Modeling Snowmelt Runoff and the Effects of Climate Change in Central New York State

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Design discharge levels in ungaged watersheds are often developed through the use of regression-type equations or by simulating precipitation-runoff with a hydrologic model. Care must be taken when using regression equations as they represent a "best-fit" of the data and may not adequately describe rarer events, such as rain-on-snow or rapid snowmelt. Commonly used maximum precipitation estimates used for hydrologic modeling (e.g., U.S. National Weather Service, 1961) do not incorporate snowmelt contributions. This paper describes a study that looked at the frequency and magnitude of wintertime runoff events and how these compare to published maximum precipitation frequencies. The annual maximum runoff is compared to annual maximum precipitation for these stations. The trends in air temperature and the effects of climate change on runoff frequencies are also presented.

1. Estimating discharge for ungaged basins

Many smaller communities in the northern United States and Canada are plagued by ice jams and associated flooding. In order to properly design ice control and flooding mitigation efforts, knowledge must obtained on the stages and discharges associated with past and potential future events. While some communities may be fortunate enough to have United States Geological

Survey (USGS) or Water Survey of Canada stage gages in the vicinity to provide these data, smaller flood-prone communities are often located in ungaged basins. Design discharges and stages for ungaged basins are typically developed using regression-type equations or by simulating precipitation-runoff using accepted hydrological models (e.g., HEC-1/HEC-HMS).

The USGS (1994) developed a series of regional regression equations for the United States for estimating the magnitude and frequency of floods for ungaged sites, commonly termed the National Flood Frequency Program (NFF). It should be noted that this document presents a clear disclaimer, " …the use of hydrographs, computed from the NFF, are NOT applicable to watersheds whose flood hydrographs are typically derived from snowmelt runoff." As found in New York State, these equations are broken into several geologically and hydrologically similar regions. The equations for New York State (Lumia, 1991) were developed using peak discharge-frequency data and basin characteristics from 313 streamflow-gaging stations ranging in size from 0.41 to 4773 mi^2 (1.06 to 12360 km^2). The streamflow gaging stations had periods of record (both continuous and partial record) of 10 to 84 years. A generalized least-squares procedure was used to divide the state into eight distinct hydrologic regions. Regression equations were developed for recurrence intervals of 2 to 500 years. The analysis investigated the basin characteristics of drainage area, main channel slope, percent basin storage, mean annual precipitation, percent forested area, average main channel elevation, and a basin-shape index. The standard error of the regionalized equations for New York State ranged from 10 to 43 percent. The equations for the study area are of the form:

$$Q5 = 26.4 A^{0.979} SL^{0.272} \left(ST + 1\right)^{-0.189} SH^{-0.130} \tag{1}$$

where $Q5$ is the 5-year return interval discharge in ft^3/s, A is basin area in mi^2, SL is the main channel slope in feet per mile, ST is the percent basin storage (lakes, ponds, swamps), and SH is a basin shape index calculated as the ratio of the square of the main channel stream length in miles to the basin area in square miles.

Another widely accepted method for determining design discharges for ungaged basins is through the use of a hydrologic model. Many models currently exist and range from fairly simple to more complex. Most require some estimate of the precipitation onto a drainage basin and several basin and routing characteristics that describe how the rainfall makes its way to the river. Hydrologic abstractions such as evapotranspiration, infiltration, interception, and local storage are often included as are many routing techniques to transfer the excess runoff to streams and rivers. Some models, such as the U.S. Army Corps of Engineers HEC-1, include snowmelt routines.

Hydrologic modeling typically uses design precipitation events (e.g., 50 year frequency – 24 hour rainfall) to develop discharges. These can be obtained from various sources such as the Rainfall Frequency Atlas of the U.S, TP-40 (NWS, 1961). An interesting question is how the frequency of rainfall events corresponds to the frequency of the resulting basin discharges. Does a 50-year return period 24-hour rainfall result in a 50-year return period peak discharge? Peak non-snowmelt rainfall events generally occur during summer thunderstorms, when infiltration, evapotranspiration, and local storage losses are typically high. Peak runoff events, however, may occur during the winter months due to rain on snow or rapid snowmelt over frozen or semifrozen ground. As a result, these wintertime events may result in considerably higher discharge levels, even if the combined rain on snow/snowmelt amount is less than the non-snowmelt rainfall event. In order to properly model snowmelt or rain-on-snow events, the total amount of liquid water delivered to the ground surface must be determined. Estimates of the time distribution of the melt (over the length of a snowmelt event) are also required to properly model runoff and streamflow.

