SNOWMELT WATER SUPPLY RESEARCH IN THE ARS GLOBAL CHANGE, WATER RESOURCES, AND AGRICULTURE PROGRAM

Albert Rango[1] and Keith Cooley[2]

ABSTRACT

The impending global warming expected to be felt most significantly in the next century will likely have a major impact on water resources and, in particular, snowmelt water supply. The Agricultural Research Service has a Global Change, Water Resources, and Agriculture Research Program in place with the purpose of evaluating the hydrologic impacts of these changes, mostly through the use of snowmelt runoff models. Seven basins in the Western U.S. are being studied. During the snowmelt season, global warming will cause a shift forward in the timing of runoff along with greater amounts of runoff early in the snowmelt season with decreases in runoff during the dry season. In addition there is a shift of runoff from the summer half year to winter half year. Improvements in model representations of evapotranspiration, the radiation balance, and sub-basin areas give a more physical basis to estimates of the hydrologic response to conditions of climate change. The development and use of integrated modular modeling systems has been necessary to make optimum use of high technology capabilities.

INTRODUCTION

Global change promises to be one of the central environmental issues of the 21st Century. Industrial and land management activities during the past two centuries have affected the Earth's environment by increasing the quantity of carbon dioxide and other gases in the atmosphere. These gases absorb energy that would otherwise be lost to space, thus warming the Earth's environment. Global warming could have dramatic effects on atmospheric processes that affect regional weather patterns which, in turn, control the health and productivity of ecological systems. In addition to its potential effect on the global energy budget, increased carbon dioxide will also influence the water and carbon budgets of terrestrial ecosystems through its effect on plant growth.

Changing weather patterns and atmospheric composition will alter the flux of energy, water and gases to the atmosphere, and influence plant distribution, water resources, and the productivity of managed ecosystems (croplands, rangelands and forests). Lack of understanding of the linkages between atmospheric and ecosystem processes is a substantial barrier to predicting the impact of future changes in global climate.

The Nation's croplands, rangelands and forests are basic to our national security and a strong national economy. These ecosystems must be managed to sustain global environmental quality, productivity, health and diversity. To effectively address the major challenges of a growing population, agriculture requires accurate predictions of the future global environment.

The Agricultural Research Service (ARS) maintains experimental sites at locations that have records of vegetation, soil, snow, and water and energy fluxes, some exceeding 50 years. The agency is a leader in development and application of physically-based models for agricultural, rangeland, and forested systems.

The ARS provides a sound scientific basis for regional, national and international management and policy decisions regarding cropland and rangeland ecosystems in the context of the global change issue. This paper documents the components of the ARS Global Change, Water Resources, and Agriculture Research Program specifically targeted to meet the needs of the U.S. Global Change Research Program (US/GCRP). In particular, this paper focusses on the ARS snowmelt water supply aspects of the global change research program. Topics to be discussed include: applications of hydrologic models to global change scenarios; advances in snowmelt runoff models; new technological developments for model applications; and plans for an intercomparison of snowmelt runoff models under conditions of climate change.

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[1] Research Hydrologist, Agricultural Research Service, Beltsville, MD 20705-2350

[2] Research Hydrologist, Agricultural Research Service, Boise, ID 83712-7716

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HYDROLOGIC RESPONSE TO GLOBAL CLIMATE CHANGE USING HYDROLOGIC MODELS

Models and Basins

At present, ARS is utilizing snowmelt runoff models as tools for assessing the hydrologic response of basins to climate change. These models are the Snowmelt Runoff Model (SRM) (Martinec et al., 1994a), the National Weather Service River Forecast System (NWSRFS) model (Anderson, 1973), and the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U.S. Army Corps of Engineers, 1975). SRM and SSARR are normal degree-day models. The NWSRFS model uses air temperature to index energy exchange across the snow-air interface, thus differing from the normal degree-day method which uses temperature as an index to snow cover outflow or water leaving the bottom of the snowpack. SRM is unique in that it requires the input of remotely-sensed snow cover extent data for simulation and forecasting of snowmelt runoff.

So far, ARS has used at least one of the above hydrologic models on seven basins scattered across Western North America. Table 1 and Figure 1 provide the area and location of these snowmelt runoff basins.

Table 1. Areas of snowmelt water supply and climate change study basins in Western North America.

