Predictions for snow cover, glaciers and runoff in a changing climate

ALBERT RANGO[1] & JAROSLAV MARTINEC[2]
1 *USDA-ARS Jornada Experimental Range, 2995 Knox St., Las Cruces, New Mexico 88003, U.S.A.*
alrango@nmsu.edu

2 *CH-7270 Davos-Platz, Switzerland*

Abstract The problem of evaluating the hydrological effects of climate change has opened a new field of applications for snowmelt runoff models. The Snowmelt Runoff Model (SRM) has been used to evaluate climate change effects on basins in North America, the Swiss Alps, and the Himalayas. Snow covered area depletes about one month earlier in response to warmer temperatures (+4°C) with runoff peaks shifted accordingly. Runoff will be higher in winter at the expense of summer runoff. In glacerized basins, runoff is not only redistributed, but increased due to glacier melting. This improved knowledge facilitates long-term decisions concerning hydropower, flooding, water allocations, and water management in general.
Keywords climate change; snowmelt runoff modelling; runoff shifts; water management

NEW TASKS FOR SNOWMELT RUNOFF MODELS

The growing awareness of the problem of climate change opened a new field of applications for snowmelt runoff models. Originally designed to simulate and forecast the seasonal runoff, they should now be capable to predict snow cover and runoff in a distant future. Thanks to its deterministic approach, the SRM model has been easily adapted to this new task. In the present climate, it is run with the real seasonal snow cover monitored by satellites as one of the input variables. In a future climate, this snow cover is transformed by changed temperatures and precipitation according to any given climate scenario, so that the future runoff can be computed. The necessary amendments to the computer program were facilitated by the transparent structure of the model which had been made possible by taking into account the role of the subsurface runoff (Martinec & Rango, 1999). As has been pointed out by other investigators (e.g. Klemeš, 1985) hydrological models which depend on calibration of their parameters are not suitable for evaluations of the climate change effect. In the meantime, such studies have been carried out by the non-calibrated SRM model in different climate zones of North America, the Swiss Alps, and the Himalayas.

HYDROLOGICAL EFFECTS OF CLIMATE CHANGE

The effects of global warming, combined in some cases with changed precipitation, were evaluated in a wide range of basin size and altitude, as illustrated in Table 1. Various climate types are represented so that the runoff coefficient (runoff/ precipitation ratio in a hydrological year) varies from 0.25 in Rio Grande, 0.57 in Kings River and to 0.78 in Illecillewaet. With the exception of the Himalayan basins, runoff is dominated by snowmelt so that it occurs mostly in the summer half of the hydrological year (April-September).

Table 1 Characteristics of basins.

Country	Mountain Range	Basin	Size km^2	Elevation Range
U.S.A., Colorado	Rocky Mountains	Rio Grande	3419	2432-4215 m a.s.l.
U.S.A., California	Sierra Nevada	Kings River	4000	171-4341 m a.s.l.
Canada, British Columbia	Rocky Mountains	Illecillewaet	1155	509-3150 m a.s.l.
Switzerland	Alps	Upper Rhine	3249	562-3425 m a.s.l.
India, Bangladesh	Himalayas	Brahmaputra	547346	0-8848 m a.s.l.
India, Bangladesh	Himalayas	Ganges	917444	0-8848 m a.s.l.

Consequently, the hydroelectric plants, for example, in the European Alps and in Scandinavia, accumulate water in the summer and release it in the winter in order to meet the electricity demands. The situation is different in the U.S.A. with regard to the extensive use of air conditioning in summer. In any event, it is important for future reservoir operations to predict how the present runoff regime will be affected by the climate change, and in particular by global warming.

The present and climate-affected runoff volumes are compared in Table 2. The runoff computed with the present temperatures "T" agrees well with the measured runoff corrected for reservoir operation or water diversion (Rango & Martinec, 2000).

Table 2 Redistribution of runoff in a warmer climate.

Basin	October-March		April-September		Hydrological Year	
	10^6 m^3	%	10^6 m^3	%	10^6 m^3	%
Rio Grande 1979						
Computed T	91.87	7.6	1120.15	92.4	1212.02	100
Computed T+4°	146.76	12.3	1046.16	87.7	1192.92	100
Rio Grande 1976						
Computed T	93.22	13.1	616.52	86.9	709.74	100
Computed T+4°	192.95	28.1	494.80	71.9	687.75	100
Rio Grande 1977						
Computed T	63.56	24.3	198.17	75.7	261.71	100
Computed T+4°	77.34	29.2	187.42	7.8	264.76	100
Illecillewaet 1984						
Computed T	169.29	10.2	1495.56	89.8	1664.85	100
Computed T+4°	341.63	18.9	1465.32	81.1	1806.95	100
T+4°. P + 20%	383.55	18.3	1717.06	81.7	2100.59	100
T, P + 20%	185.91	9.5	1769.01	90.5	1954.92	100
Kings River 1973						
Computed T	428.78	17.1	2080.53	82.9	2509.33	100
Computed T+4°	973.66	37.2	1642.67	62.8	2616.33	100
Upper Rhine T, P, adapted for 1961-1990						
Winter: T + 2.1°, P+5%	872	22.5	3010	77.5	3882	100
Summer: T + 2.4°, P-10%	970	28.0	2491	72.0	3461	100

In a warmer climate, the winter runoff will be increased at the expense of the summer runoff. The magnitude of this effect varies from basin to basin and, as data for Rio Grande show, also from year to year (Rango & Martinec, 2000). In the Illecillewaet basin, a comparison of three hypothetical climate scenarios reveals that the annual runoff will increase in a warmer climate due to glacier melt (as long as glaciers last) and increase further should precipitation (P) become higher. The effect of P + 20% is greater than that of T+4°. In the Rhine basin, temperature and precipitation have been adapted for the period 1961-1990 in order to represent today’s climate better than a single year (Ehrler, 1998).

