Snowmelt Runoff Modeling Using GIS Parameter Estimation in a Western Adirondack Watershed

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ABSTRACT

Difficulties in obtaining satellite imagery and aerial photography to determine snowcovered area for use in snowmelt runoff models raise the need for other methods of estimation. A raster geographic information system (GIS) and a digital elevation model constructed for this project were used to model the basin topography in a heavily forested, western Adirondack watershed. The calculated daily snowmelt (from daily degree-day data and the degree-day factor) was multiplied by an irradiance index to yield distributed values of snowmelt for each elevation zone on each day. These values were then subtracted from the previous day's snow water equivalent. By calculating the area of cells with water equivalent greater than .1 inches (.25 cm), a daily estimate of snowcovered area was obtained, and entered into the Snowmelt Runoff Model (SRM; Martinec, Rango and Major,1983). Initial results are promising, with r2 (Nash-Sutcliffe)values of .8141 for predicted and measured streamflow for the 1987 season.

INTRODUCTION

Some of the most successful snowmelt-runoff models have been designed for high mountain basins, with few terrestrial factors such as forest cover or land use affecting the model, and with aerial or satellite overviews possible on a regular basis. Areas in the eastern United States or Canada have heavily forested basins with (frequently) dense cloud cover during the snowmelt season. This and infrequent satellite overflights during the short term of snowmelt in these eastern watersheds limit the availability of data for estimates of snowcovered area, snow depletion rates, and other snowpack parameters affecting snowmelt. In addition, the spatial and spectral resolution of imagery is currently not adequate for determination of snow under heavy forest cover (Eschner et al, 1977). Finally, timely acquisition of expensive imagery and photography is a problem for many public and private agencies involved in water resource management.

Geographic information systems (GIS) are promising tools in modeling hydrologic processes. The structure of a GIS allows analysis of basin topography and other physical characteristics, and is also capable of spatially distributing variables affecting snowmelt and subsequent runoff. Energy inputs to the snowpack from solar radiation can be differentially assigned as functions of local elevation and inclination of the local topographic surface.

This study attempts to estimate snowcovered area using a GIS produced distribution of daily snowmelt, by developing an index of potential direct beam irradiance with values dependent upon the geometry of each local topographic facet in relation to the sun. This index, which assigns an irradiance value for each cell in the basin according to its slope and azimuth direction, was derived from the Cosine Law of Irradiance as presented by Reifsnyder and Lull (1965), Lee (1962) and Kaufmann and Wetherred (1982); with modifications for aspect and slope factors effectively calculating the "equivalent slope"(Lee, 1962) for each cell's local topographic facet. The index was not modified by other spatially variable factors such as forest cover in order to test the method with as operationally simple a method as possible.

STUDY AREA

The Independence River is one of only two uncontrolled major tributaries of the Black River, which drains the western Adirondack Mountains and eastern Tug Hill upland in northern New York State. The Independence watershed is an elongated, east-west oriented basin lying on the western flank of the Adirondacks, and largely within the Adirondack Park (See Figure 1). The drainage is young and poorly defined in many places. Soils are glacial outwash and till, varying from thin layers over Precambrian bedrock to a deep,coarse sandy deposit under most of the river's main channel. Topography ranges from the Adirondack foothills on the eastern end of the watershed (maximum elevation 2340 ft/702 m), to flat, largely wetland areas of glacial outwash interspersed with kames, kettle lakes and drumlins in the central portion of the basin. The river flows with a steeper gradient in the lower reaches of the watershed, emptying into the Black River at an elevation of 840 feet(261 m). (Waller and Ayer, 1975)

The 98 square miles (254 km2) of the watershed to its mouth are approximately 80 percent forested, largely with hardwoods. The major portion of annual runoff is from snowmelt. As one of two uncontrolled subbasins of the Black River, the Independence is of particular interest in studies seeking to control annual flooding of agricultural areas in the Black River flats downstream of the Independence outlet. (US Army Corps of Engineers, 1988)

Available runoff and climatological data is of long term and good quality. The Black River Regulating District is the administrative agency for the basin, collecting hydrologic and climatological data from the contributing agencies (USGS, USWS). The flow at the Donnattsburg gauge(91.7 mi2/238km2 of drainage area) has been recorded since 1942, with telemetry installed since the summer of 1989. Climatological stations used (Figure 1) fairly well represent the basin, although there is poor correlation between temperature and elevation among them, perhaps due to recent rapid development in some of the stations' immediate vicinity.