Basin	Area
Rio Grande at Del Norte, CO	3419 km^2
Kings River below Pine Flat Dam, CA	4000 km^2
Reynolds Creek experimental watershed, Owyhee County, ID	234 km^2
Big Wood River at Central, ID	4144 km^2
Lower Willow Creek near Hall, MT	190 km^2
Ruby River at Ruby Reservoir, MT	1544 km^2
Illecillewaet River at Greeley, BC	1155 km^2

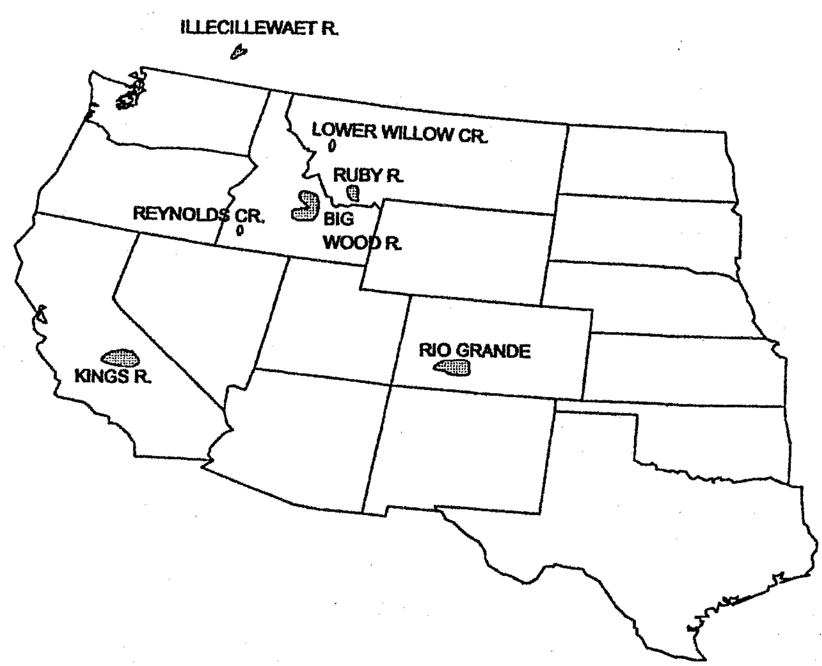

Figure 1. Western North American basins used by the Agricultural Research Service to evaluate the snowmelt runoff response to climate change.

Study Basin Results

Climate change simulations with SRM have focussed on determining how various climate scenarios will cause changes in both model variables and parameters. The three input variables for SRM - temperature, precipitation, and snow cover - could all conceivably change under conditions of climate change. Because most scenarios involve global warming, changes in temperature were a primary consideration. Because a warmer climate would not only cause less snow to accumulate but also cause the snow cover to deplete faster, the effect of a future climate on basin snow cover was modeled (Rango and Martinec, 1994). If the basin snow cover was assumed to remain unchanged in a warmer climate, the snowmelt runoff volume would be excessive. Precipitation changes were also considered, but, because they are less certain and tend to further complicate the effect on snow cover, precipitation was usually assumed to remain the same in the SRM climate change runs.

Additionally, changes induced in SRM parameters by climate change were also considered. Primarily this involved a change in the temporal variability of parameters because a global warming will cause a forward advance of springtime conditions. Studies in several of the study basins revealed a forward shift in melting by about 5, 20, and 35 days associated with a 1, 3, and 5°C increase in temperature respectively (van Katwijk, et al. 1993). The SRM basin parameters were shifted forward in time to coincide with this time shift in melting.

Figure 2 shows the effect of a 5°C warming on the Rio Grande Basin in Colorado in a high runoff year (1979). Note the forward shift in peak runoff and greater amounts of runoff early in the snowmelt season. Figure 3 shows a bar graph of the monthly change in Rio Grande flow for a high (1979), average (1984), and low (1977) year. It is evident that strong increases in runoff are experienced in the early runoff season with equally important decreases during June and July. Figure 4 shows the effect of a 5°C warming on the Kings River, CA hydrograph for 1978 using SRM. The forward shift in timing of the hydrograph is again evident.

