katwijk, et al., 1993). Even more runoff occurs in April and May (increases of 229% and 42%, respectively), whereas decreases in June and July are reduced (to 55% and 45%, respectively). Where the four month total flows would have decreased by 6% with a 5°C temperature increase, the CO_2-induced maximum transpiration reduction will counteract that to produce an increase of 11% in the four month flow totals.

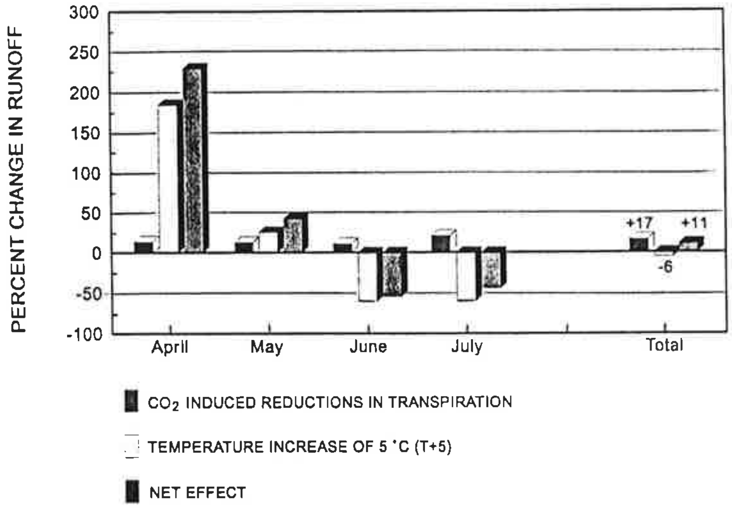

Figure 5 Monthly changes in runoff amount from CO_2-induced warming (+5° C) and CO_2-suppressed transpiration (-12%) on the Rio Grande and Kings River

It seems that extreme years on the Rio Grande basin are more affected by a 5°C increase in temperature than are average years. In average years, the seasonal flow is decreased by about 6% (assuming the transpiration effect to be minimal) in response to the 5°C warming. In the record drought year (1977) the seasonal flow decreased by about 20%. In the highest recent year of record (1979), the 5°C warming caused a few percent increase in flow and monthly changes in flow were amplified (e.g., the April increase was in excess of 300% and the July decrease in flow was about 90%).

It has been the experience that a warming, particularly in the 4-5°C range, will produce an overall decrease in flow. Precipitation decreases of 10-20%, which seem to be produced more commonly in western North America than increases, would tend to amplify the flow decrease. Such results have been reported by Nash and Gleick (1993) in the Colorado River basin. The annual decreases we have experienced as well as those experienced by others as a result of GCM input, generally seem to be in the 5-25% range. These figures will change if transpiration is reduced and if long-term shifts of vegetation type occur.

DISCUSSION

A climate change in mountain snow basins will affect the runoff characteristics of the snowmelt-fed streams. The climate change envisioned for the 20th century has several components, the most commonly cited being an increase in temperature of between 4-7°C (Nash and Gleick, 1993) in some western mountain regions of North America. Less certain are changes in precipitation, snow cover extent, transpiration, clouds, and radiation. Consideration of mainly changes in temperature and snow cover in three mountain basins revealed some hypothetical characteristic changes in runoff.

First, winter half year runoff will increase at the expense of summer half year flows because of increased winter snowmelt, a greater proportion of rain to snow in the winter accumulation period, and a reduction of snowpack water equivalent at the beginning of melt. Some basins experienced a doubling of winter volumes. Second, in the snowmelt season there is a redistribution of monthly flows because of the warmer temperatures and an advancement of the spring season and the beginning of snowmelt. The months April and May (and to a degree, March) generally experience large volume increases whereas June and July (and sometimes August) incur major decreases in flow. As an extreme example, the model results for one year on the Rio Grande basin showed a 300% increase in April flow and a 90% decrease in July flow resulting from a 5°C warming. Third, the annual change in runoff from temperature increases alone will result in a decreased flow volume; however, the uncertain changes in precipitation, transpiration, radiation, and clouds could either counteract or further intensify this effect. Nash and Gleick (1993) support this general conclusion on the Colorado River basin. Temporary increases in annual runoff as a result of global warming could occur in basins with significant area covered by glaciers until the glaciers themselves are depleted. Fourth, extreme hydrologic years may be affected more severely than average years. The model results indicated that for extreme years high flows increased more and low flows declined by greater amounts than was the case for the average year. Finally, limited experimentation with precipitation and transpiration changes (as a function of increased CO_2) indicate that if these changes are at a maximum, they could have major influences on the resulting runoff.