Snow courses, although none exist within the Independence basin boundaries, are well distributed around the watershed. Water equivalent and snow depth data are available on an approximately 15 day periodic basis during the snowmelt season from the Eastern Snow Conference. See Figure 1 for the distribution of data sources used in this project.

METHODOLOGY

Construction of the DEM

The digital elevation model (DEM) was constructed by overlay of a square grid (ground cell size 868 feet/265 m on a side) on a set of 1:62500 USGS quadrangle maps. A single elevation value was assigned to each of the cells in the 126 by 51 grid. Streams were "channeled" into the DEM according to their placement on the base topographic maps. Average elevations were assigned to cells not containing water, unless the cell contained a local topographic high or low, in order to preserve local surface features in the very flat areas of the watershed. This method of elevation assignment was judged to best represent the area as a hydrologic unit and as topographic modeling surface.

Surface Modeling in IDRISI

IDRISI is a non-commercial, raster GIS constructed with an open architecture which facilitates customizing for specific purposes. It was chosen for this study because of its surface modeling capabilities (including a watershed function) and for its preservation of data

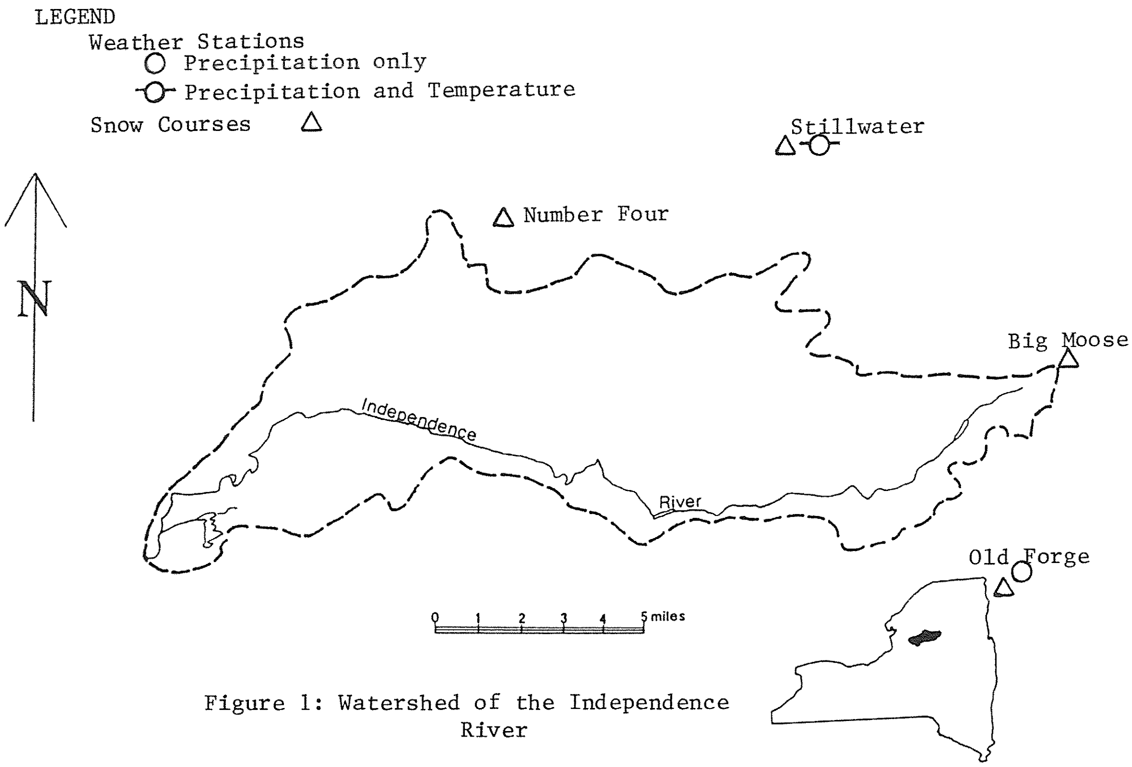

Figure 1: Watershed of the Independence River

layers in distinct data files at each stage of manipulation and analysis.

