USACRREL'S SNOW, ICE, AND FROZEN GROUND RESEARCH AT THE SLEEPERS RIVER RESEARCH WATERSHED

T. Pangburn and H.L. McKim
U.S. Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755

ABSTRACT

The Sleepers River Research Watershed in Danville, Vermont, has one of the longest historical data bases for a cold regions area. NOAA/NWS have been conducting research in snow hydrology at the watershed for the past 24 years; CRREL has been involved for the past 6 years.

CRREL's major research involves: 1) developing and testing a sensor that will measure the water equivalent of snow in near real time, and 2) modifying existing hydrologic models to accept remotely obtained data on snow, ice, and frozen ground.

INTRODUCTION

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) has been conducting research at the Sleepers River Research Watershed in two major areas over the past several years. These areas are: 1) developing and testing hydrometeorologic sensors in cold regions environments for near-real-time data collection, and 2) modifying existing hydrologic models to accept in situ and remotely obtained data on snow, ice, and frozen ground.

BACKGROUND

The Sleepers River Research Watershed (SRRW) in Danville, Vermont, has one of the longest historical data bases for a cold regions area. It was started in 1957 by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture. This 43 $mi.^2$ watershed was chosen by ARS over many alternative sites as the most representative of glaciated northern upland regions. The main drainage point (W-5, Fig. 1) is located at longitude 72°02'22"W and latitude 44°26'04"N. ARS maintained as many as 16 major stream gauging sites and 33 meteorological sites at one time. The length of the historical record, the subdivision, and the number of control points are unique. In 1966, the Office of Hydrology of the National Weather Service, NOAA, joined ARS in a cooperative snow hydrology study (Anderson et al., 1977). The purpose of the study is to better understand the processes involved in snow metamorphosis and snowmelt for collection of data for the NWS Hydrologic Research Laboratory Study, "Snow Accumulation and Ablation Conceptual Model." The W-3 subwatershed and the NOAA Snow Research station (W-3, R-3, Fig. 1) within the SRRW are a major part of this program and remain an excellent site for studying cold regions hydrology. As an indication of the importance of this data set, it was chosen by the World Meteorological Society as one of six high-quality data sets for the WMO project on the Intercomparison of Models of Snowmelt Runoff (World Meteorological Organization, 1982). In September of 1979, ARS discontinued research at the SRRW. CRREL began research within the SRRW in winter 1978-79 and, in October of 1979, NWS/NOAA and CRREL entered into a support agreement for joint operation of the SRRW. Since then, several other institutions and agencies have performed research at the SRRW.

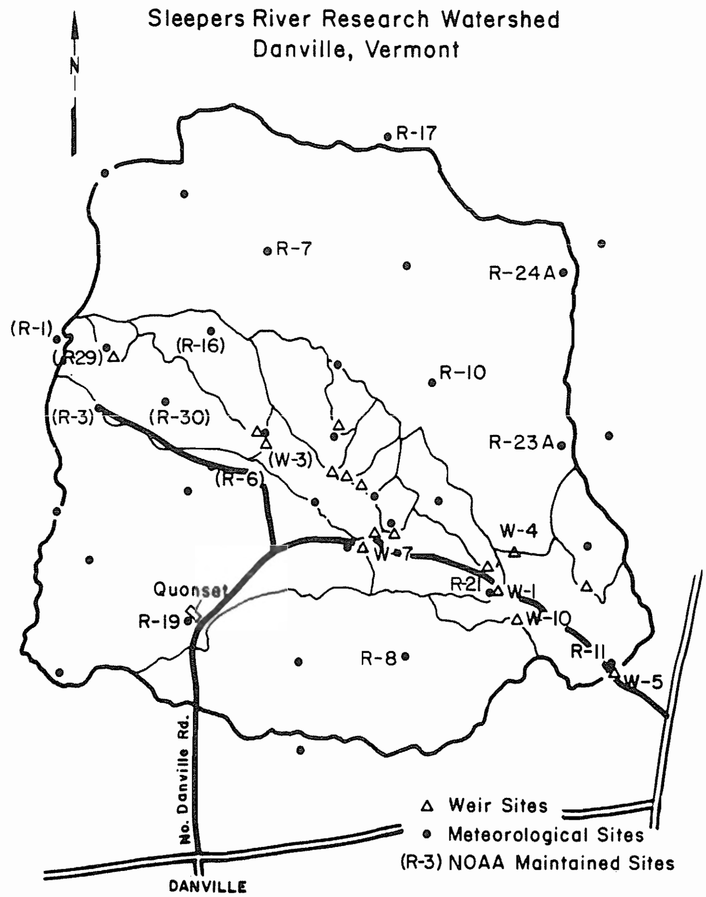

Figure 1. Sleepers River research watershed.

HYDROMETEOROLOGIC SENSORS

The hydrometeorologic sensors that CRREL has tested at the SRRW can be classed in these areas:

- Water equivalent of the snowpack - load cell triangle
- Soil moisture/soil frost - tensiometer/transducers and frost tubes
- Water current and stage recorders - mechanical and electromagnetic current meters and mechanical and acoustic stage recorders.