Any or all of these hydrological responses to climate change, if they should occur, will strongly affect how water management in mountain snowmelt basins is carried out. Reservoir operating rules are closely linked to the runoff patterns of today's climate as well as to the water demands and needs of the public. Although the climate and runoff patterns will change, the water demands in the new climate will not be synchronized with the expected redistribution of runoff. In the United States, water demand is greatest during the summer months because of irrigation and power (air conditioning) needs. In other parts of the world, e.g., Europe, the greatest water demand occurs during the winter months when energy for heat and light is needed. Complicating all this are requirements for flood control, recreation, domestic water supplies, and environmental concerns. There appears to be little flexibility today for changes in reservoir operating rules as the water demands continue to escalate. Hydrological responses to climate change may force these changes to be made.

As the runoff patterns change, more stress will be placed on existing water control structures. Some structures, already old or in poor repair, may fail as a result of the enhanced flows in extreme years and increased April and May flows in all years. New water control structures will be required to either replace existing structures or to assist in controlling the new runoff regime in the changed climate. Mounting expenses can easily be envisaged for building new structures and maintaining existing structures.

Another aspect of Western water management that could be affected is the prior appropriation doctrine in water law, especially in high runoff years. In high years with excess water, who owns the rights to this climate change-influenced water supply? Because there will be a redistribution of flow, will current water rights be forced to take their water at different times than they do now? In low to average runoff years, the prior appropriation doctrine will operate much as it does today, although consistently lower runoff could accelerate changes in the prior appropriation system of water rights to accommodate different uses by society.

As the climate changes, segments of society other than those directly linked to runoff will be affected. For example, the skiing industry will certainly suffer as the snow cover retreats up the mountains sooner and faster in the spring.

International and interstate water compacts may have to be renegotiated as the hydrological response to climate change becomes more evident. The hydrological conditions under which original compacts were developed may no longer apply. Two of the streams in this study become international downstream, and both countries may have different perceptions of the effects of the new water regime as a result of the climate change.

CONCLUSIONS

The effects of global climate change on water supplies in mountainous snowmelt regions may be significant. The most widely cited change will be an increase in global temperature which is the focus of this investigation. The warmer temperatures will decrease snow cover which in itself could adversely affect the skiing industry by shortening the ski season. In addition, the warmer temperatures will generally promote an annual reduction in streamflow although this may not be true of all basins. Warmer temperatures and reduced snow reserves will promote a shift in runoff from the summer half year to the winter half year with the winter flows increasing by as much as twice. For the basins included in this study, the increase in temperature will also advance the beginning of snowmelt so that April and May will experience around 185% and 25% increases in flow, respectively, as a result of a 5°C rise in temperature. At the same time, the simulated runoff for June and July will average about 60% less. The runoff in April and May will be increased even more if a reduction in transpiration accompanies the increase in atmospheric CO_2, whereas, under these same conditions, June and July decreases in runoff won't be quite so severe. It also appears that in extreme years of very high or very low runoff, the effects of climate change will be intensified. In order to keep things simple and because GCM projections of precipitation change are uncertain, precipitation effects were not considered quantitatively in this particular study.

The hydrological responses to climate change have not only been shown in this study, but have been confirmed by other investigators on other basins. Although the level of confidence of our predictions is somewhat uncertain now, we can say that major hydrological changes will occur if the projected climate change takes place. Water management decision-makers and policy experts need to be aware of these potential changes so that appropriate plans can be made to modify reservoir operating rules, replace, upgrade, or build new structures, incorporate required changes in water law, and renegotiate interstate and international water compacts, as needed. Continuing growth of the demand for water will further increase the need for a timely and appropriate water management and policy response to the impending climate change.

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