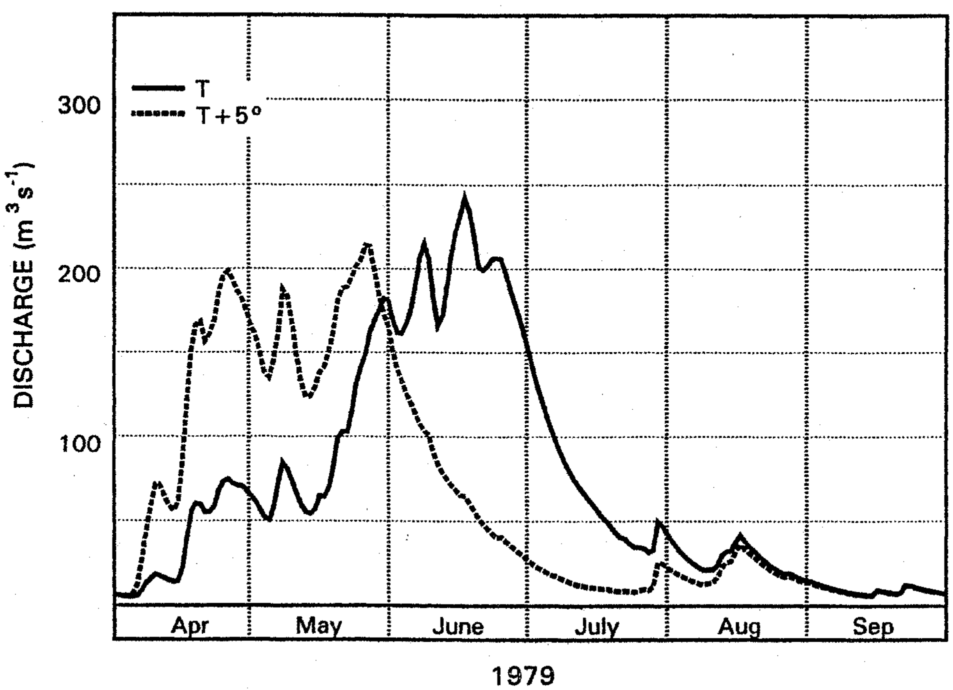

Figure 2. Change in the hydrograph on the Rio Grande Basin at Del Norte, CO as a result of a +5°C temperature increase in a high runoff year (1979).

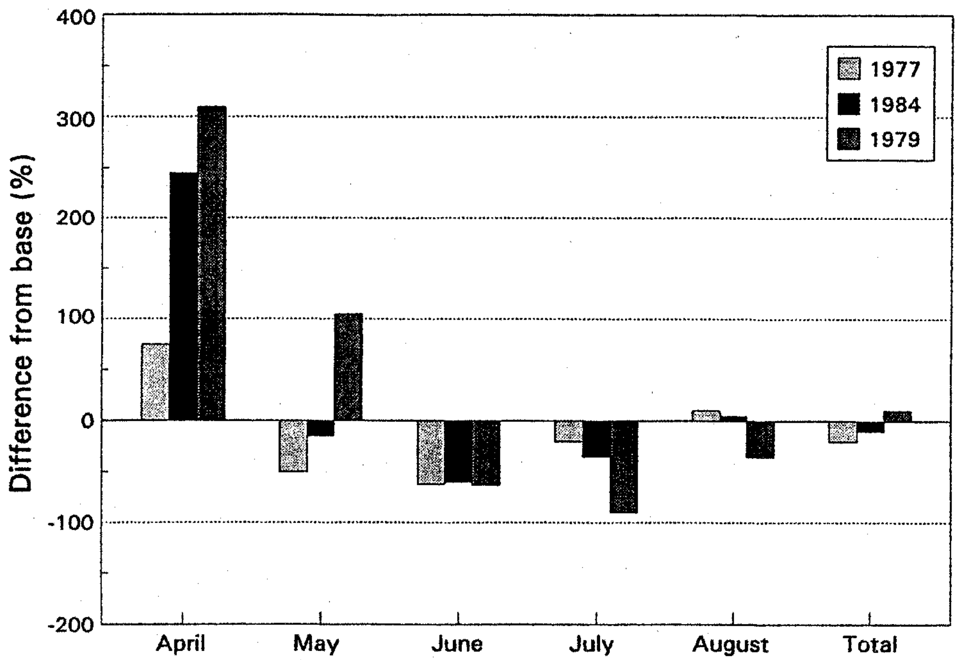

Figure 3. Percent change in monthly runoff on the Rio Grande Basin as a result of a +5°C temperature increase in high (1979), average (1984), and low runoff (1977) years.