2.   Determining runoff from snowmelt

A modified version of the U.S. Army Corps of Engineers Streamflow Synthesis and Reservoir Regulation (SSARR) model, called SSARR_grid, was used to simulate snow water equivalent (SWE), snowmelt, and runoff for first-order and co-op weather stations in Central New York State. Figure 1 shows the locations of the NWS weather stations used in this study. NWS first-order stations were located at Syracuse, Albany, and Binghamton. The data for these stations included daily values of maximum and minimum air temperature, precipitation, snowfall, snow depth on the ground, and measured snow water equivalent (SWE). Hourly precipitation data was also available for the first-order stations. The data for the co-op stations included only daily values of maximum and minimum daily air temperatures and precipitation. The intent of the study was to model the entire period of record for these weather stations in order to develop frequency curves for the amount of water delivered to the ground surface in a 24-hour period.

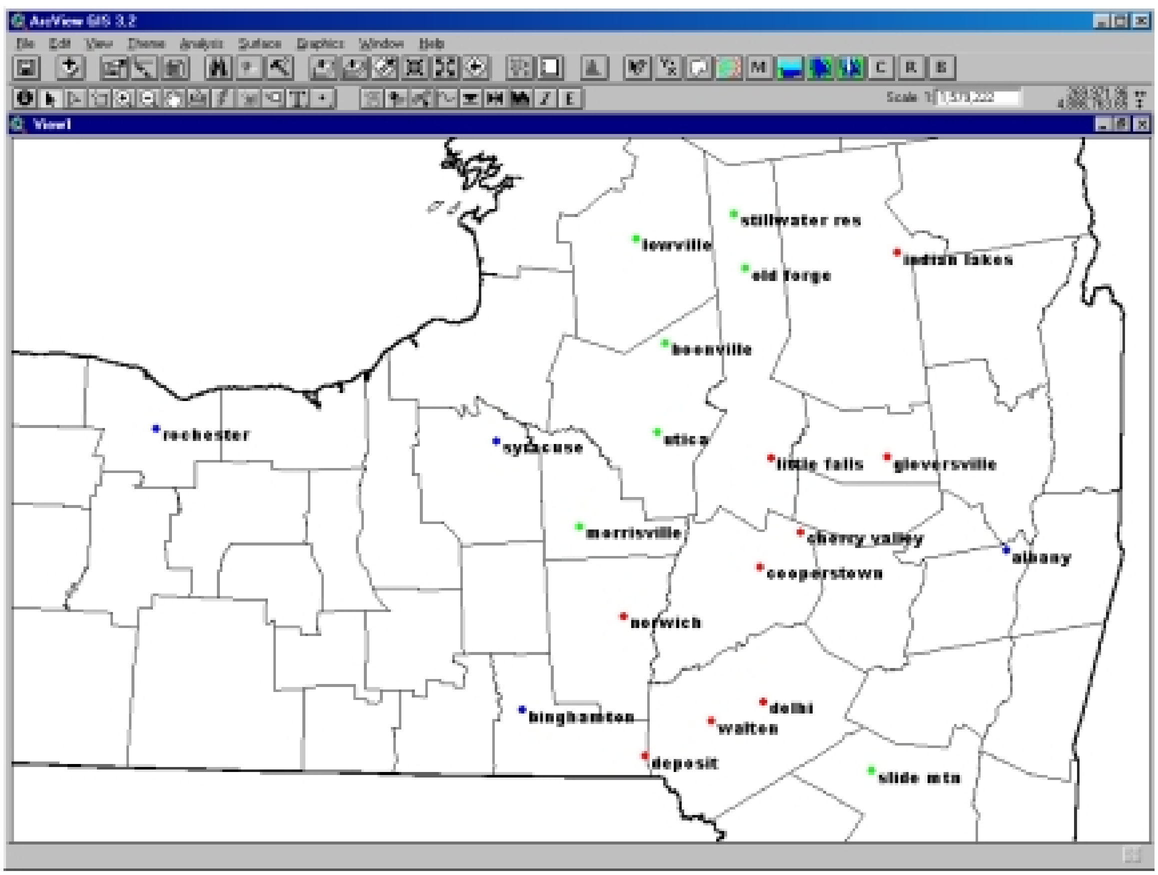

Figure 1   Locations of weather stations used in the study

SSARR_grid was extracted from the SSARR "Snow-Band" snowmelt computation, part of the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U.S. Army, 1991). This procedure estimates snow properties including the liquid water available at the ground surface for each time step. A time step may be any interval less than or equal to 24 hours. The snow process algorithm can be briefly described as follows:

- SSARR_grid accumulates precipitation as snow if there is precipitation and the air temperature is less than the set "base" temperature (generally 32°F).
- SSARR_grid will pass precipitation directly to the ground if there is no snow cover and the air temperature is greater than the base temperature.
- A melt rate coefficient describes how the melt rate can vary with time. In the present study the melt rate coefficient was set at a constant value throughout the winter season.
- A separate melt rate coefficient is included for rain-induced melt.
- The melt rate of the snow cover is equal to the melt rate coefficient times the difference between the air temperature and the base temperature.