IDRISI was used in the study not only to model the topographic surface from the DEM through creation of slope and aspect maps, but also for areal analysis (including hypsometric analyses of basin and snowcovered areas) and regionalization of climatic variables.

The surface of the DEM was modeled using the SURFACE function in IDRISI, with both slopes (in degrees) and aspects calculated using a maximum-slope algorithm on neighboring cells. Areal analysis of aspects and slopes using the HISTO and AREA functions allowed classification of slopes and aspects into representative groupings, and for visual analysis of the basin topography.

<u>Development of a spatial index of irradiance</u>

Aspects were classified into four categories based on similarity of potential irradiance values in tests of the Cosine Law adaptations for tilted surfaces (Kaufmann and Wetherred, 1982). These four aspect classes, when further tested in combination with three slope classes of two, five, and ten degrees of slope (derived from analysis of the slopes on the watershed as the mean values of representative slope classes), yielded twelve distinct classes of irradiance values.

The equivalent surface, hour angle correction factor (two hours past solar noon, the time of maximum direct beam solar radiation effect on the snow surface), and "irradiance multiplier" (Kaufmann and Wetherred, 1982) were calculated using 43 degrees north latitude as the mean watershed latitude, for each cell in the basin. Index values were then expressed as the ratio of the cell's potential instantaneous irradiance to that of a horizontal surface. Resulting index values ranged from .80 to 1.20 for the 12 combinations of slope and aspect used in the initial tests.

Snowmelt from irradiance index

The resulting image file of cell values differentiated by each cell's slope and aspect was used to distribute daily snowmelt. The daily melt, S_m, in inches (cm), was derived from the equation

$$S_m = a(\text{sumT}),$$

calculated daily for each of the four elevation zones in the watershed, where:

a = the degree-day factor, re-calculated every 15 days , and
sumT = the total degree-days for each day, taken from average temperature minus the critical temperature for each elevation zone

(Martinec and Rango, 1981)

The daily melt value was then multiplied over the irradiance index map, resulting in a range of melt values varying with the potential irradiance on the topographic facets in the watershed. This "melt" image was created for each day and each elevation zone. Beginning with the initial snow water equivalent data from the snow survey measurements extrapolated to each elevation zone and for every 15 day period, the day's melt image was subtracted from the snow water equivalent left from the previous day. Histograms and summary area statistics were generated by IDRISI to calculate the remaining percent of snowcovered area, taken to be all cells with greater than .1 inches (.25 cm) of water equivalent. Additional precipitation (snow and rain) during each period was added to the water equivalent daily, until snowpack conditions seemed to be such that liquid precipitation would become immediately available for runoff. After this, only precipiation occurring as snow (that is, below the designated critical temperature for each zone) was added to the water equivalent.

Snow depletion tables were constructed from the daily snowcovered area values derived by this method, and entered into the SRM for each elevation zone as the snowcovered area factor, S_n. Location of each day's snowcovered and snow free areas were also available for verification and analysis from the water equivalent IDRISI image file for the corresponding day.

After the snow depletion data was entered for the test year, SRM was run using the sequence and procedures of parameter tests suggested in the User's Manual (Martinec, Rango and Major, 1983). No manipulation of parameters was attempted (other than correction of gross input or calculation errors) for the 1987 model calibration season, in order to judge the GIS parameter estimation method as objectively as possible. Other SRM parameters and variables were calculated according to instructions in the manual, which requires several decisions based upon interpretation of the data and a knowledge of basin response. A short discussion of the SRM itself, including its applicability to the lower elevation and relief of basins such as the Independence River, and how the decisions required in calculating basin parameters, follows.