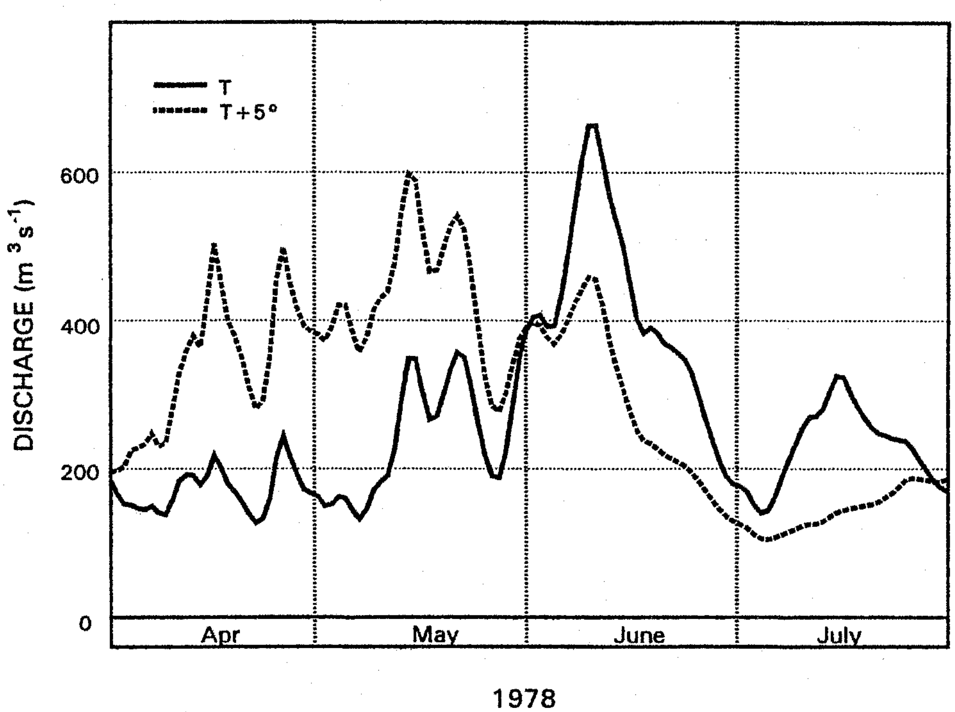

Figure 4. Change in the hydrograph on the Kings River Basin, CA as a result of a +5°C temperature increase in 1978.

The NWSRFS model and the SSARR model have been used on basins in Idaho and Montana. The example chosen here is for the NWSRFS model on Lower Willow Creek, Montana. As a basis for comparison, NWSRFS was first run for the 1973 to 1984 water years, and parameter values were adjusted until observed and simulated snowpack and streamflow were most nearly alike. In this study, for simplicity, the model parameters under this best fit situation were retained for the climate change runs. In future studies, many of these parameters will have to be changed because they would be affected by climate change. NWSRFS was used to simulate snowpack and streamflow for changes in average daily temperature of +2°C, +4°C, -2°C, and in average daily precipitation of +10% for the same time period (1973-1984). Figure 5 shows the significant decrease in the snowpack associated with a 4°C warming and a 10% precipitation increase in 1974, 1975, and 1981 on Lower Willow Creek. Changing the air temperature by 2-4°C can have a significant impact on the accumulation and melt of the snowpack depending on the original temperature regime of the area. If the normal temperature range in a basin is near the threshold temperature that separates rain from snow, a small change in temperature could change the snowpack considerably. However, if the site is normally very cold or warm, a few degree change may not alter the snowpack characteristics very much (Cooley, 1990).

