INCLUSION OF FROZEN GROUND EFFECTS IN A FLOOD FORECASTING MODEL[1]

Eric A. Anderson
Hydrologic Research Laboratory, U.S. National Weather Service

Patrick J. Neuman
North Central River Forecast Center
U.S. National Weather Service

INTRODUCTION

Across the northern portions of the conterminous United States, seasonally frozen ground can have a very significant effect on the amount of runoff produced during the winter and spring. Frozen ground effects are probably the greatest in the heavily agricultural basins of the upper Midwest. Here a lack of vegetation during the winter, shallow snow cover, and very cold temperatures produce optimal conditions for deep frost penetration.

Although quite a bit of research has been conducted on the hydrologic effects of frozen ground [Dingman, 1975, presents a good summary], most of the work has been either theoretical or based on point or small plot studies. None of the models used for river forecasting, to our knowledge, contain algorithms to estimate the amount of frozen ground and quantitatively determine the resulting runoff on a continuous basis. Molnau and Bissell (1983) have developed a continuous frozen ground index (CFGI) which is used to determine when frozen ground should affect runoff in agricultural watersheds in the Pacific Northwest portion of the United States. So far the CFGI has not been integrated into a forecasting model, but is used as a guide to predict the enhancement of runoff due to frozen ground conditions.

In 1980 the Hydrologic Research Laboratory (HRL), in cooperation with the North Central River Forecast Center (NCRFC), began a project to model the effect of frozen ground on runoff. In keeping with the models currently used for river forecasting and the availability of real-time data, the initial phase of the project is aimed at developing a conceptual type model using air temperature and snow cover as the only indices to energy exchange. A preliminary frozen ground model was developed; however, since HRL is spending a large portion of its resources on developing a new operational forecast system, the NCRFC has done most of the model testing. Most of the testing has been with historical data; however, the frozen ground model has also been tested for the past three winters as part of a field evaluation of the new operational system [Neuman, 1983]. Unfortunately, there has not been much frozen ground during the recent winters.

[1] For presentation at the Fifth Northern Research Basins Symposium and Workshop, March 19-23, 1984, Vierumaki, Finland.

This paper gives a brief evaluation of the preliminary model based on tests using historical data. Once the new operational forecast system is finished, a complete evaluation will be done and the frozen ground model will be modified as needed.

MODEL EQUATIONS

There are two main parts to the preliminary frozen ground model. First, is the computation of a frost index and second, is the modification of the rainfall-runoff model based on the frost index.

Frost Index

The empirical frost index (FI) is computed as:

$$FI_2 = FI_1 + \Delta FI \tag{1}$$

where FI is in °C and the subscripts refer to the beginning and end of a computational time interval. FI is always ≤ 0 °C. The change in FI is computed as:

$$(T_a < 0\ °C) \quad \Delta FI = - C \cdot \sqrt{T_a^2 + FI_1^2} - C \cdot FI_1 + H_c \tag{2}$$

$$(T_a \geq 0\ °C) \quad \Delta FI = C \cdot T_a + C_t \cdot P + H_c \tag{3}$$

where: $$C = C_g \cdot (1 - A_s) + C_g \cdot A_s \cdot (1 - C_s)^W \tag{4}$$

C_g = bare ground frost coefficient for a given time interval,

C_s = reduction in C_g per mm of snow water-equivalent,

A_s = areal extent of snow cover (decimal fraction),

W = snow water-equivalent (mm),

T_a = mean air temperature for the time interval (°C),

H_c = daily thaw rate from ground heat (°C),

C_t = thaw coefficient for water entering the soil (°C · mm^{-1}), and

P = water entering the soil during the time interval (mm).

A time interval of 6 hours was used in this study. Water-equivalent is used as an index to the insulating effect of the snow cover because the snow model being used [Anderson, 1973] doesn't include snow depth. The change in the frost index is depicted graphically in Figure 1 for the case where H_c and either C_t or P are zero.

Modification of Rainfall-Runoff Model

The frost index could be used with any rainfall-runoff model as an index to the amount of frozen ground that exists. In this study the rainfall-runoff