- The cold content of the snowpack is simulated with an antecedent temperature index. The cold content accumulated during cold events must be satisfied before there can be melt runoff.
- Liquid water held in the snowpack is simulated with a "bucket" concept. The bucket's capacity is a percentage of the SWE that must be filled before melt water can runoff.

A schematic of the snow process algorithm is shown in Figure 2. For the present study, interception, evapotranspiration, and ground melt were assumed to be negligible. The melt rates were also assumed to be constant over the entire snow accumulation and melt period.

The SSARR_grid model was calibrated by adjusting the values of the base temperature, the temperature used to separate rain and snow events, the rain melt factor, and the snowmelt factor. A constant value of the snowmelt factor was used for the entire winter. The calibration effort used daily average air temperature (the mean of the reported maximum and minimum air temperature) and precipitation measurements for the three first-order stations for which SWE measurements were available. SWE measurements were available for Albany from 1948-1997, for Binghamton from 1951-1997, and for Syracuse from 1948-1997.

Several methods of SSARR_grid calibration were attempted. The first used measured daily values of average air temperature and precipitation to calculate daily values of SWE. These were compared to the measured daily values of SWE. The second method accumulated the measured hourly precipitation data for the first-order stations into 6-hour time periods. The air temperature was interpolated into 6-hour time periods and the SSARR_grid model was calibrated to the measured daily SWE values. The sum-of-squares difference between the SWE values calculated by SSARR_grid and the measured SWE was minimized using a downhill simplex method as described by Daly et al. (2000). This method belongs to a class of multidimensional minimization procedures. The accumulation of SWE and the timing of the snowmelt were the most important processes to model. Therefore, a third calibration used only the time periods of the winter in which the SWE was accumulating and melting, rather than the entire November