In the Himalayan basins (Seidel & Martinec, 2002), the major concern is summer floods. In a warmer climate, for example T+4° C, an increase of peak flows by 20-30% is indicated.

EVALUATION OF CLIMATE EFFECTS BASED ON A NORMALIZED YEAR

As data for Rio Grande in Table 2 show, results for these selected years point in the same direction (more runoff in winter), but are also influenced by specific conditions (snow covered areas, temperatures, precipitation) in each year. The present climate is better characterized by a "normalized" year, in which temperatures and precipitation correspond to long term averages (1957-1994), but their daily variations are taken over from a real year by the updated SRM computer program (Martinec *et al*., 2008). When the year 1979 in the Rio Grande basin is normalized (designated as 9979) the effect of a temperature increase T+4° C is greater than with the year 1979 (see Tables 2 and 3):

Table 3 Redistribution of runoff with the use of a normalized year.

Basin	October – March		April – September		Hydrological year	
	10^6 m^3	%	10^6 m^3	%	10^6 m^3	%
Rio Grande 9979						
Computed T	74.66	11.7	561.66	88.3	636.32	100
Computed T+4°	153.06	24.2	479.58	75.8	632.64	100

As a prediction of runoff conditions in a future year, these data are more realistic because the original year 1979 was unusual in two respects:

1. Extremely cold winter reducing the effect of a warmer climate.
2. Very high precipitation and snow accumulation resulting in a high runoff.

Runoff volumes in Tables 2 and 3 are totals of daily computed flows. The runoff peak is shifted from May to April. Each evaluation also predicts the future water equivalent of the seasonal snow cover on 1 April and the depletion curves of the snow covered areas in the subsequent months.

CLIMATE EFFECTS IN GLACIERIZED BASINS

The runoff increase in the Illecillewaet basin due to glacier melt with T+4° (Table 2) was computed with the present glacier area. However, this area will gradually decrease before the climate scenario will take place. Therefore the effect of a changed climate cannot be evaluated in one step. Glaciers must be modelled year by year using a stochastic series of temperatures and precipitation which reach the value of a climate scenario in the year in question. In the starting year, the depletion curves of the snow coverage and the glacier area must be known as well as temperatures and precipitation. From the computed glacier melt volume, the reduced glacier area for the next year is estimated by statistically derived relations between the volume and area of glaciers (Bahr *et al*., 1997). With this new glacier area, plus temperature and precipitation data, the glacier melt volume and the reduced glacier area for the next year are calculated. In a cold year, which can occur even in a warming climate, unmelted snow may prevent glacier melt and is carried over to the subsequent hydrological year. Sooner or later, the glacier melt will start again and the computation of the glacier decline can continue until the target year of the climate scenario or until he disappearance of glaciers, whichever comes first.

TEST OF PREDICTION RELIABILITY

Unlike weather or runoff forecasts, predictions of the hydrological effects of climate change, referring for example to the year 2100, cannot be compared with reality within a reasonable time. Therefore, the method was tested by “predicting” snow conditions and runoff not for a distant future year, but for an actual year with measured data.

Table 4 Runoff volumes in the Rio Grande basin.

Runoff	October-March	April-September	Hydrological Year
	10^6 m^3	10^6 m^3	10^6 m^3
Computed 1979	91.87	1120.15	1212.02
1977 Predicted by changed climate	49.92	244.05	293.07
1977 Measured	76.26	190.37	266.63

Daily temperatures and precipitation in 1977 were used as a changed climate for 1979 to "predict" the snow conditions and runoff in 1977. Data in Table 4 are a comparison between prediction and reality.

CONCLUSION

Modelling and prediction of the future climate-affected snow cover, of the decline of glaciers and of changed runoff regimes provide essential information for hydropower production, flood control, winter sport resorts, water allocation, and generally for water management.

REFERENCES

Bahr, D. B., Meier, M. F. & Peckham, S. D. (1977) The physical basis of glacier volume / area scaling. *Journal of Geophysical Research* **102**(B9), 20355-20367.

Ehrler, C. (1998) Climate change and alpine snow cover. *NFP 31*, ETH Zurich, Switzerland.

Klemeš, V. (1985) Sensitivity of water resources systems to climate variations. *WCP Report No. 98*, WMO Geneva.

Martinec, J. & Rango, A. (1999) Snowmelt runoff conceptualization based on tracer and satellite data. *IAHS Publ. No. 258*. 47-55.

Martinec, J., Rango, A. & Roberts, R. (2008) Snowmelt Runoff Model (SRM) User’s Manual (7th Edition). *New Mexico State University, Agricultural Experiment Station, Special Report* 100, Las Cruces, NM. USA

Rango, A. & Martinec, J. (2000) Hydrological effects of a changed climate in humid and arid mountain regions. *World Resources Review*. **12**(3) 493-508.

Seidel, K. & Martinec, J. (2002) NOAA/AVHRR monitoring of snow cover for modeling climate-affected runoff in Ganges and Brahmaputra rivers. EARSeL Workshop Bern, Switzerland, *EARSeL eProceedings* ***2***.