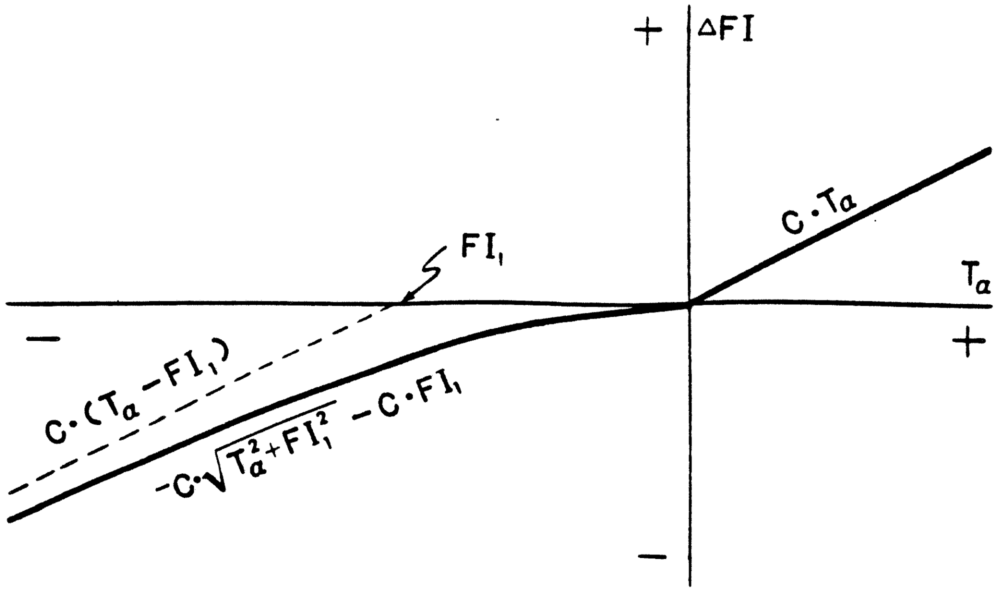

Figure 1. Graphical depiction of the change in the frost index (ΔFI) versus air temperature (T_a) with no ground heat or free water thaw.

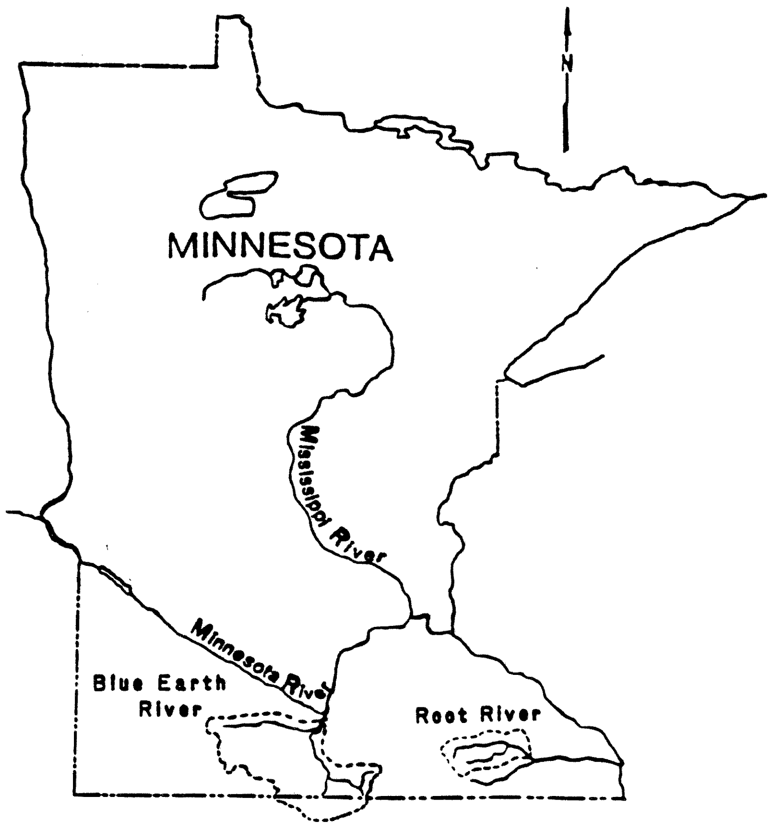

Figure 2. Map showing location of test basins.

model used is the soil moisture accounting (SMA) portion of the Sacramento Model [Burnash et al, 1973]. The frost index is used to reduce the percolation and interflow withdrawal rates. The reduction (R) in these rates is computed as:

$$R = R_s + (R_d - R_s) \cdot D_L^{x} \qquad (5)$$

where R_s is the reduction at saturated conditions,

$$R_s = (1 - C_r)^{FI_L - FI} \qquad (6)$$

FI_L = FI value above which there is no reduction in percolation or interflow withdrawal (°C),

C_r = reduction in percolation and interflow withdrawal per °C of FI below FI_L under saturated soil conditions,

R_d = 1.0,

D_L = lower zone soil moisture deficiency ratio (i.e. lower zone deficiency over capacity), and

x = exponent

The frost index can significantly reduce percolation and interflow withdrawal under saturated conditions, whereas there is no reduction under dry conditions. Some studies have even shown an increase in infiltration rates at dry conditions when the ground is frozen.

In the preliminary frozen ground model, the movement of water into the upper soil moisture zone is not affected by the frost index. As frost accumulates, moisture is held in the upper zone until its capacity is satisfied. Subsequent moisture input becomes surface runoff.

RESULTS

Two of the basins on which the preliminary frozen ground model has been tested are located in the southern part of the State of Minnesota. These are the Root River above Lanesboro (1593 km^2) and the Blue Earth River above Rapidan (6290 km^2). The locations of the basins are shown in Figure 2. Both basins are predominately agricultural with corn, soybeans, and other grains the major crops. The terrain is generally flat to rolling though there are gullies along the river in the eastern portion of the Root watershed.

The Root River responds quite a bit faster than the Blue Earth River because of its smaller size and steeper channel slopes. The time to peak under frozen ground conditions when surface runoff predominates is about 12 hours for the Root River as compared to about 3 days for the Blue Earth River.