Water Equivalent of the Snowpack

Numerous researchers have remotely monitored the water equivalent of the snowpack using fluid-filled pressure-type snow pillows (i.e. Cox et al., 1978; Samuteford, 1976; Anderson et al., 1977). In a few specific instances the pressure-type snow pillow has effectively monitored the water equivalent of the snowpack, but in general, the performance of the snow pillow has not been of sufficient quality to accurately measure the water equivalency. The problems generally encountered are:

- Bridging of the snowpack above the snow pillow
- Butyl-rubber pillow is susceptible to damage
- Bedding of pillow is susceptible to heaving
- Leakage of reservoir fluid causes capillary wicking and gives erratic readings

- Air entrapment in pillow and transducer lines - causes erratic readings and displacement of zero reference
- Installation is difficult
- Storage of heat in pillow reservoir can decrease the snowpack above the snow pillow
- Limitation of moisture and temperature transfer between soil and snowpack, which changes the natural condition of the snowpack.

The first problem, bridging due to ice layers within the snow pack, has caused the most discrepancy between snow survey and snow pillow measurements. This is a major problem, especially in the eastern U.S.,where rain-on-snow events occur frequently, and during the melt season when the diurnal temperature patterns cause several ice layers to form within the snowpack. Ice layers form a "bridge" that effectively separates the snow above the "bridge" from the measured snow-water equivalent at the snow pillow.

At the NOAA Snow Research Station, CRREL has installed a load cell triangle (Pangburn and Pratt, 1980), which has solved some of the problems encountered with the snow pillow. This device is composed of a rigid triangular platform (reinforced plywood) positioned upon three strain gauge type load cells (Fig. 2). The rigid platform of the load cell triangle is not as susceptible to damage as a butyl-rubber snow pillow and it is relatively easy to install. None of the hydraulic problems of the snow pillow, i.e. air entrapment, storage of heat within the fluid reservoir, and leakage of reservoir fluid, are experienced with the triangular load cell design. However, bridging and limiting transfer of moisture and temperature between the ground and the snowpack are problems that the triangular load cell does not readily solve by design. The electrical outputs of the load cells are conditioned to supply a single output, which is set to produce a full-scale output of 5 volts when a weight equivalent to 10 inches of water is on the platform. The triangular load cell is interfaced to a data collection platform (DCP). A value of snow-water equivalent is measured every 4 hours (six readings per day). This data is stored in the DCP and then telemetered daily by the Geostationary Operational Environmental Satellite (GOES) to a NOAA "downlink" station at Wallops Island, Virginia. The data are trans-

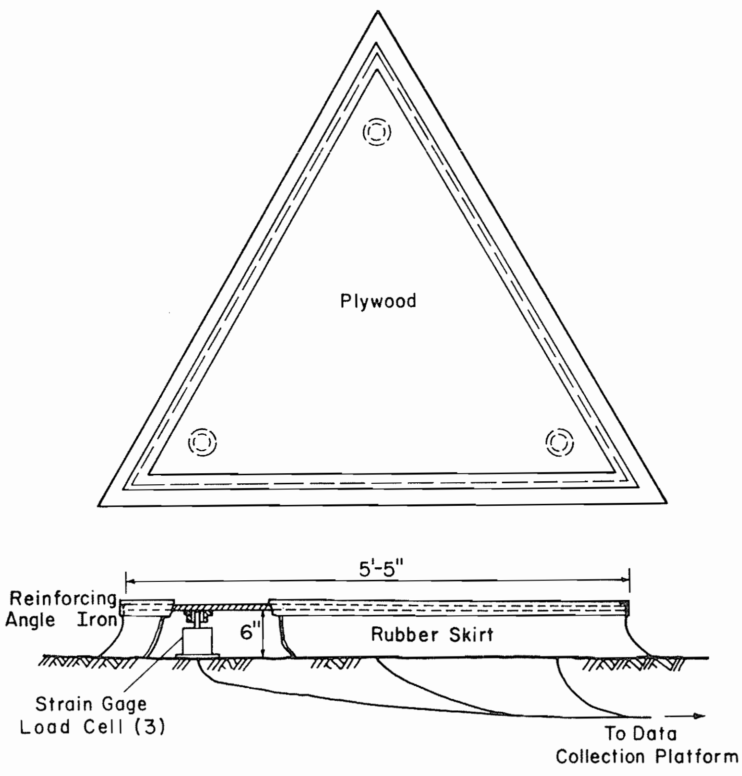

Figure 2. Load cell triangle snow-water equivalent sensor.