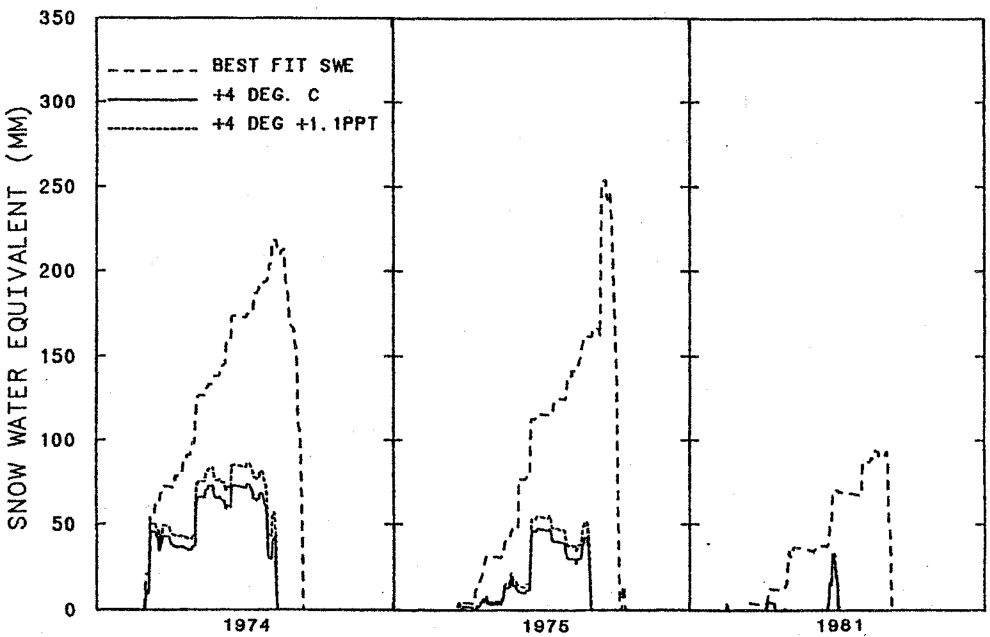

Figure 5. Simulated snow water equivalent (SWE) at the Combination SNOTEL site for the water years 1974, 1975, and 1981 under normal conditions (best fit), a +4°C warming, and a +4°C warming plus a 10% increase in precipitation on Lower Willow Creek, MT.

The changes in average monthly runoff caused by an increase or decrease in temperature are shown in Figure 6 for Lower Willow Creek. The warming of 2°C and 4°C caused a decrease in runoff of 12 and 22% and there is evidence of the forward shift in timing of the runoff. If a 2°C cooling occurs, the runoff volume will increase by 15% (Cooley, 1990).

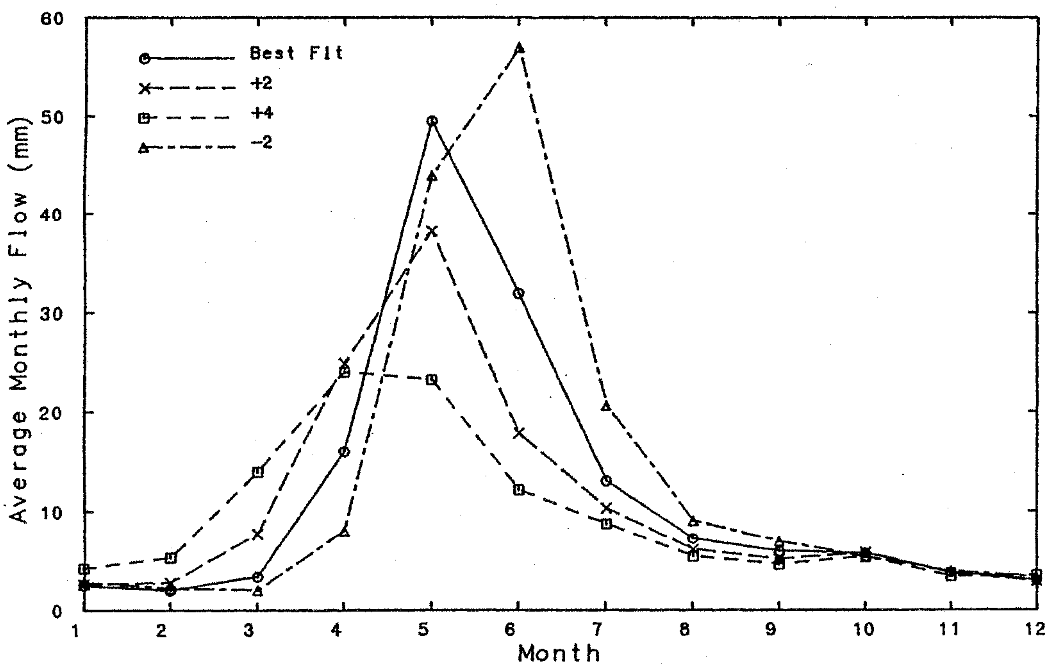

Figure 6. Simulated average long term (1974-1984) monthly streamflow for Lower Willow Creek, MT under normal conditions (best fit), a +2°C warming, a +4°C warming, and a -2°C cooling.

When SRM is used for simulation and forecasting, it is usually operated only during the snowmelt season. However, it is valuable to know how the flow will change year round and, in particular, how the relative distribution between the summer and winter half years will change under conditions of climate change. The present conditions on the Rio Grande basin are represented by the water year 1976, in which the runoff from October through March and the runoff from April through September constituted 14% and 86% of the annual runoff, respectively. A method was developed to predict the redistribution of the winter and summer runoff by any desired rise of temperature. The snow water equivalent on 1 April as evaluated from snow cover monitoring is reduced according to the smaller proportion of snow in the winter precipitation and the increased winter snowmelt due to higher temperatures. Climate adjusted depletion curves of snow covered areas derived from this reduced snow cover are used as an input variable together with temperature and precipitation in order to simulate the climate-influenced runoff from 1 October to 30 September. For a hypothetical temperature rise of +4°C, Figure 7 shows the winter runoff is approximately doubled from 14 to 30% and the proportion of the summer runoff decreases from 86 to 70%. The summer climate-adjusted hydrograph indicates time shifting of flow peaks and a redistribution of runoff in the respective months (Martinec et al., 1994b).

