FORECASTING OF SNOWMELT RUNOFF USING WATER TEMPERATURE DATA

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ABSTRACT

For the 1986 snowmelt season at the W-3 subwatershed of the Sleepers River Research Watershed, a technique was developed to quantify the volume and timing of snowmelt runoff using stream water temperature. A method reported by Kobayashi (1985) for separation of the snowmelt hydrograph was tested. A method employing air temperature and solar radiation was developed which was used to calibrate the SSARR model. Improvements in the predictive capabilities of SSARR were attained using this method.

Introduction

Snowmelt runoff forecasting has been historically based on either the "energy balance" or "temperature-index" approaches. In these approaches the volume and timing of discharge is based on inputs from meteorological parameters (temperature, insolation, precipitation, etc.) and their effect on the state of the snowpack (density, water equivalent, etc.) to produce a resultant melt rate and discharge. The errors associated with these methodologies are confounded by the error associated with the measurement of these parameters, as well as the analytical techniques which are used to depict the physical process. In this paper, preliminary results are described on a new technique which uses the water temperature of the resultant discharge to quantify the volume and timing of snowmelt runoff. By treating the watershed as a large snowmelt lysimeter the calibration of a runoff model, in this case the SSARR model, (U.S. Army Corps of Engineers, 1972) can be accomplished. This is possible in temperate basins where subsurface or baseflow temperatures (2 - 10°C) during the melt season are considerably different than the temperatures of the snowmelt (0°C). Kobayashi (1985) used water temperature to separate the daily snowmelt hydrograph into surface and subsurface components based on the mass and heat conservation equations. However, these equations were used for a basin with very low surface runoff, in comparison to subsurface runoff, and this approach will be shown not to apply where the surface component in the spring snowmelt is more dominant.

Another important aspect of measuring the water temperature during the winter season is the study of watershed cooling and warming relationships in relation to tributary effects on main channel ice formation and breakup. Calkins (1986) stated that there is a need for a hydrologic model that can predict both the flow rate and the temperature of runoff during the winter season to determine the hydrologic input to ice formation. This paper outlines some findings in this area.

Study Area

The W-3 subwatershed (Fig.1) of the Sleepers River Research Watershed was used for this study. This 8.42-square-kilometer watershed has been the subject of detailed measurement of snow cover and the hydrometeorological variables affecting snow cover energy exchange since December 1968 as part of a project to study the physical processes involved in snow metamorphosis and snowmelt (Anderson, et. al. 1977). This watershed was also chosen as one basin used by the WMO for an international test of snowmelt models (World Meteorological Organization, 1982). The outlet of the W-3 is at an elevation of 346 m above sea level and the highest point of the watershed is about 695 above sea level, with a mean elevation of 491 m above sea level. The NOAA Snow Research Station (R-3) is a
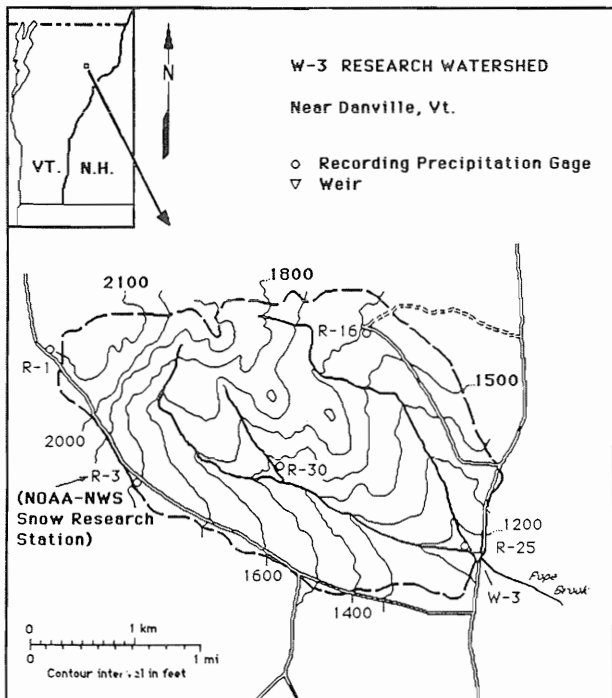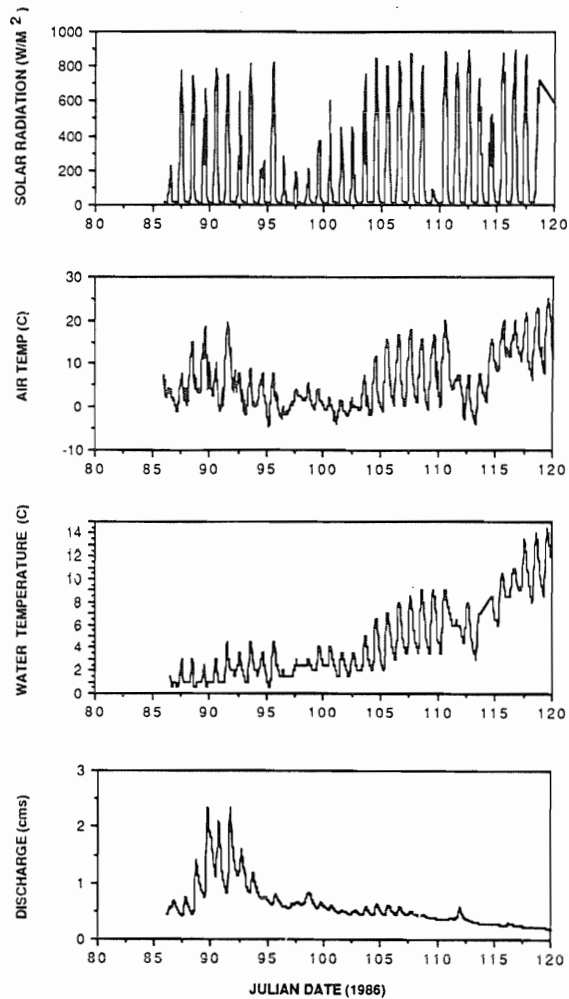
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Figure 1. W-3 Subwatershed