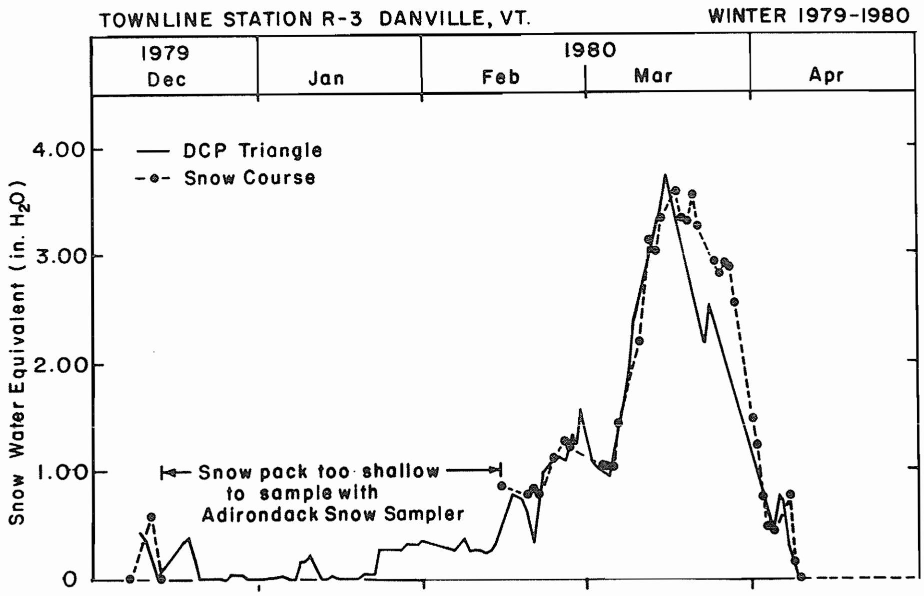

Figure 3. Load cell triangle data.

ferred via dedicated high-speed land-line links to a central data distribution facility in the World Weather Building in Maryland. Data is then accessed by CRREL via a telephone modem. Figure 3 shows data from the 1979-80 winter season, comparing the triangular load cell to manual snow course measurements. The snow load triangle has been redesigned for the 1984-85 winter season. The triangle's surface will be installed at the ground/snow interface and different load cells and other materials will be used to decrease the cost per unit. In the future a permeable material, such as GORE-TEX™, will be used in place of the plywood platform to decrease the load triangle's effect on moisture and temperature transfer between the ground and snowpack.

Snow Moisture/Soil Frost

Tensiometer/transducer systems have been used to measure pore-water pressure under unfrozen conditions for many years (Klute and Peters, 1968; Watson, 1967). The pore-water pressure is related to the volumetric soil moisture content through a moisture retention curve. In more recent years (McKim et al., 1976) a remote-reading tensiometer/transducer system has been developed for use in subfreezing temperatures. At the SRRW five of these systems were installed at R-3, R-10, R-17, R-19, and R-21. Each site consists of three tensiometer/transducers and three ground-temperature thermistors. A tensiometer/transducer and thermistor were installed adjacently at three depths -- 6 in., 18 in., and 36 in. The systems are interfaced to a GOES DCP. Data is collected every 4 hours by the GOES DCP and is transmitted daily. These systems have operated properly in the field over several winter seasons. Figure 4 shows the temperature and soil water tension data from the 18-in.-deep system at the R-3 site for January 1980. The tensiometer/transducer system generally operates throughout the winter season. However, with the onset of subzero temperatures and ground frost (22-23 January, Fig. 4), which causes increased pressure due to ice formation, tension decreases rapidly and returns to its general trend 3-4 days later. This 3-4 day interruption in the trend may be attributed to the length of time that the freezing front takes to traverse completely the length (5 cm) of the porous ceramic tip of the tensiometer. The rate of movement of the freezing front is consistent with established values for frost penetration (Haugen, personal communication, 1984).

To obtain a better understanding of the spatial and temporal variability of frost depth within the SRRW, CRREL installed 36 methylene blue frost gauges (Brown and Rickard, 1972) within the W-3 subwatershed during the winter of 1983-84. These frost gauges were installed with respect to the factors of cover type, aspect, and elevation. The experiment was designed so that the variability of frost depth could be determined within and among cover types.