This approach assumes that the precipitation totals remain unchanged in a new climate change regime, mostly for simplicity and also because no firm estimates of the change in precipitation are available. Once the changes are better specified in GCM climate change scenarios, they would be easily input to any of the three hydrologic models being used.

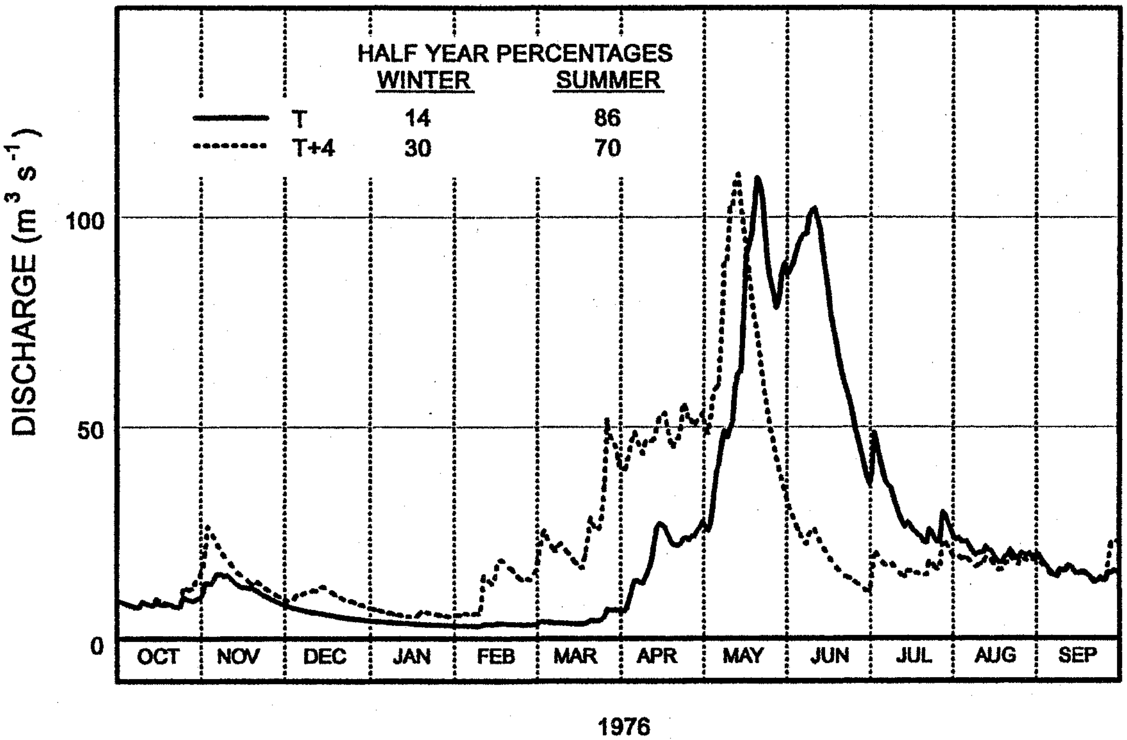

Figure 7. Comparison of winter and summer runoff in the Rio Grande Basin above Del Norte, CO as simulated by SRM with actual 1976 temperatures (T) and with temperatures increased by +4°C (T+4).

ADVANCES IN SNOWMELT RUNOFF MODELING

In the NWSRFS model, a fixed average monthly evapotranspiration curve is used for all years and elevation zones. ARS has attempted to account for the dynamic response of evapotranspiration in two ways. Evapotranspiration was estimated using daily temperature values and changes in streamflow were noted mostly because of a shift in timing of the evapotranspiration. The dynamic curve indicated that less evapotranspiration occurred in the early spring and late fall and more in the middle of summer than that shown by the fixed average monthly evapotranspiration values. Thus there was generally more water stored in the snowpack and available for runoff during the high melt and most productive early spring runoff period.

The second way that the dynamic nature of evapotranspiration was accounted for was consideration of the possibility of changing vegetation cover in response to a change in climate. As an example of a simulated average monthly hydrograph that includes both the effects of daily dynamic evapotranspiration conditions and a change in vegetation (conversion of upper zone forest to dry sagebrush vegetation) in response to a +4°C increase in temperature, Figure 8 for Lower Willow Creek is presented. Not only is the volume of streamflow reduced dramatically (-65%), but the peak flow occurs about two months earlier under this warmer and drier scenario (Cooley et al., 1992).