Figure 2. Data from 1986 Winter Season at W-3

complete energy balance site and is located near the mean elevation at 552 m above sea level. The mean annual temperature at R-3 is about 22°C and the mean annual precipitation is about 1080 mm. January temperatures average about -8°C with about 40 to 60 days in the winter with minimum temperatures of -20°C or lower. Snowfall averages 2540 mm with a maximum water equivalent of the snow cover normally about 225 to 300 mm. A complete description of W-3 and R-3 is given in Anderson et al. (1977).

Data Collection

Figure 2 shows the hydrograph, water temperature, solar radiation and air temperature for 21 March 1986 (Julian day 80) through 30 April 1986 (Julian day 120) for W-3. Prior to the snowmelt period in late March, water temperatures are controlled by a 100 percent snow-covered area and a high percentage of subsurface runoff. During this time water temperatures are maintained at near 1°C. Once snowmelt begins there is a diurnal cycle of 2 - 3°C. As the melt season progresses and the snow cover recedes and more of the channel becomes open the water temperature increases until at the end of April when the water temperature average is near 12°C with a diurnal cycle of 4 - 6°C. This data shows that there is heat available from sources (i.e. solar radiation and air temperature) other than soil heat in the presence of a 100 percent snow-covered area. The
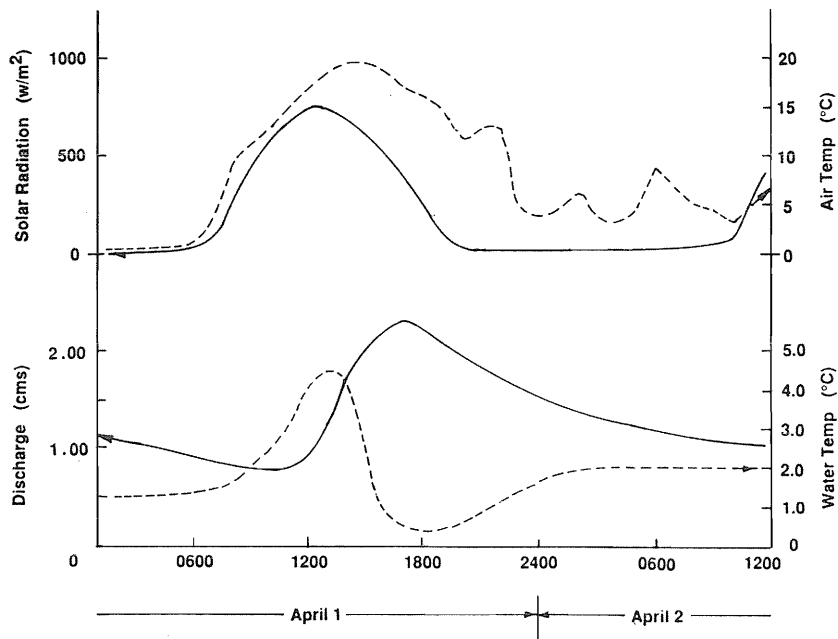
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Figure 3. W-3 Snowmelt Event for 1 - 2 April 1986