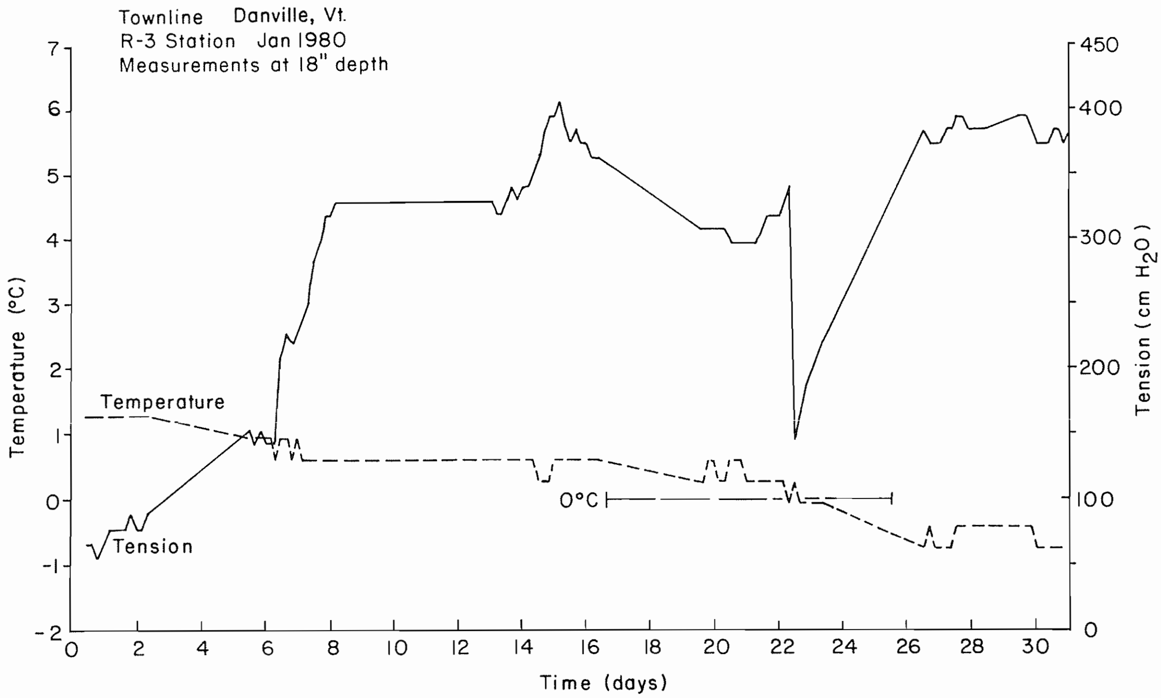

Figure 4. Tensiometer/transducer soil tension and thermistor soil temperature data.

Water Current and Stage Recorders

At the Sleepers River Research Watershed the concrete V-notch weirs have well-defined open water rating curves; during winter the weir notches are kept open manually. Stream gauging measurements have seldom been made under an intact ice cover. A test has been carried out on the moving carriage of USACRREL's Ice Engineering Test Basin (Pangburn, 1983) to determine the accuracy of current meters in subzero temperatures. The test used three types of current meters: cup-type, propeller-type, and electromagnetic meters. The analysis showed that the cup-type meters held true to their calibration where the other meters showed pronounced effects of temperature. In the future these meters, along the others, will be tested at the SRRW to determine the most acceptable field current metering system for use under ice covers.

COLD REGIONS RUNOFF MODELING

Using the data base of the SRRW, the U.S. Army Streamflow Synthesis and Reservoir Regulation (SSARR; U.S. Army Corps of Engineers, 1972) model has been modified to simulate runoff within the cold regions environment. The SSARR model is first calibrated for warm periods and is then modified to capture cold regions effects on runoff prediction.

SSARR Model Calibration for Warm Periods

All discussions of the initial hydrologic model of the W-3 subwatershed are based on initial work by Stokely (1980), who designed and implemented a DYNAMO watershed model based on the generalized watershed portion of the SSARR model (U.S. Army Corps of Engineers, 1972). Stokely (1980) used the basic equations taken directly from SSARR model documentation. As precipitation falls on the watershed, it is initially divided between runoff and soil moisture based on a table of percent runoff (ROP) versus the soil moisture index (SMI) (Fig. 5). Water that does not run off is stored as soil moisture. Soil moisture is depleted by potential evapotranspiration, using daily observed pan evaporation, which is reduced as the soil moisture volume becomes less. The total runoff is then apportioned between baseflow, subsurface flow, and surface flow. The amount of water that

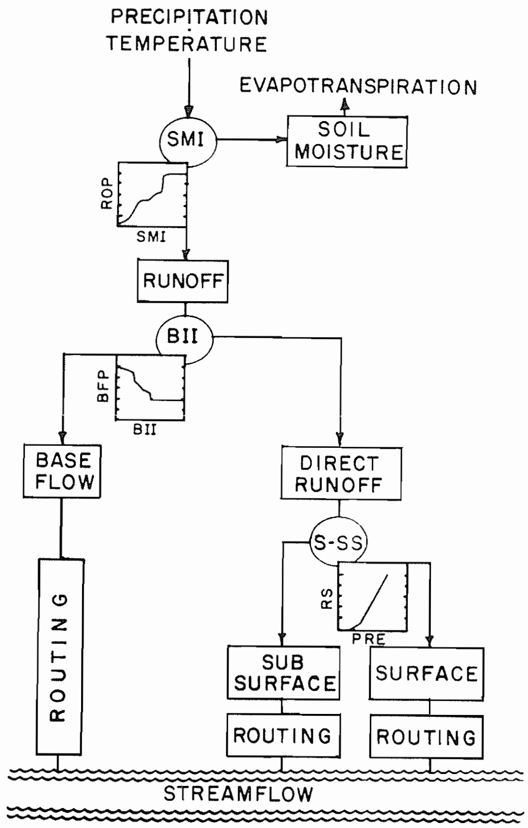

Figure 5. SSARR model schematic.

percolates to baseflow is defined by a table. Percolated water is subtracted from precipitation, after soil moisture requirements are satisfied, by a table of values that relates the percent of total runoff (BFP) that becomes baseflow to the baseflow infiltration index (BII) (Fig. 5). The BII value is a model state that is updated as a function of time. The rate of change of BII with time is governed by a time constant.

After baseflow has been subtracted from runoff, the remaining volume, direct runoff, is the sum of subsurface generation and surface flow generation. In the original SSARR model (U.S. Army Corps of Engineers, 1972), surface flow is determined as a surface-subsurface separation function of the direct runoff. This function is generally some minimum percent of the direct runoff, plus an additional percent if the direct runoff exceeds the maximum subsurface input rate. Stokely (1980) adjusted the surface-subsurface separation function based on the fact that there is seldom an observation of surface flow at the SRRW (Dunne and Black, 1977). He made surface flow (RS) a function (Fig. 5) of the precipitation rate (PRE) with surface flow only occurring when PRE exceeded published values of the average infiltration capacity of SRRW soils (Pionke et al., no date). Once base-, subsurface, and surface flows are generated, SSARR uses a routing method to delay and smooth quantities of flow to the stream. In general, linear storage routing is used, based on the continuity equation for any number of phases for each of the three flow types. By varying the number of phases and the storage coefficients (routing constants) for each flow type, considerable freedom exists in shaping a flow hydrograph predicted for the model. Stokely (1980) calibrated the model for summer periods and found that a single reservoir or phase sufficed for each flow type for the W-3 subwatershed. The time constants for surface flow, subsurface flow, and baseflow were found to be 2.5, 5, and 243 hours, respectively. Using these time constants to determine the outflow from each reservoir, stream flow is defined as the sum of the three outflows.