THE SNOWMELT RUNOFF MODEL (SRM)

The Martinec-Rango Snowmelt Runoff Model (1983) is a proven degree-day model developed for high mountain basins "with significant snow accumulation". (Martinec, Rango, Major, 1983) It has been tested successfully on basins with widely differing areas, but tests on lower elevation, forested mountain basins remain scarce. The basic flow equation used in the model is as follows:

$$Q_{n+1} = c_n\left[a_n(T_n + \Delta T_n)S_n + P_n\ A\right] * 0.01/86400(1 - k_{n+1}) + Q_n k_{n+1}$$

where Q = average daily discharge in cfs(cms)
c = runoff coefficient (c = runoff/precipitation)
a = degree-day factor (in/F/d or cm/C/d), a function of snow density
T = number of degree-days (degF*d or degC*d)
ΔT = adjustment by temperature lapse rate for each elevation zone
S = ratio of the snowcovered area to the total area

P = precipitation contributing to runoff(in/cm). A designated critical temperature (T_{crit}) determines whether precipitation is read as rain or snow.
A = area of the basin or zone in mi2/km2
k = recession coefficient, calculated daily by the model, from seasonally calculated x and y coefficients in the equation $Q_{n+1} = xQ_n^y$ (see discussion of parameters, below)
n = sequence of days during the computation period

The SRM modification for the personal computer was used for this study.

The snowcovered area parameter, S, has previously been provided by satellite imagery, snowline overflights, or aerial photography. In this project, snowcovered area was obtained from the GIS model output.

SRM's output includes a computed versus observed hydrograph for the snowmelt season, a goodness-of-fit measure (the Nash-Sutcliffe r^2), percent seasonal difference between computed and actual runoff, and mean runoff for computed and observed data. The program also supports the summary output with graphical representations of snow depletion curves and tables of basin variables. These outputs were used for overall evaluation of the success of the parameter estimation method.

The following six parameters, required in addition to the snow covered area values in SRM, and the methods used for their estimation or calculation, are discussed in part because of the sometimes intuitive judgment necessary to derive them successfully.

Runoff coefficients, the most problematic of the basin parameters, were calculated using each 15 day period's total runoff and precipitation, the latter including estimated contributions from snowmelt during the period. The GIS melt computations were used for this, averaged for the basin's zonal areas. SRM allows separation of runoff coefficients from snow and rain, which is especially difficult for an area such as the Independence River, with alternate inputs during the winter season of rain and snow, and the very rapid ripening processes of the snowpack. The coefficients for 1987 ranged from .40 to .78, with the higher values as expected during times of melt.

Temperature lapse rates of .27 degrees Fahrenheit (.1 degrees Celsius) for every 100 feet (31 meters) were used, which translates to .72 degrees F (.27 C) for each of the four elevation zones. The base temperature station (at Stillwater Reservoir - see Figure 1) is near the hypsometric mean of Zone 2 in the basin, so that temperatures were extrapolated both up and down from the observed value.

Critical temperatures were chosen on the basis of previous work in the watershed (Colquhoun, 1971) and from analysis of the GIS output. The amount of melt calculated by the GIS was compared to the water equivalent found at each available snow survey on the corresponding date, to serve as a check of the melt computations' reliability. The amount of melt is a function of the degree-day values, so that critical temperature (above which precipitation falls as rain, below as snow) selection could also be judged on the basis of the correspondence of melt amounts and the snow survey data.

Degree-day factors were calculated as functions of the snow density, derived from the snow survey water equivalents. The equation used by SRM for degree-day factors is

$$a = 1.1\frac{(\text{density of snow})}{(\text{density of water})}$$

As expected, degree-day factors increased toward the end of melt for the 1987 season. (It should be noted, however, that 1987 was a season with a single large melt event. This area may have several distinct snowpacks with several melt events during a single season. In these cases, snow densities (and therefore degree-day factors) and runoff coefficients cycle up and down several times during a single season. Further study will reveal if the model works as well for years in which this alternation occurs.)

Recession coefficients are calculated daily within SRM from the equation $Q_{n+1} = xQ_n^y$ (Martinec, Rango, Major, 1983), although SRM does allow one change to be input if necessary.

The coefficients were determined from the slope of a line drawn halfway between the 1:1 line and the lower envelope curve of a log plot of Q_n versus Q_{n+1}, as suggested for basins of this size by Martinec and Rango (1983).

Finally, the <u>time lag</u> value of 12 hours was taken from Colquhoun's (1971) previous work on snowmelt modeling in the Independence River basin, and verified through analysis of precipitation and runoff data for the watershed.