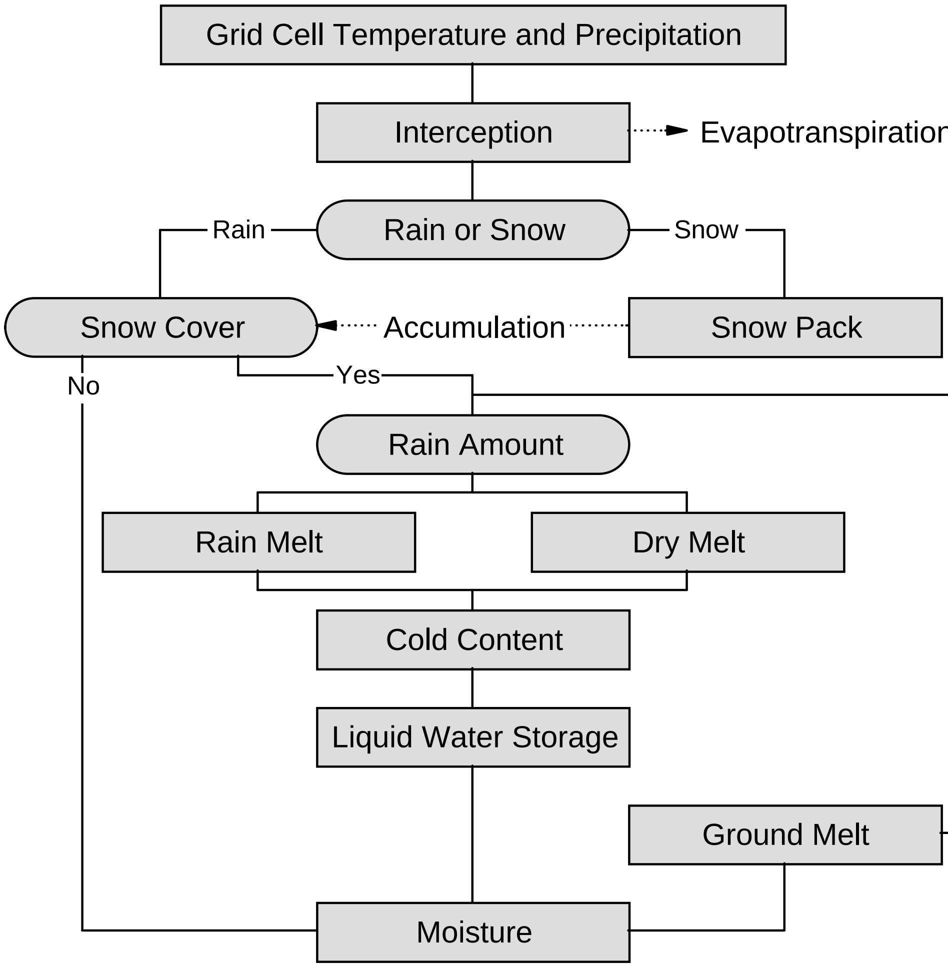

Figure 2 Schematic of the snow process algorithm.

through April period. Figure 3 shows the results of the calibration efforts and a comparison of the measured to modeled SWE for both the 24-hour and 6-hour time step. As can be seen from the figure, there is little difference between the two time step lengths.

Since the co-op stations did not have hourly precipitation values available, it was decided to use the calibration results based on the 24-hour time step. SSARR_grid coefficient values for the co-op stations were developed using an inverse distance squared relationship based on the calibrated coefficients for Syracuse, Binghamton, and Albany. The SSARR_grid model was then run for the period of record for all the co-op stations and the first-order stations. Table 1 shows the period of record for the stations.