The two data sets were compiled using precipitation and air temperature data from the U.S. climatological network. Observed mean daily discharge data were obtained from published records of the U.S. Geological Survey. The mean annual precipitation, potential evapotranspiration, and runoff are 700, 950, and 120 mm for the Blue Earth River and 750, 900, and 190 mm for the Root River, respectively. The mean monthly temperature for southern Minnesota varies from 21 °C in July to -12 °C in January. The average minimum temperature for January is -17 °C.

Root River

The Root River data set was originally prepared in the early 1970's for a model calibration workshop because it was one of the more difficult rivers to forecast in the Upper Midwest. The period of record used was water years 1964 through 1972.

As throughout the upper Midwest, the amount of frost and its effect on runoff varies greatly from year to year. During some winters snow accumulates early, thus insulating the ground. During other years the ground will freeze to depths of 1 to 2 meters before significant snow accumulates or rain occurs. Thus, modeling basins in this area without accounting for frozen ground is difficult and leads to generally poor results.

One of the first steps in calibrating the Root River was to make sure that the correct volume of snowmelt input was being computed. This was done by comparing the water-equivalent computed by the snow model to an estimate of areal water-equivalent based on observed point samples made prior to the main snowmelt period. Figure 3 shows that the computed values are quite reasonable.

Table 1 shows a statistical comparison of observed and computed mean daily flows both with and without using the frozen ground model. Figure 4 shows a comparison of observed and computed peak flows during the frozen ground and snowmelt periods. Figure 5 shows a comparison of daily flow hydrographs during the two winters when frozen ground had the largest effect on runoff. It is clear from these comparisons that the use of the preliminary frozen ground model significantly improves the results.

Table 1. Statistical comparison of models on the Root and Blue Earth Rivers for the entire period of record.

River	Model	NTD*	SD**	SM***
Root	Sacramento (no frozen ground)	.46	1.83	.63
	with Frozen Ground	.80	1.07	.42
Blue Earth	API	.61	1.42	1.00
	Sacramento (no frozen ground)	.66	1.25	.80
	with Frozen Ground	.81	1.0	.73

*NTD = coefficient of determination for daily flows
**SD = standard error/mean observed (daily flows)
***SM = standard error/mean observed (monthly volumes)

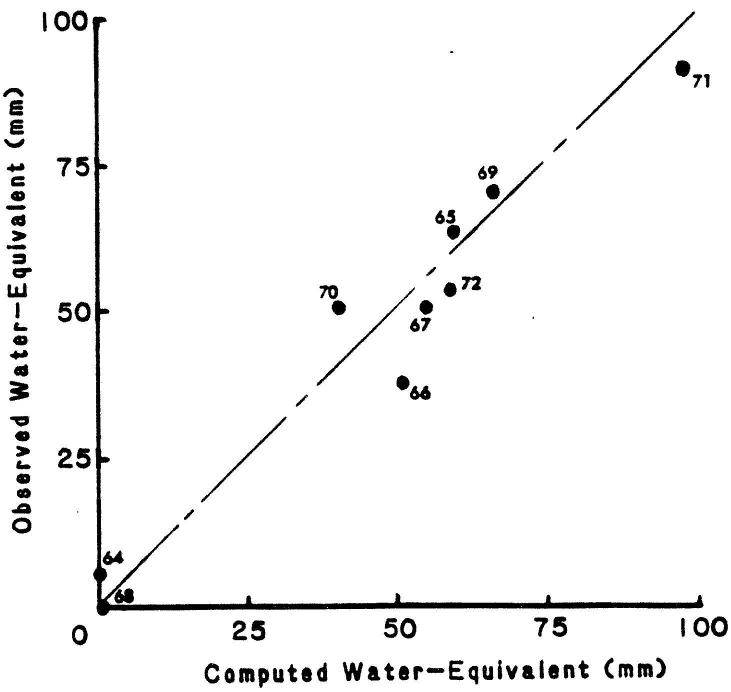

Figure 3. Comparison of snow water-equivalent prior to the main snowmelt period for the Root River (points are labeled by year).