Other decisions in the process of model preparation included the treatment of additional precipitation during the study period, as mentioned earlier. While the snowpack was judged to be dry, or at least not fully "ripe", rain and snow amounts were added to the overall water equivalent at the start of the corresponding 15 day period. When the snowpack was at the point of melt (in 1987, this was determined to be by March 15), precipitation was considered available for immediate runoff, and not added to the water equivalent values remaining in the distributed model for each zone.

RESULTS

At the time of this paper, only one year's calibration of the SRM had been completed, that for 1987. Project objectives include at least four additional years of study, including the 1990 season for verification.

The snowmelt season of 1987 was one of constant snow cover until a week of high temperatures at the end of March, during which the majority of the snowpack was melted. The snowpack was fully ripe at the time of the melt event, having reached a density of .35 inches/inch (350 kg/m^3) at the beginning of the March 1-15 period. Precipitation (rainfall) inputs during and after the week of intense melt were judged to flow through the melting pack and enter as immediate runoff, and were thus not added to the daily water equivalent values.

SRM results for the 1987 run, as shown in Figure 2, were promising. As shown by the hydrographs, the volume and timing of the computed runoff both relate well to the observed flow.

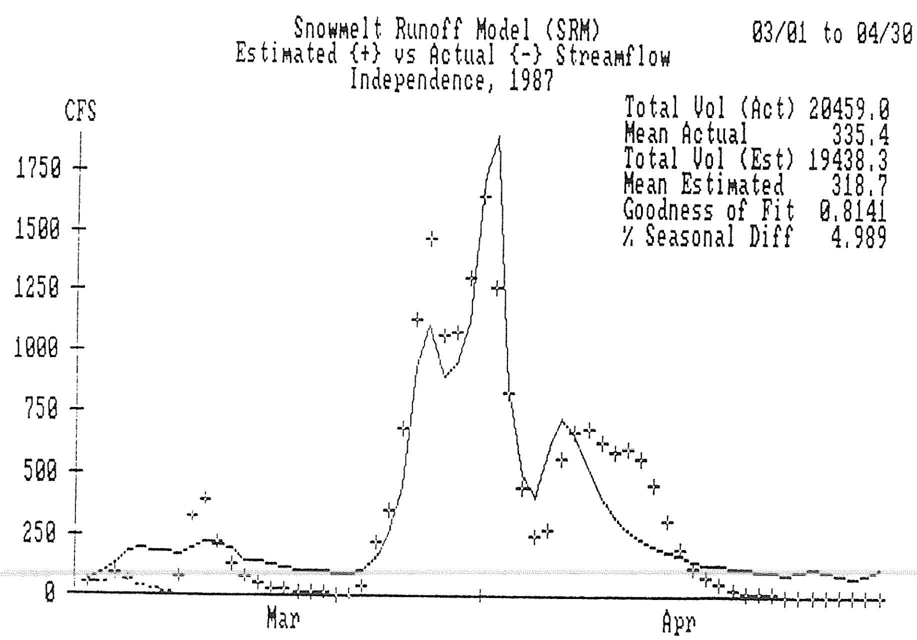

Figure 2: SRM output for 1987

Although differences in actual and estimated total volumes are quite small (with a percent seasonal difference of 4.989) and the hydrographs during the major melt event represent a good computed estimate, there are significant differences in base flow between the computed and actual hydrographs. Base flow was under-estimated and the smaller melt and/or precipitation events were over-estimated. In part this may be explained by the damping effect of the coarse sand deposit which underlies the main channel, on the basin response. This deep deposit's effects are also seen in rainfall hydrographs for the basin, which are much less flashy than those from comparable subbasins in the area.

The recession coefficient calculations may also be subject to additional refinement, although the major recession limb fit is obviously quite good.

GIS model results

The snow depletion computations derived from the irradiance index and degree-day data estimated a very short period of disappearance of snowcovered area, from a three day period for Zone 1, the lowest elevation zone, to a five day time span for the highest zone. However abrupt the snow depletion curves look, they do conform to the standard curve for this process and were sufficient for a successful test of the SRM for 1987. Figure 3 illustrates the depletion curves for the four elevation zones.