With the tables and parameters available, the calibrated SSARR model must be supplied with the necessary input data. Initial values must be specified for baseflow infiltration

(BII) and soil moisture (SMI) indices as well as initial values in the baseflow and subsurface and surface flow reservoirs. SMI is specified using actual point volumetric soil moisture data averaged over the subwatershed using a Theisson polygon analysis. The initial value of SMI is obtained by multiplying the average thickness of the A-horizons of soils in the subwatershed (Poinke et al., no date) by the actual volumetric moisture content. When periods of simulation are chosen such that they are preceded by periods of dryness, the initial volumes of the surface flow and subsurface reservoirs as well as the BII are initialized as zero. The initial volume of the baseflow reservoir may be calculated using the observed initial flow and the baseflow routing constant (243 hrs). The input data required are the hourly weighted basin precipitation and the daily pan evaporation measurements. In the absence of daily pan evaporation, mean values of seasonal evapotranspiration may be used.

To fine-tune the model, two different statistics are used to measure the model efficiency. The first is the Nash-Sutcliffe (1970) coefficient (analogous to the coefficient of determination, R^2), which compares the predicted and observed values at each point during the simulation. This coefficient is expressed as

$$E = \frac{\sum_{i=1}^{N} (q_c - \bar{q}_c)^2 - \sum_{i=1}^{N} (q_c - q_e)^2}{\sum_{i=1}^{N} (q_c - \bar{q}_c)^2}$$

where E = accuracy coefficient (fraction)
q_c = observed flows (cfs)
$\bar{q}_c$ = mean of observed flows (cfs)
q_e = predicted flows (cfs)
N = number of data points

The E value corresponding to a perfect fit ($q_{c_i} = q_{e_i}$) is 1.00. Stokely (1980) defined E values greater than or equal to 0.80 as high. The second statistic that is used is the peak capture discrepancy, PC, which measures the simulation's ability to capture the important flood peak,

$$PC = \frac{\text{Predicted peak discharge - Actual peak discharge}}{\text{Actual peak discharge}}$$

The modeller aims to maximize the accuracy coefficient, E, while at the same time minimizing the peak capture discrepancy. An example SSARR model run is shown in Figure 6 for the

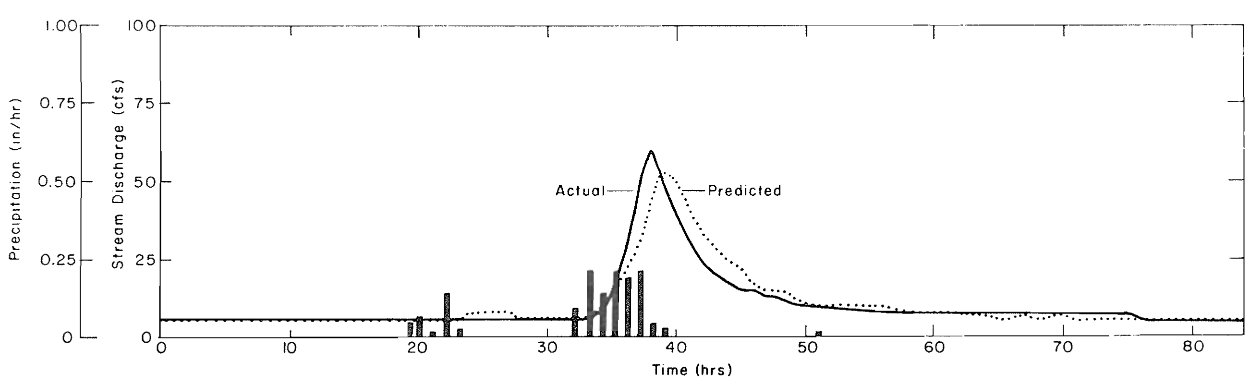

Figure 6. 12-15 June 1967, SSARR simulation (from Stokely, 1980).

period 12-15 June 1967. This period has an accuracy coefficient (E) of 0.8380 and a peak capture discrepancy of -0.3500.

Plan of Attack for Cold Regions

Modifications to SSARR

With a calibrated model for W-3 summer storms, methods are required for making modifications to reflect cold regions effects. Discrepancies between predicted and actual flows due to cold regions effects are associated with the dynamic behavior of the hydrologic effect of various cold regions phenomena. E values are of the order of 0.6 or less when the warm period model is ran on cold season events. The phenomena include the temperature dependence of the kinematic viscosity of water and soil moisture retention, seasonal interception changes, snow accumulation and ablation, frozen ground, and ice formation in stream channels. All of these phenomena affect the timing and volume of discharge from the watershed. Algorithms are developed to account for the hydrologic effects of these phenomena, and modifications are made to improve the capabilities of SSARR model forecasting in cold regions.