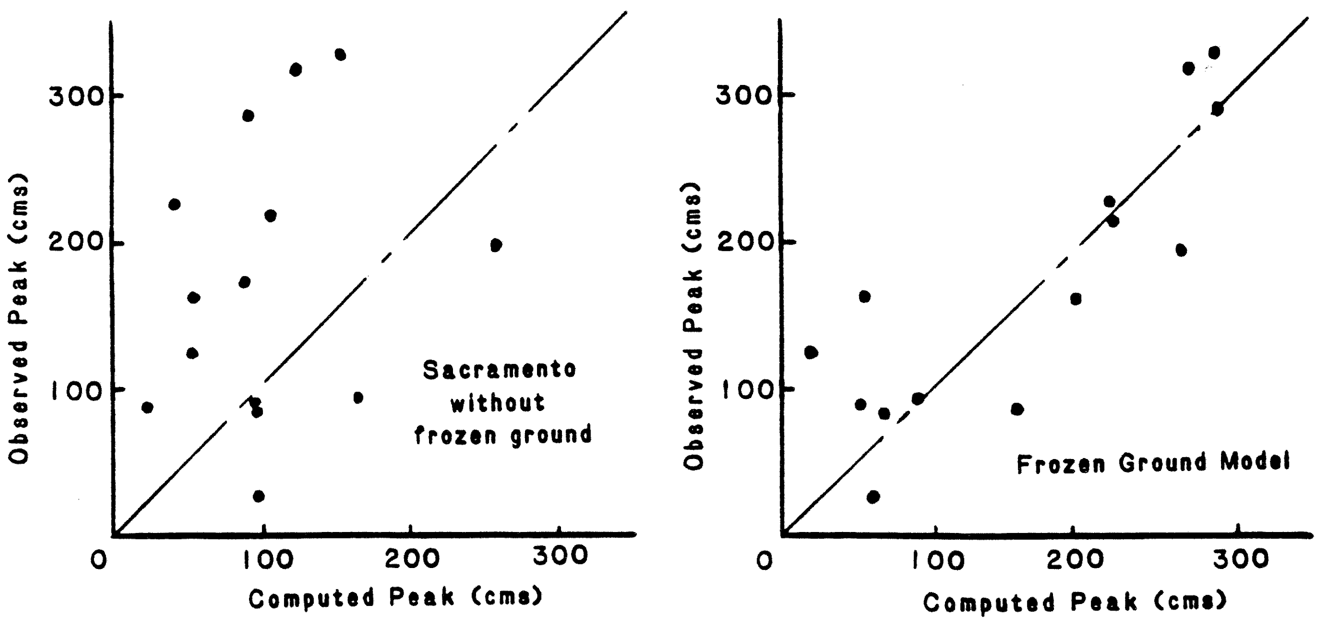

Figure 4. Comparison of major frozen ground and snowmelt runoff peaks on the Root River.

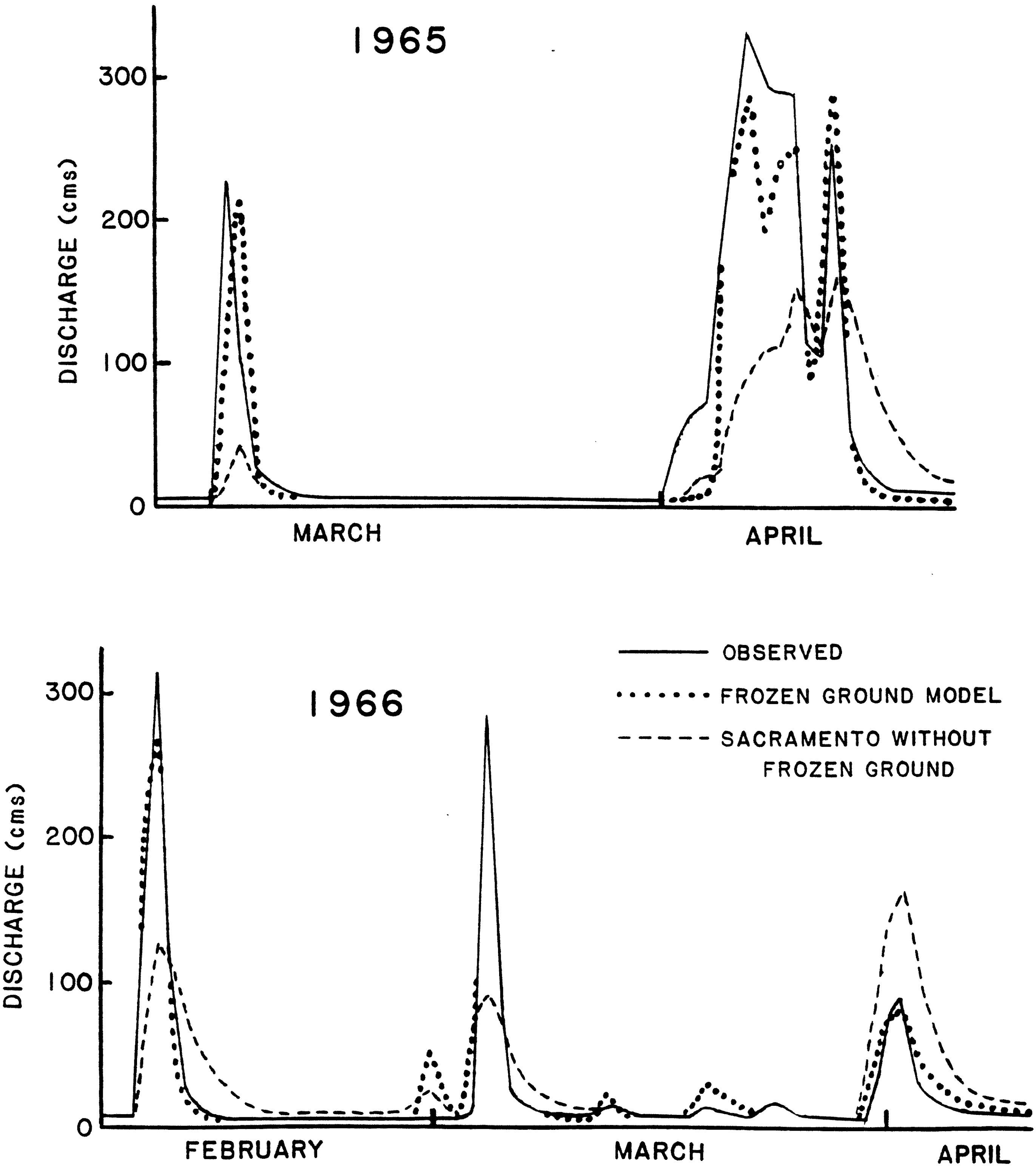

Figure 5. Hydrograph comparisons for the Root River during the two winters when frozen ground had the largest effect on runoff.