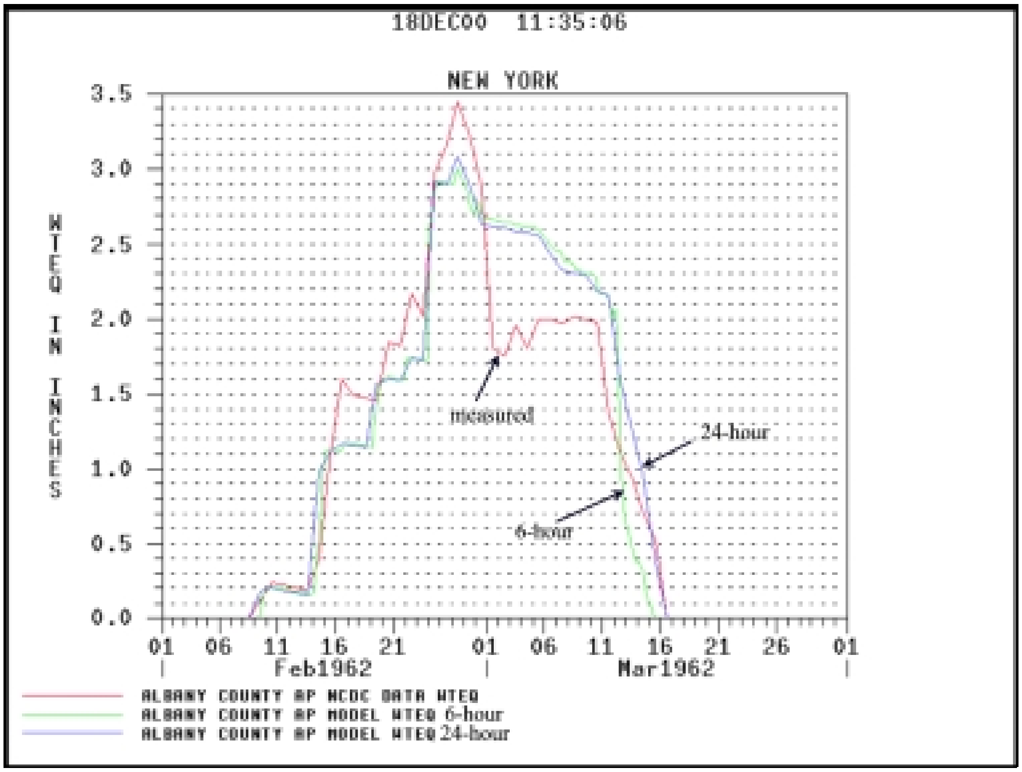

Figure 3 Calibration of SSARR_grid for 6-hour and 24-hour time steps

Table 1 Period of Record for First-Order and Co-op Weather Stations

Station	Elevation ft (m)	Period of record
Albany	273 (83.3)	1922 - 1997
Binghamton	1600 (487.7)	1926 - 1997
Boonville	1580 (481.6)	1948 - 1997
Cherry Valley	1360 (414.5)	1952 - 1997
Co-operstown	1200 (365.8)	1926 - 1997
Delhi	1440 (438.9)	1926 - 1997
Deposit	1000 (304.8)	1962 - 1997
Gloversville	900 (274.0)	1948 - 1997
Indian Lakes	1660 (506.0)	1948 - 1997
Little Falls	900 (274.3)	1926 - 1997
Lowville	860 (262.1)	1926 - 1997
Morrisville	1300 (396.2)	1926 - 1997
Norwich	1020 (310.9)	1926 - 1997
Old Forge	1720 (524.3)	1948 - 1997
Slide Mountain	2650 (807.7)	1960 - 1997
Stillwater Reservoir	1690 (515.1)	1948 - 1997
Syracuse	410 (125.0)	1922 - 1997
Utica	712 (217.0)	1950 - 1997
Walton	1480 (451.1)	1956 - 1997

3. Developing runoff frequencies

The results of the snowmelt modeling produced values of water delivered to the ground surface over 24- and 48-hour periods for the entire period of record for all the first-order and co-op stations. The annual peak value was obtained for each station, making sure that there was snow on the ground at the beginning of the melt period. An extreme value (Gumbel) distribution was fit to these values for each of the modeled stations. Values of water delivered to the ground for a given return frequency were then calculated as:

$$P_E = a - b\left(\ln\left[\ln\left(\frac{1}{\alpha}\right)\right]\right) \tag{2}$$

where P_E is the value of water delivered to the ground for the return period corresponding to α (e.g., for a 2-year return period, $\alpha = 0.50$), *a* and *b* are extreme value coefficients.

Figure 4 shows a map of the Mohawk River basin and the basins of the three tributaries for which ice jam flooding mitigation studies were being conducted. The three basins (Moyer Creek, Steele Creek, and Fulmer Creek, west to east, respectively) are ungaged. Steele Creek had a recording stage gage for two years in the late 1960's and some measure of peak flow (annual peaks) was obtained for a total of 18 years. The basins are largely rural and agricultural/forested with small population centers near their confluences with the Mohawk River. The proper design of ice control mitigation efforts would require estimates of the discharge expected in the three creeks during the winter period. We also needed estimates of the open water discharges expected during non-ice periods.