water temperature data also show a broadening of the timing of the diurnal cycle as the snowmelt season progresses. This can be seen by comparison of the incoming solar radiation and the water temperature cycles. The time length of the diurnal solar radiation cycle is approximately 12 hours throughout this period; however, the time length of the diurnal water temperature cycle starts at approximately 6 hours and progresses to nearly 12 hours at the end of the snowmelt period. This implies that a considerable amount of cooling of the stream temperature is occurring due to the input of snowmelt at 0°C. The runoff diurnal cycle is at a minimum at about 1000 hours and the peak has reached normal by 1800 in the evening.

Figure 3 shows an example of a diurnal snowmelt event for 1 - 2 April 1986. Water temperature is stable through the early morning hours at 1°C. After solar radiation and air temperature begin to increase at 0600 hours, water temperature begins to increase two hours later at 0800. Water temperature continues to increase on the rising limb of the snowmelt hydrograph until sufficient snowmelt water is available to drastically decrease the water temperature beginning at 1300 hours. The snowmelt hydrograph reaches its maximum and the water temperature reaches its minimum at 0.5°C at 1800 hours. As solar radiation and air temperature decrease, the hydrograph recedes and the water temperature increases to a constant 2°C. This typical hydrograph shows that the surface runoff from snowmelt is a high percentage of the total runoff and is affected by solar radiation even in the presence of an intact snow cover.

Separation of Snowmelt Hydrographs

Kobayashi (1985) used the mass and heat conservation equations to determine the contribution of surface runoff to total runoff as follows:

$$Q = Q_s + Q_{ss} \qquad\qquad (1)$$

$$TQ = T_s Q_s + T_{ss} Q_{ss} \qquad\qquad (2)$$

where Q is total runoff, Q_s is surface runoff and Qss is the subsurface runoff. T, T_s, and T_{ss} are the temperature of each runoff component. These equations are simiplified and, assuming T_s is equal to zero, the resulting equation is:

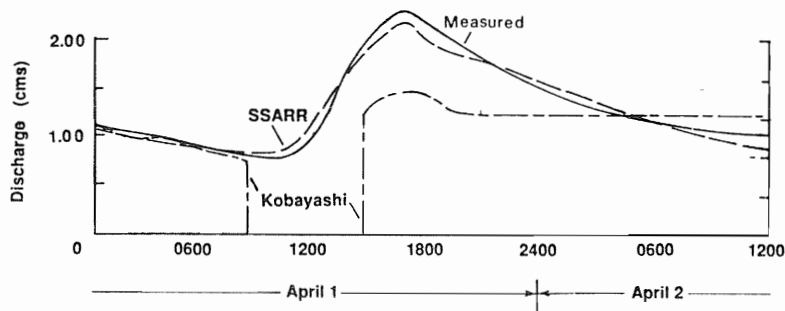$$Q_s/Q = (T_{ss} - T/T_{ss}) \qquad\qquad (3)$$

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Figure 4. Prediction vs. Measured Discharge
Using Kobayashi (1985) and SSARR

Kobayashi (1985) states that, due to the limited effect of solar radiation and the high percentage of subsurface runoff in the snowmelt hydrograph, equation (3) accurately separates the components for his basin of study. When equations (3) is applied to the April 1 - 2 snowmelt event, it greatly underpredicts the volume of the hydrograph (Figure 4). In the period (0800 - 1600 hours) where the water temperature (T) is greater than the initial subsurface flow temperatures (T_{SS}) equation (3) does not hold as the equations are based on only the "native temperature" of the discharged rates and cannot account for air temperature and snowmelt.