In order to evaluate the form of the frost index used in the preliminary model, a comparison was made between the frost index and frost depth. The best frost depth information available, that covered the entire period of record, was in the Wisconsin Snow and Frost Depth Report [Peterson et al., 1963]. This report is published two to three times per month during the winter. The map of frost depth given in each report is based on data collected from funeral directors and cemetery officials throughout Wisconsin. Even though the Root River is in Minnesota (about 75 kilometers from the Wisconsin border), it seemed like a comparison with the adjacent Wisconsin frost depth estimates would be valuable. Figure 6 shows a comparison between the computed frost index and the frost depths extrapolated from the Wisconsin data. In most years the comparison is quite satisfactory. Major differences occur in early 1964 and during 1972. There was little runoff in 1964, but the 1972 runoff, as well as a point frost depth sample just north of the watershed, indicates that frozen ground conditions existed in spite of a moderate snow cover, in terms of water-equivalent, throughout the winter. The water-equivalent of the snow cover kept the frost index from accumulating in the model during 1972. Climatological data show that the snow depths in 1972 were considerably less than for 1969 and 1970, which had similar amounts of water-equivalent, indicating a high snow density throughout much of 1972.

Blue Earth River

The period of record used for the Blue Earth River was water years 1962 through 1976. The Blue Earth River, just like the Root River, was modeled using the Sacramento SMA Model both with and without accounting for frozen ground. The Blue Earth River was also modeled using the Antecedent Precipitation Index (API) rainfall-runoff model that is currently used operationally at the NCRFC. The API model [Kohler and Linsley, 1951] is an empirical procedure that uses the week of the year to account for seasonal effects. Since significant frozen ground doesn't exist every winter, the API model tends to under-forecast during years with frozen ground and over-forecast during other winters. In operational use, the forecaster tries to compensate for this condition by subjectively adjusting the model prior to runoff periods.

Table 1 contains model statistics for the three models used on the Blue Earth data set. Figure 7 shows a comparison of snowmelt season peak flow errors for each year for each of the three models. The value of the observed peak is tabulated to show the magnitude of the runoff for each year. Also, the minimum frost index is tabulated as an indication of whether significant frozen ground existed. As expected, the API model tends to undercompute the peak during years with a large negative frost index and overcompute the other years. The Sacramento SMA model without frozen ground badly underestimates the peaks during the large frozen ground floods of 1962 and 1965. Figure 8 shows a comparison of the daily flow hydrographs for the 1965 flood. As can be seen in both figures, the use of the frozen ground model improves the results.