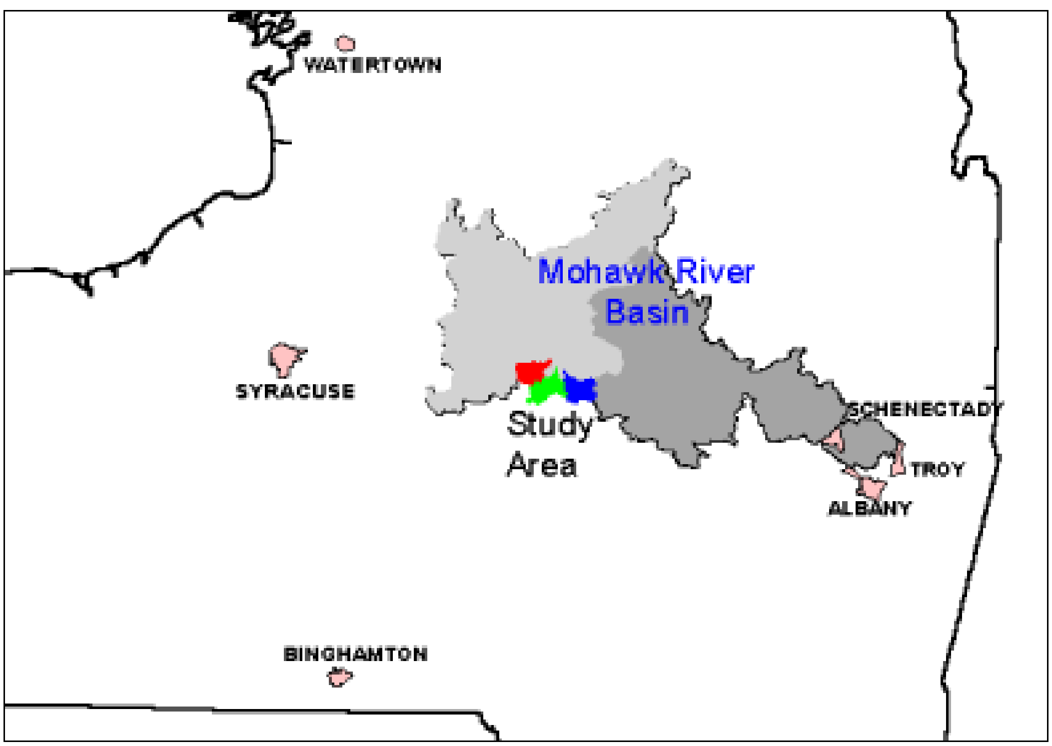

Figure 4 Map showing the Mohawk River basin and the study area

From inspection of past ice jam flooding reports and local newspaper accounts, it was suspected that snowmelt-induced ice cover breakup may result in more severe flooding than summer thunderstorm or hurricane-generated rainfalls. It was decided to model the basins using HEC-1 in order to estimate the discharges for several return period frequencies. These discharges would be used to determine both open water and ice jam stages for existing conditions and for the ice control mitigation plan. Standard maximum precipitation data (TP-40) would be used to calculate discharges for open water periods. The maximum water delivered to the ground frequency distributions developed above would be used to determine the snowmelt and ice breakup/jamming discharges.

The results of the snowmelt modeling and the frequency distributions developed for the first-order and co-op weather stations were analyzed to see how best to relate them to the three ungaged basins. The effects of latitude, longitude, and elevation on the maximum water delivered to the ground were investigated. Figure 5 shows a general plot of the 2, 25, and 100-year return period frequency runoff (water delivered to the ground surface) vs. elevation. Some of the variation in this relation can be attributed to latitude differences while some may be due to local variations in snowfall (lake effect snow storms off Lake Ontario). The final analysis separated the weather stations into southern and northern ranges for an elevation vs. runoff relationship. This relationship was used to determine the amount of water delivered to the ground in each HEC-1 modeled sub-basin of the three creeks.