Cold Temperature Effects

Stokely (1980) first tested cold snowless periods to separate out the effects of temperature on the timing of flood peaks and on soil moisture retention. In general, the model underpredicts the amount of runoff during this time period and the predicted early recession reveals a low-rapid fall in discharge values compared to actual values. These discrepancies suggested variations in runoff production, which are controlled by the SMI/ROP relation and runoff component timing coefficients.

Stokely (1980) attributed the discrepancies of discharge timing to the temperature-dependence of the kinematic viscosity of water. The flow of water through porous media depends directly on the hydraulic conductivity of the particular medium. This, in turn, varies inversely with μ, the kinematic viscosity of water. As temperature falls from 60°F to 32°F, μ increases by about 60%. Therefore, to modify SSARR for colder periods, the time constraints for the surface flow and subsurface reservoirs (Fig. 5) were multiplied by a factor that contained this kinematic viscosity relationship. The baseflow time constant was not changed because groundwater temperatures remain relatively constant throughout the year (Davis and DeWiest, 1966). Mean daily air temperatures were used in this study to determine the kinematic viscosity adjustment factor.

With respect to the underprediction of runoff volumes, Stokely (1980) modified the model to account for interception changes due to autumnal foliage drop and the temperature dependence of soil moisture retention. Nearly 80% of the autumnal foliage drop in central Vermont and New Hampshire occurs during a single week, usually starting the first windy or rainy day after October 5 (Ryan, 1979). When simulations are made after this data there is an increase in the amount of precipitation that reaches the ground. An increase of 9.33% was made to the total percent runoff (ROP, Fig. 5) to incorporate this effect into the SSARR model. This percentage was derived by considerations of the various cover types within W-3. Stokely (1980) performed a numerical analysis to determine the temperature dependence of soil moisture retention. He found that as temperature falls, field capacity increases. Field capacity is "the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased" (Ward, 1975). This relationship is embodied in the SMI term of SSARR (Fig. 5). As temperature decreases, the storage capability of the SMI volume increases and an increased ROP occurs. As was done with the viscosity-related modification, mean daily air temperature is used as an input parameter for soil moisture retention modifications.

Snow Accumulation and Ablation

To simulate watershed dynamics for snow-covered periods, a DYNAMO version of the National Weather Service River Forecasting System (NWSRFS) snowmelt model was coupled with the temperature-modified watershed component of SSARR (Stokely, 1980). Two approaches are generally used for simulating snowmelt. One is the energy balance approach, which depicts

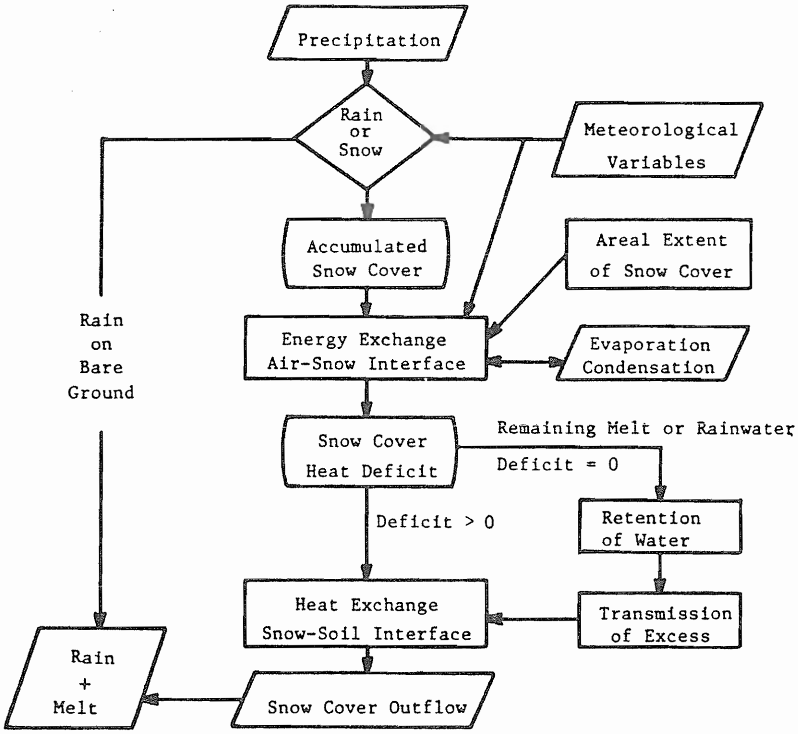

Figure 7. Conceptual diagram of NWSRFS snowmelt model (from Anderson, 1978).

most of the detail of the physical system but requires extensive data sets that are not generally available in an operational environment. The second approach is the temperature index method, which uses air temperature as a lumped indicator of basic snowmelt. Temperature index is the basis for the NWSRFS model. The NWSRFS model was chosen by Stokely (1980) because as "a 'state-of-the-art' model which is simultaneously operational, it does not require the extensive data necessary to implement an energy balance model. It is associated with a federal agency directly responsible for accurate flood forecasting, the National Weather Service." The DYNAMO version of the NWSRFS, based upon Anderson (1973), is shown in a schematic in Figure 7. The model consists of two general sectors, a meltwater production unit and a meltwater storage and transmission component. With the temperature-modified SSARR watershed component and NWSRFS snowmelt model, simulations for snow-covered periods show high average E values of 0.948 and peak capture discrepancies of 0.0516 (Stokely, 1980).