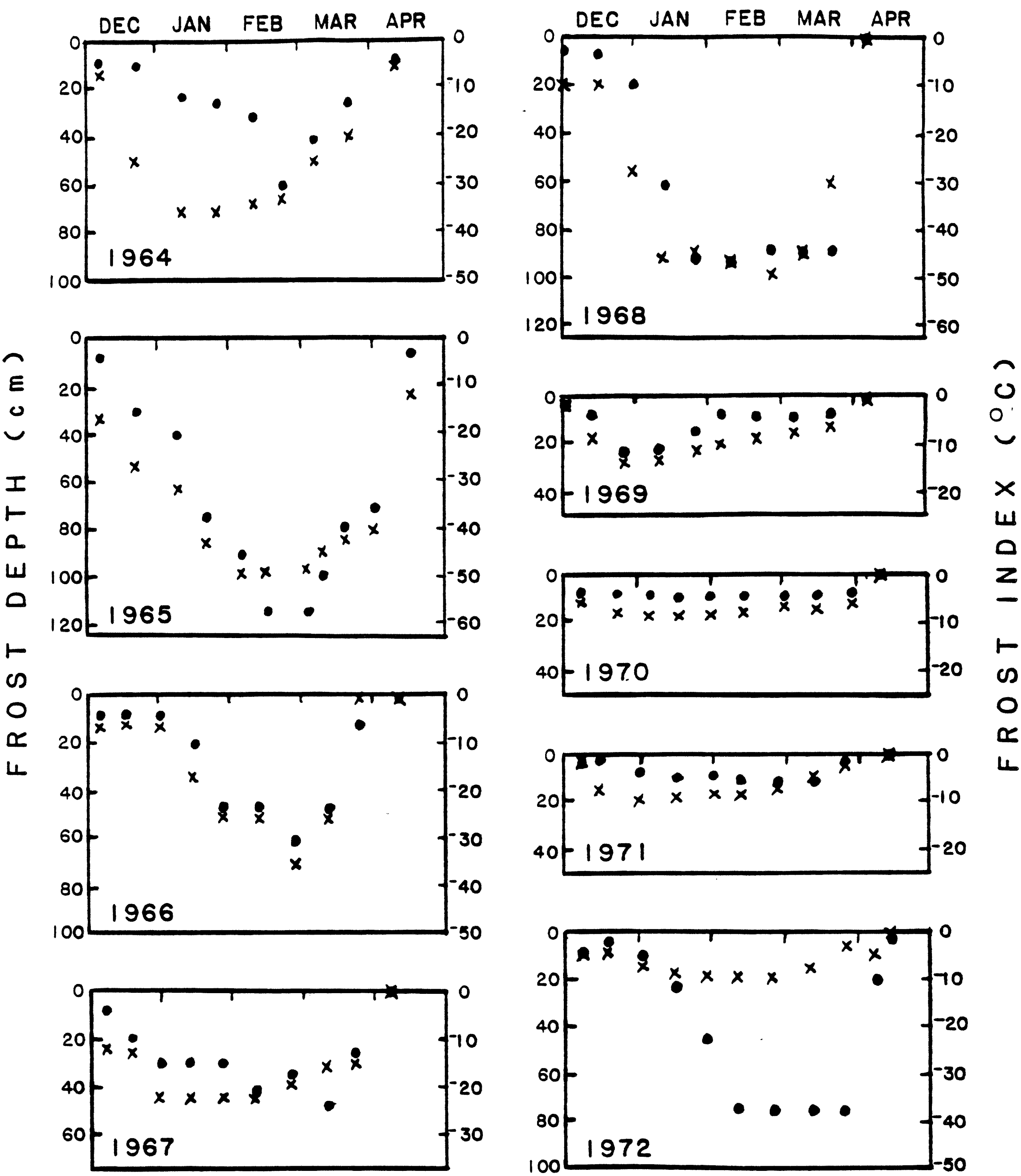

Figure 6. Comparison of the computed frost index (x) with measured frost depth (●) for the Root River.