Progress has also been made with SRM which normally uses a simple degree approach for melting snow in a basin. A simple radiation component was combined with the degree-day approach (restricted degree-day method) in an effort to improve estimates of snowmelt and reduce the need to adjust the melt factor over the ablation season. Because radiation measurements are not often available, a simple model for simulating shortwave and longwave components of the radiation balance that requires minimal information (i.e., daily cloud cover estimates, air temperature, and relative humidity) was developed. It was found that clouds and their effects on daily insolation at the surface can produce significant differences between measured and model estimates. In comparisons of snowmelt and runoff estimates, the restricted degree-day approach yielded melt rates and runoff that were in better agreement with observed outflow than the degree-day method and were practically the same as those generated by a more rigorous energy balance method (Kustas et al., 1994).

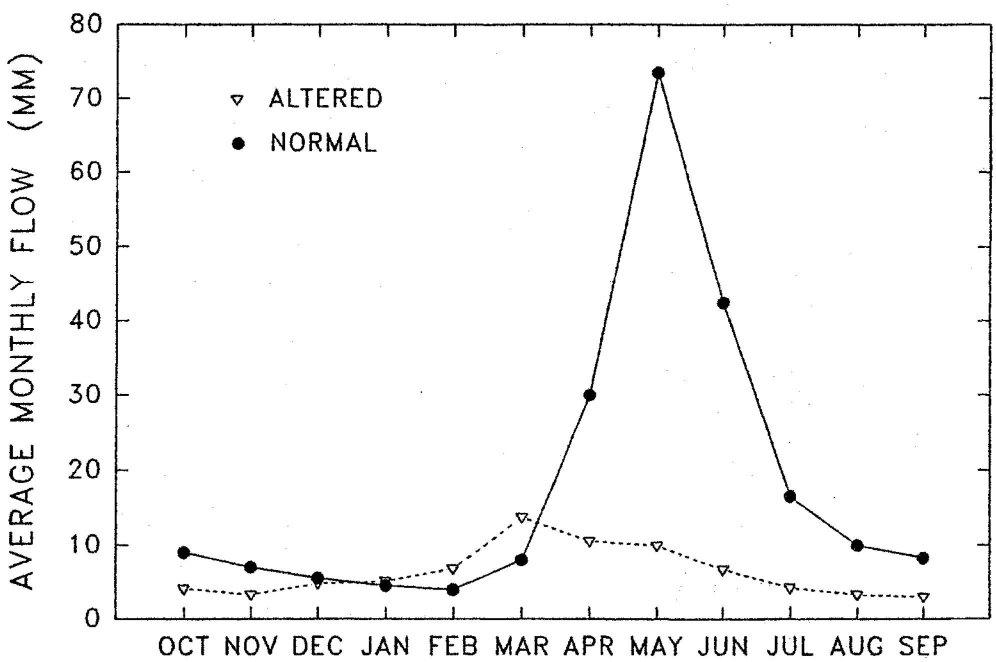

Figure 8. Simulated average monthly streamflow for Lower Willow Creek under normal climate and dynamic daily evapotranspiration, and under altered climate (as represented by the climate of a dry sagebrush site) and dynamic daily evapotranspiration.

INTEGRATION OF NEW TECHNOLOGIES FOR MODEL APPLICATIONS

Many new technologies and many new data types have become available in recent years which have relevance to both hydrologic modeling and climate change analysis. In order to use these new techniques most effectively, it is necessary to integrate the techniques or approaches into a common system. As an example, the Alpine Snow Cover Analysis System (ASCAS) has been developed for monitoring changes of snow cover distribution in mountainous regions as well as for the determination of snowmelt runoff and the evaluation of climate change effects (Rango and Baumgartner, 1994). Various modules comprising the important steps for accomplishing the above functions have been developed. The transfer of data between the different modules or software packages (i.e., image processing, geographic information systems, database management, hydrologic modeling, and scientific visualization) is essential for operational use of ASCAS. In its present form, ASCAS operates on a single personal computer where it is possible to run all software modules. This makes it possible for a small water resources agency, such as a hydropower company, to do runoff simulation and forecasting and climate change evaluations inhouse.

Because ASCAS employs geographic information systems and has access to digital elevation data, the basins under study can be subdivided in various ways. SRM typically subdivides watersheds on the basis of elevation zones, but it is now possible to produce hydrologic unit areas on the basis of both elevation and aspect which is more suitable for distributed hydrologic modeling. This capability of ASCAS makes it compatible with the new restricted degree-day approach of SRM discussed previously. After further development, the restricted degree-day version of SRM will be incorporated in ASCAS.