Frozen Ground

Stokely (1980) and Peaco (1981) both analyzed the effect of frozen ground on SSARR model prediction. Bullard (1954) notes that frozen ground is particularly important in connection with snowmelt floods in the eastern United States. Storey (1955) states that frozen soil influences runoff production, in that "its structure determines how fast rain or melting snow can enter the soil. The depth of penetration of soil frost determines how fast the frost leave the soil during thaws... The extent of frozen soil indicates how much of a watershed might be affected."

Stokely (1980) used the theory of Bloomsburg and Wang (1969) to calculate when soils become impermeable. Each soil type is analyzed in this fashion and a percent frozen area is determined. As particular soil types become impermeable, more water is routed to the surface flow reservoir and to the stream channel in the SSARR model. The remainder of the watershed, which is not frozen or impermeable, is modelled in the normal SSARR snowmelt mode. Stokely (1980) could only locate three potential frozen ground runoff events in the data of Anderson et al. (1977). These events showed great predictive improvement, but

Stokely (1980) concluded that additional frozen ground events would be necessary to expand and substantiate his findings.

Peaco (1981) related areal extent of frost to an index of the soil heat deficit. He concluded that additional data and research are needed to develop the appropriate index. The surface energy transfer data, such as that collected at R-3, and concurrent soil heat deficit measurements could be used to develop such an index.

Ice Cover on Rivers

There has been considerable research on in-channel effects of flow under ice covers on rivers, but limited research on the effect of ice covers on watershed flood forecasting has not yet been accomplished. The 1981-82 winter season was analyzed to determine the effect of an ice cover on SSARR model runoff prediction at W-3. No frozen ground was measured during the 1981-82 winter season, so the temperature-modified SSARR model with the NWSRFS snowmelt model was used. Thirteen storm periods were analyzed with six periods having observed ice cover on Pope Brook, the W-3 main channel. When the model simulated the ice cover storms, two areas of discrepancy were observed: first, an underprediction of the total volume of runoff and, secondly, what appeared to be a cyclic over-/under-prediction during the simulated event. It is hypothesized that the underprediction of the total runoff is caused by storage of water as ice in the channel. The cyclic behavior is attributed to change in the travel paths of water to the stream channel because the normal paths are blocked by impermeable ice. With observations of ice, SSARR is again modified by an additional storage reservoir in the stream channel and a term that diverts water from surface flows to the subsurface reservoir.

SUMMARY

Using the facilities and data from the SRRW, CRREL has tested hydrometeorologic sensor systems in a cold region environment and has calibrated and validated cold regions modifications to the U.S. Army SSARR model. Figure 8 shows the improved accuracy of the modified SSARR model for a snowmelt event with an intact ice cover. The period in Figure 8 is 17-20 January 1982 with an E-value of 0.934 and a peak capture discrepancy of 0.104. In the future CRREL will utilize the SRRW to better define relationships between ice cover, frozen ground, and runoff prediction.

ACKNOWLEDGMENTS

The work described here was conducted as part of the Corps of Engineers Civil Works Cold Regions Hydrology program, CWIS 31587, "Inventory Techniques for Ground Beneath Snow Cover."

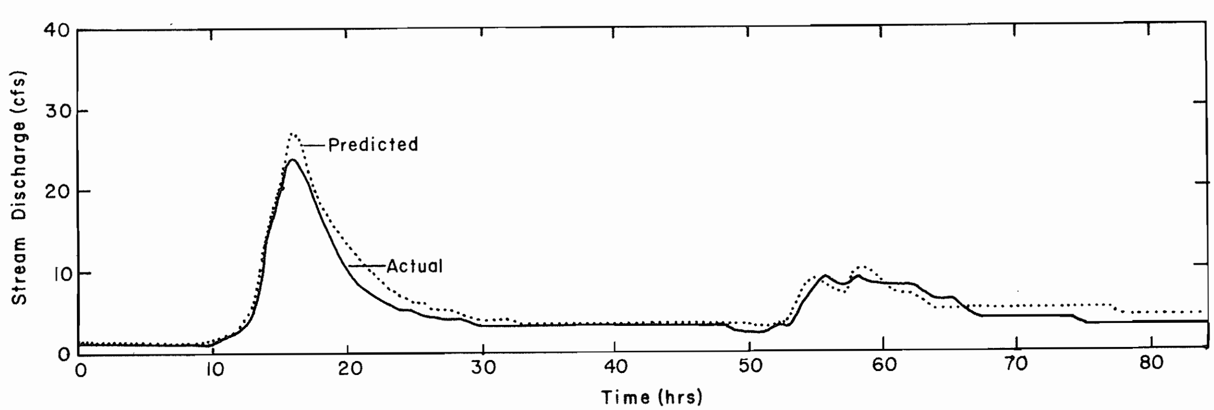

Figure 8. January 1982, cold regions modified SSARR simulation.