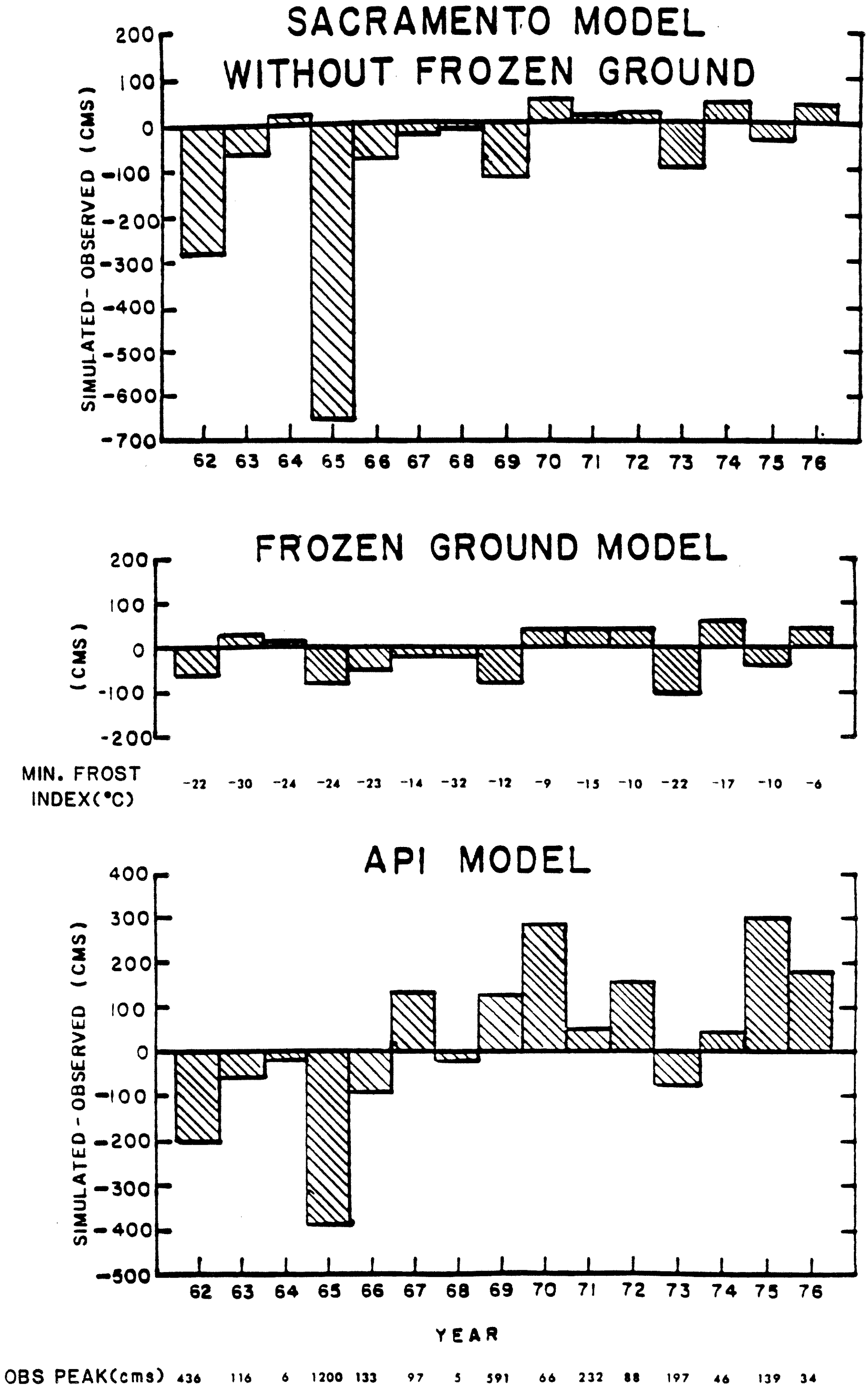

Figure 7. Comparison of maximum observed daily discharge during the snowmelt season with the simulated peaks for various models on the Blue Earth River.

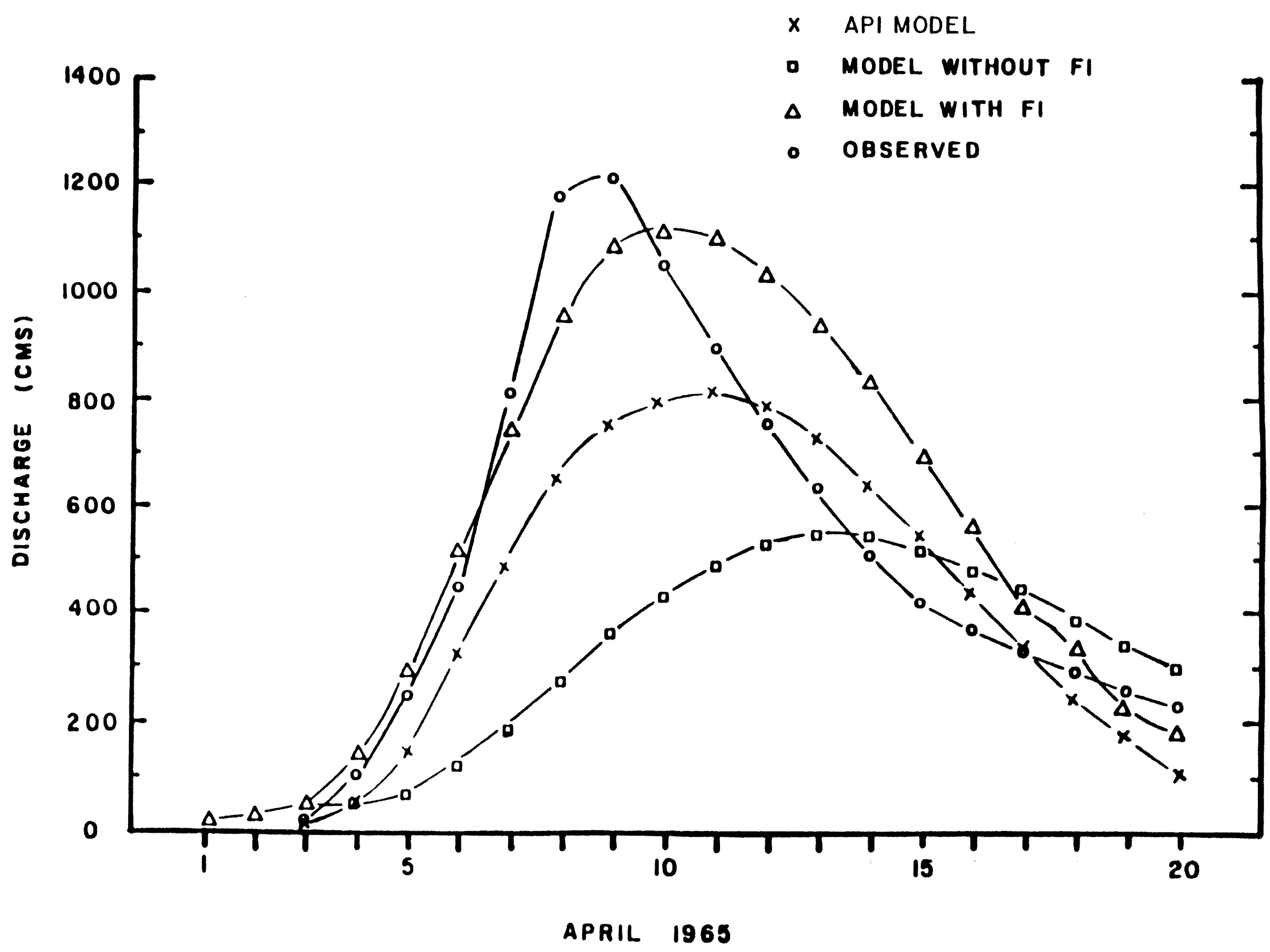

Figure 8. Comparison of results for the 1965 flood on the Blue Earth River.