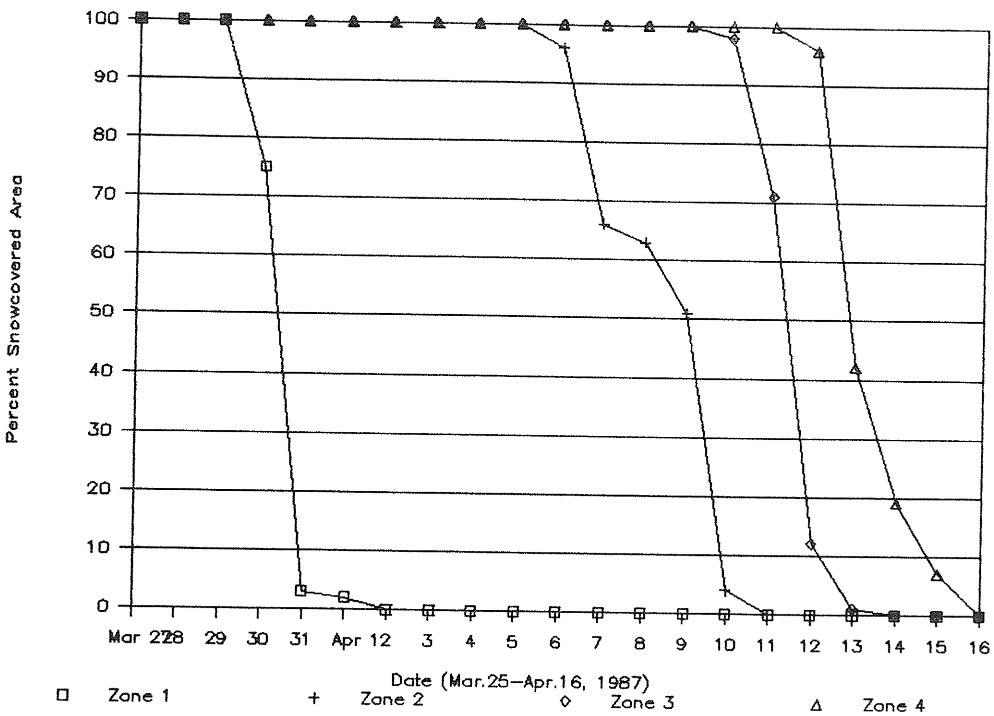

Figure 3: Snow depletion curves, 1987 season (Zone 1 is the lowest, Zone 4 the highest elevation zone)

EVALUATION

The successful results for 1987 are especially encouraging because of the various generalizations and rather subjective decisions made in analysis of SRM's basin variables and in the preparation of all basin parameters. The GIS model is quite primitive, with only one layer of attribute data, a spatial distribution of potential direct solar irradiance based upon averaged classes of aspect and slope facets in the watershed. With inclusion of other data layers of factors affecting snowmelt processes, especially that of forest cover in this project area, the index of irradiance values could be modified and refined to reflect more accurate distribution of snowmelt and thus snowcovered area.

Overall success of the model can only be judged after more years' calibration and verification. As mentioned already, the climate of the western Adirondack area and of northeastern uplands in general, is quite variable, with major thaws likely at any time during the winter months, and with rapid changes in snowpack conditions and depths throughout the season. It is possible that the SRM will be less adaptable to such climatic changes. GIS spatial modeling capabilities, however, should be especially applicable in these conditions, because of their ability to store and update many layers of data, and to provide rapid, repetitive analyses such as that of the melt computations outline in this project.

Ideally, the snowmelt runoff model itself would be built on a GIS platform, which would eliminate duplication of snowmelt computations as carried out in this project (one in the IDRISI melt computations, the other in the SRM flow equation), and allow distribution of climatic variables within the main model. This project's purpose, however, was to test the GIS snowcovered area estimates as substitutes for those obtained from satellite imagery or other remotely sensed data, for use in an existing snowmelt runoff model. The success of the distributed melt and snowcovered area computations from the simple index used in IDRISI encourages further and more complete analysis of geographic information systems as modeling tools in the spatial distribution of variables affecting snowmelt and runoff processes.

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