REFERENCES

Anderson, E.A. (1973) NWSRFS -- Snow Accumulation and Ablation Model. NOAA Technical Memorandum NWS Hydro-17, U.S. Department of Commerce, Silver Spring, Maryland.

Anderson, E.A., Whipkey, R.Z., Greenan, H.J. and Machell, C.T. (1977) NOAA-ARS Cooperative Snow Research Project -- Watershed Hydroclimatology and Data for Water Years 1960-1974. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, MD, and U.S. Department of Agriculture, Agricultural Research Service, University Park, PA.

Anderson, E.A. (1978) Streamflow Simulation Models for Use on Snow-Covered Watersheds. In: Proceedings: Modeling of Snow Cover Runoff (S.C. Colbeck and M. Ray, eds.) U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, pp. 336-350.

Bloomsburg, G.L. and Wang, S.J. (1969) Hydrology of Frozen Ground Floods. NTIS PB-187 269, U.S. Department of Commerce.

Brown, J. and Rickard, W. (1972) The Performance of a Frost-Tube for the Determination of Soil Freezing and Thawing Depths, Soil Science, Vol. 113, No. 2.

Bullard, W.E. (1954) A Review of Soil Freezing as Affected by Snow Cover, Plant Cover, and Soil Conditions in Northwestern United States. In: Symposium on Snow and Ice, International Association of Scientific Hydrology, Publication No. 39, pp. 132-136.

Cox, L.M., Bartee, L.D., Crook, A.G., Farnes, P.E. and Smith, J.L. (1978) The Care and Feeding of Snow Pillows. In: Proceedings, 46th Annual Western Snow Conference, Inn at Otter Crest, Oregon, 18-20 April 1978, p. 40-47.

Davis, S. and Dewiest, R.J.M. (1966) Hydrogeology. John Wiley and Sons, Inc., New York.

Dunne, T. and Black, R. (1977) An Experimental Investigation of Runoff Prediction in Permeable Soils. Water Resources Research, Vol. 6, pp. 473-490.

Haugen, T. (1984) Personal communication, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Klute, A. and Peters, D.B. (1968) Hydraulic and Pressure Head Measurements with Strain Gauge Pressure Transducers. Proceedings of Wageningen Symposium, Vol. 1, p. 156-165.

McKim, H.L., Berg, R.L., McGaw, R.W., Atkins, R.T. and Ingersoll, J. (1976) Proceedings: Second Conference on Soil-Water Problems in Cold Regions. Edmonton, Alberta, Canada, 1-2 September 1976, pp. 31-45.

Nash, J.G. and Sutcliffe, J.V. (1970) River Flow Forecasting Through Conceptual Models, Part I -- A Discussion of Principles. Journal of Hydrology, Vol. 10, pp. 282-290.

Pangburn, T. (1983) A Method of Calibration For Current Meters Using the Ice Engineering Facility Test Basin Platform. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, Technical Note, 15 pp.

Pangburn, T. and Pratt, B. (1980) Measurement of Snow Water Equivalent Using a Load Cell Triangle Sensor. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, Technical Note, 13 pp.

Peaco, D. (1981) Frozen Ground Hydrology in Watershed Simulation: Model Development and Analysis of the 1979-80 Winter in the Sleepers River Research Watershed in Northeastern Vermont. Resource Policy Center Report DSD No. 332, Thayer School of Engineering, Dartmouth College, Hanover, NH, M.S. Thesis.

Pionke, H.B., Bahleda, K. and Chamberlin, B.J. (no date) Data Directory, Data and Data Collection Site Characteristics for the Sleepers River Watershed, N. Danville, Vermont. Northeast Watershed Research Center, University Park, PA.

Ryan, D. (1979) Ecosystem Research at the Sleepers River Research Watershed. Resource Policy Center Report No. 162, Thayer School of Engineering, Dartmouth College, Hanover, NH.

Santeford, H.S. (1976) Effects of Snow Pillow on Heat and Vapor Transport in the Black Spruce/Permafrost Environment of Interior Alaska. Proceedings: Second Conference on Soil-Water Problems in Cold Regions, Edmonton, Alberta, Canada, 1-2 September 1976, pp. 1-14.

Stokely, J.L. (1980) Watershed Modeling in Cold Regions: An Application to the Sleepers River Research Watershed in Northeastern Vermont. Resource Policy Center Report No. 232, Thayer School of Engineering, Dartmouth College, Hanover, NH, M.E. Thesis.

Storey, H.C. (1955) Frozen Soil and Spring and Winter Floods. Water: Yearbook of Agriculture, U.S. Department of Agriculture, pp. 179-184.

U.S. Army Corps of Engineers (1972) Program Description and User Manual for SSARR - Stream Flow Synthesis and Reservoir Regulation. U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Ward, R.C. (1975) Principles of Hydrology. McGraw-Hill, London.

Watson, K.K. (1967) A Recording Field Tensiometer with Rapid Response Characteristics. Journal of Hydrology, Vol. 5, No. 1, pp. 33-39.

World Meteorological Organization (1982) WMO Project for the Intercomparison of Conceptual Models of Snowmelt Runoff. Hydrological Aspects of Alpine and High Mountain Areas, Proceedings of the Exeter Symposium, IAHS Publication No. 138, Exeter, U.K., pp. 193-202.