SUMMARY

The test results from the preliminary frozen ground model on the Root and Blue Earth Rivers indicate that the model can significantly improve the simulation of runoff during periods when the ground is frozen. Even though these results are promising, there is some additional work that needs to be done before the first phase of the frozen ground modeling project is completed. In addition, the results also suggest further studies that are needed.

Completion of Frost Index Frozen Ground Model

When the preliminary model was developed, there was no effort made to control the number of parameters. The idea was that testing of the model would determine if some of the parameters could be eliminated or at least fixed as constants and whether new parameters would be needed. Table 2 gives the calibrated values of the parameters for the Root and Blue Earth Rivers. The values are quite similar. On the Root River the values of C_g and C_s were increased to provide a greater difference between the frost index during years with and without a snow cover throughout the winter. On the Root River, where there were more significant rain-on-frozen ground events, the use of C_t caused the frost to thaw faster than the frost depth data and the hydrograph indicated. Some further testing is still needed before finalizing which frozen ground model parameters will be kept and which will be set to a constant or eliminated.

Table 2. Frozen ground model parameter values for the Root and Blue Earth Rivers.

River	C_g	C_s	H_c	C_t	C_r	FI_L	x
Root	.10	.08	.12	0.	0.4	-3.	8.
Blue Earth	.05	.05	.10	0.2	0.4	-2.	8.

The current frost index uses water-equivalent to determine the insulating effect of the snow cover. The insulating effect of the snow could be better estimated if snow depth data were also used, since the thermal conductivity of snow varies considerably with density. The snow model could be modified to compute a continuous estimate of depth for use with the frost index. This would alow the frost index to accumulate more rapidly when the snow cover is very dense and slower when there is fresh, low density snow.

Even though the current frost index seems to give satisfactory results, it might be a good idea to test other indices such as the CFGI. There also needs to be some further testing of the model on watersheds in other areas where frozen ground effects runoff. Testing is needed in areas where freezing and thawing can occur several times thoroughout the winter. Testing in permafrost areas might also be interesting though the model was developed primarily for areas with seasonally frozen ground.

So far, the frost index frozen ground model has been used with the Sacramento SMA Model. The frost index could also be used with other rainfall-runoff models, such as the API model, to account for the effect of frozen ground on runoff.

Future Studies

Further improvements in the modelling of runoff from areas with frozen ground, beyond those attainable using a frost index, are probably going to require a more physically based approach. The next step might be to develop a simple heat transfer procedure for computing the energy flux into or out of the ground, as well as the frost and thaw depths. Such a procedure would require knowledge of the depth and density of the snow cover plus the amount of moisture in the soil.

The development of a more physically based frozen ground model would also require a more extensive data set to test the model. In order to make sure that the components of the model were working correctly and to allow for a better understanding of model errors, a research basin in an area with significant frozen ground effects would be needed. The research basin would need a good basic data network including measurements of energy exchange variables, plus detailed information on snow cover, soil moisture, soil temperature, river ice, and frost and thaw conditions.

The use of the frozen ground model, even in its current form, increases operational real-time data requirements. Snow cover conditions must be monitored throughout the winter since an over or underestimation of the snow cover will affect the frost index. Whereas, errors in snow accumulation can be corrected just prior to runoff by making measurements of the snow cover, the frost index needs to be kept up-to-date throughout the winter. A procedure to objectively update the frost conditions would be helpful, but would probably require a network of frost depth or soil temperature sensors that report in real-time.

The frost index frozen ground model, when completed, should improve flood forecasting capabilities in the upper Midwest and other areas where seasonally frozen ground affects runoff. However, there is much more that can be done to bring about further improvements.

REFERENCES

1. Anderson, Eric A., 1973: "National Weather Service River Forecast System--Snow Accumulation and Ablation Model," NOAA Technical Memorandum NWS HYDRO-17, U.S. Dept. of Commerce, Silver Spring, Md., 217 pp.

2. Burnash, Robert J.C., Ferral, R. Larry, and McGuire, Richard A., 1973: "A Generalized Streamflow Simulation System," Joint Federal-State River Forecast Center, Sacramento, Calif., 204 pp.

3. Dingman, S. Lawrence, 1975: "Hydrologic Effects of Frozen Ground," Special Report 218, Cold Regions Research and Engineering Laboratory, Hanover, N.H., 55 pp.

4. Kohler, M.A., and Linsley, R.K., 1951: "Predicting the Runoff from Storm Rainfall," U.S. Weather Bureau Research Paper 34.

5. Molnau, Myron and Bissell, Vernon C., 1983: "A continuous Frozen Ground Index for Flood Forecasting," Proceedings of the Western Snow Conference, P.O. Box 14884, Spokane, Wash., pp 109-119.

6. Neuman, Patrick J., 1983: "The Use of the National Weather Service River Forecast System for Modeling Frozen Ground in the Minnesota Basin," Preprints for the Fifth Conference on Hydrometeorology, Oct. 17-19, 1983, Tulsa, OK, sponsored by the American Meteorological Society, pp. 43-49.

7. Peterson, A.E., Burley, M.W., and Caparoon, C.D., 1963: "Frost Depth Survey: A New Approach in Wisconsin," revised from Weatherwise, April 1963.