To add terms for heat sources the stream channel can be initally considered to be a single well-mixed reactor and be treated by the mass and heat conservation equations with production terms for air temperature and solar radiation, as follows:

$$dV/dt = Q_{ss} + Q_s - Q \qquad (4)$$

$$dTV/dt = T_{ss}Q_{ss} - T_sQ_s - TQ + K_1(T_A - T) + K_2R_s \qquad (5)$$

$$TdV/dt + VdT/dt = T_{ss}Q_{ss} - T_sQ_s - TQ + K_1(T_A - T) + K_2R_s$$

$$T(Q_{ss} + Q_s - Q) + VdT/dt = T_{ss}Q_{ss} - T_sQ_s - TQ + K_1(T_A - T) + K_2R_s$$

$$dT/dt = [T_{ss}Q_{ss} - T(Q_s - TQ)]/V + K_1(T_A - T)/V + K_2R_s/V \qquad (6)$$

where V is the storage volume of the stream reservoir, T_A is the air temperature, R_s is the incoming solar radiation and K1, and K2 are derived constants. T, T_s, T_{ss} and Q are as defined for equation 3.

The production terms of equation 6 account for the heat supply by air temperature and solar radiation. The parameters K1, and K2 are lumped parameters which could be considered to embody the heat capacity of water and the open ice and snow-free area of the stream channel. K1 was found to be equal to 0.025 and K2 equal to 2.06×10^{-3} for the 1986 snowmelt season. Using equation 6 the snowmelt hydrograph can be separated and the volume and timing of snowmelt (surface runoff) can be calculated. In the W-3 basin this analysis shows that greater than 50 percent of the snowmelt runoff is surface runoff.

Runoff Forecasting

Once the hydrograph has been separated and the volume and timing of snowmelt has been derived, the SSARR (Streamflow Synthesis and Reservoir Regulation, U.S. Army Corps of Engineers 1972) model (Figure 5) can be employed to test the improvement in forecasting that can be attained using this water temperature methodology. Previously, modifications have been made to SSARR to account for other cold regions effects. They are as follows:

   * Discharge timing - change in routing constants due to the increase in the
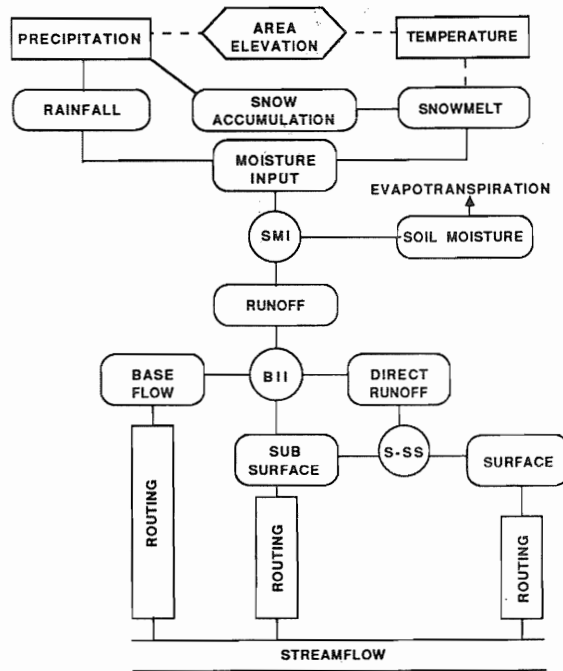   kinematic viscosity with decreasing temperature

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Figure 5.   Schematic of SSARR Model

* Changes in soil moisture retention with temperature - as temperature falls, field capacity increases

* Decreased infiltration and overland flow from partial areas due to soil frost

* Effects of an ice cover on watershed runoff prediction, aufeis production and dislocation of normal travel paths

These modifications have been described in an earlier paper by Pangburn and McKim (1984). With the information obtained from the water temperatures of the 1986 snowmelt period, the SSARR model was run and compared to the prediction of SSARR using the normal calibration procedure employing 10 years of discharge data. Improvement was gained in the predictors of both volume and timing of the snowmelt discharge. Two statistics are used to quantify the improvement. 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. The second statistic is the peak capture discrepancy, which measures the simulation's ability to capture the important flood peak. The Nash-Sutcliffe coefficient was improved from 0.86 to 0.95 by using the water temperature derived variables and the peak capture discrepancy improved from 9.7 to 1.2 percent. The SSARR simultion for the April 1 - 2 snowmelt event is shown in Figure 4.

Summary

The calibration of the SSARR model using a water-temperature-based scheme has shown to make improvements in the prediction of snowmelt runoff for the 1986 winter season. The W-3 subwatershed snowmelt hydrograph cannot be separated using the methods described by Kobayashi (1985). Future research will be conducted in this area to further define the relationships of watershed cooling and warming.

Acknowledgments

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