Another modular system, the Modular Modeling System (MMS) as developed by the USGS (Leavesly et al., 1992), is being used by ARS also. MMS has many of the same functions included in ASCAS but it was developed for different purposes. MMS is attempting to compile a library of hydrologic models where the appropriate model can be selected depending on the application. A further objective is to exchange model algorithms at different scales in MMS to construct new models appropriate for very specific problems. Such new models may be necessary in certain climate change evaluations.

INTERCOMPARISON OF SNOWMELT RUNOFF MODELS UNDER CONDITIONS OF CLIMATE CHANGE

It is extremely difficult to provide consistent and comparable estimates of the hydrologic response to climate change to operational water managers. This task is made especially difficult by the use of different GCM's and different GCM scenarios, different hydrologic models, different ways to address changes in model variables and parameters, and different operational applications and needs. The ARS held a workshop on this topic in 1993 in Santa Fe, NM (Gleick et al., 1994). It was decided that it would be valuable to conduct an intercomparison of snowmelt runoff models under conditions of climate change so that some consistent information could be supplied to operational water managers.

The results of the workshop can be summarized as follows:

1. Three to four test basins should be selected in Western North America.

2. Actual GCM runs in the regions represented by the selected basins should be used to impose conditions of climate change in low, average, and high runoff years.

3. Use various hydrologic models to generate hydrologic climate change scenarios for each basin.

4. Keep track of changes in model parameters, variables, and hydrologic response. Trace differences back to differences in model algorithms and model application.

5. Identify needed improvements in data or model procedures to provide the best possible information to managers, e.g., what improvements in precipitation inputs do we need?

A small working group is currently attempting to develop an approach to be used in conducting the project. Developers of major snowmelt runoff models will be invited to participate.

REFERENCES

Anderson, E.A., 1973. "National Weather Service River Forecast System - Snow Accumulation and Snow Ablation Model", NOAA Technical Memorandum NWS-HYDRO-17, U.S. Department of Commerce, Washington, D.C.

Cooley, K.R., 1990. "Effects of CO_2-Induced Climatic Changes on Snowpack and Streamflow", Hydrological Sciences Journal, Vol. 35(5), pp. 511-522.

Cooley, K.R., Flerchinger, G.N., and Hanson, C.L., 1992. "Effects of Climate Changes on Water Supplies", Proceedings of the International Symposium on Managing Water Resources During Global Change, American Water Resources Association, Reno, NV, pp. 185-194.

Gleick, P.H., Rango, A., and Cooley, K., 1994. "The Use of Hydrological Models for Evaluating the Impacts of Climate Change on Snowmelt Water Supply Basins", EOS Transactions, American Geophysical Union, Vol, 76(9), pp. 107.

Kustas, W.P., Rango, A. and Uijlenhoet, R., 1994. "A Simple Energy Budget Algorithm for the Snowmelt Runoff Model", Water Resources Research, Vol. 30(5), pp. 1515-1527.

Leavesley, G.H., Restrepo, P., Stannard, L.G., and Dixon, M., 1992. "The Modular Hydrologic Modeling System-MHMS", Proceedings of the International Symposium on Managing Water Resources During Global Change, American Water Resources Association, Reno, NV, pp. 263-264.

Martinec, J., Rango, A., and Roberts, R., 1994a. "Snowmelt Runoff Model (SRM) User's Manual", Geographica Bernensia, P. 29, Department of Geography, University of Bern, Switzerland, 65 pp.

Martinec, J., Rango, A., and Roberts, R, 1994b. "Modelling the Redistribution of Runoff Caused by Global Warming", Proceedings of the Symposium on Effects of Human-Induced Changes on Hydrologic Systems, American Water Resources Association, Jackson Hole, Wyoming, 9 pp.

Rango, A. and Baumgartner, M.F., 1994. "Data Transfer, Necessary Interfaces, and Applications in a Modular Snow Hydrology Modelling System", Proceedings of the International Symposium on Remote Sensing and GIS, American Society for Testing and Materials, San Francisco, CA.

Rango, A. and Martinec, J., 1994. "Areal Extent of Snow Cover in a Changed Climate", Nordic Hydrology, 11 pp.

U.S. Army Corps of Engineers, 1975. "Program Description and Users Manual for the SSARR Model", U.S. Army Corps of Engineers, North Pacific Division, Portland, OR.

van Katwijk, V.F., Rango, A. and Childress, A.E., 1993. "Effect of Simulated Climate Change on Snowmelt Runoff Modeling in Selected Basins", Water Resources Bulletin, Vol. 29(5), pp. 755-766.