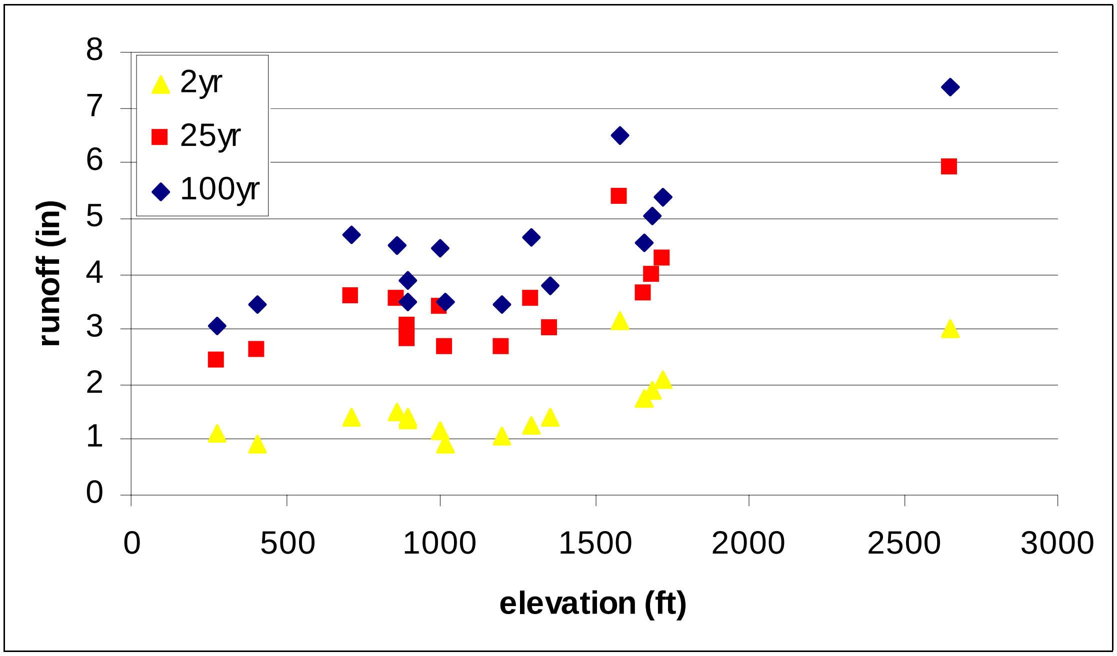

Figure 5 Runoff vs. elevation for the modeled stations (2, 25, and 100 year return periods)

4. Calculating design discharges

Design discharges were estimated using a hydrologic event-based simulation model, the U.S. Army Corps of Engineers HEC-1 flood hydrograph model, in which the rainfall-runoff process is simulated for discretized subbasins and channels to produce streamflow hydrographs. In HEC-1, the rainfall and infiltration are assumed to be uniformly distributed over each subbasin area.

Excess rainfall is determined by subtracting infiltration and detention losses. Factors that affect infiltration include hydrologic soil group, type of land cover, and antecedent (pre-storm) moisture conditions.

For the present study, the Synder Unit Hydrograph (UH) was selected as the rainfall-runoff transform method.   The Synder Unit Hydrograph utilizes physically-based parameters including estimated watershed slope, length, length to subbasin centroid, and land cover. The key Snyder UH coefficients are basin lag, which ranged from 1.0 – 7.7 hours, and the Peaking coefficient, which ranged from 0.12 to 0.79. The Synder UH loss rates were determined using the SCS curve number method.   Figure 6 depicts Steele Creek, one of the three creeks in the study area, showing the discretization of subbasins in the total contributing drainage area of approximately 27.3 mi^2 (70.7 km^2). Steele Creek consists of predominately B and C soil types with infiltration rates of 0.15 - 0.30 in/hr (0.38 – 0.76 cm/hr), and 0.05 - 0.15 in/hr (0.13 – 0.0.38 cm/hr), respectively. Channel slopes range from 0.01 - 0.08 ft/mi (0.005 – 0.04 m/km).   Sub-basin impervious land cover ranged from 0 - 32%. Design discharges were developed for both snowmelt and non-snowmelt conditions, using SCS curve number type 2 and 3 conditions, respectively. These curve numbers ranged from 55 to 75 for type 2, and 76 to 91 for type 3.

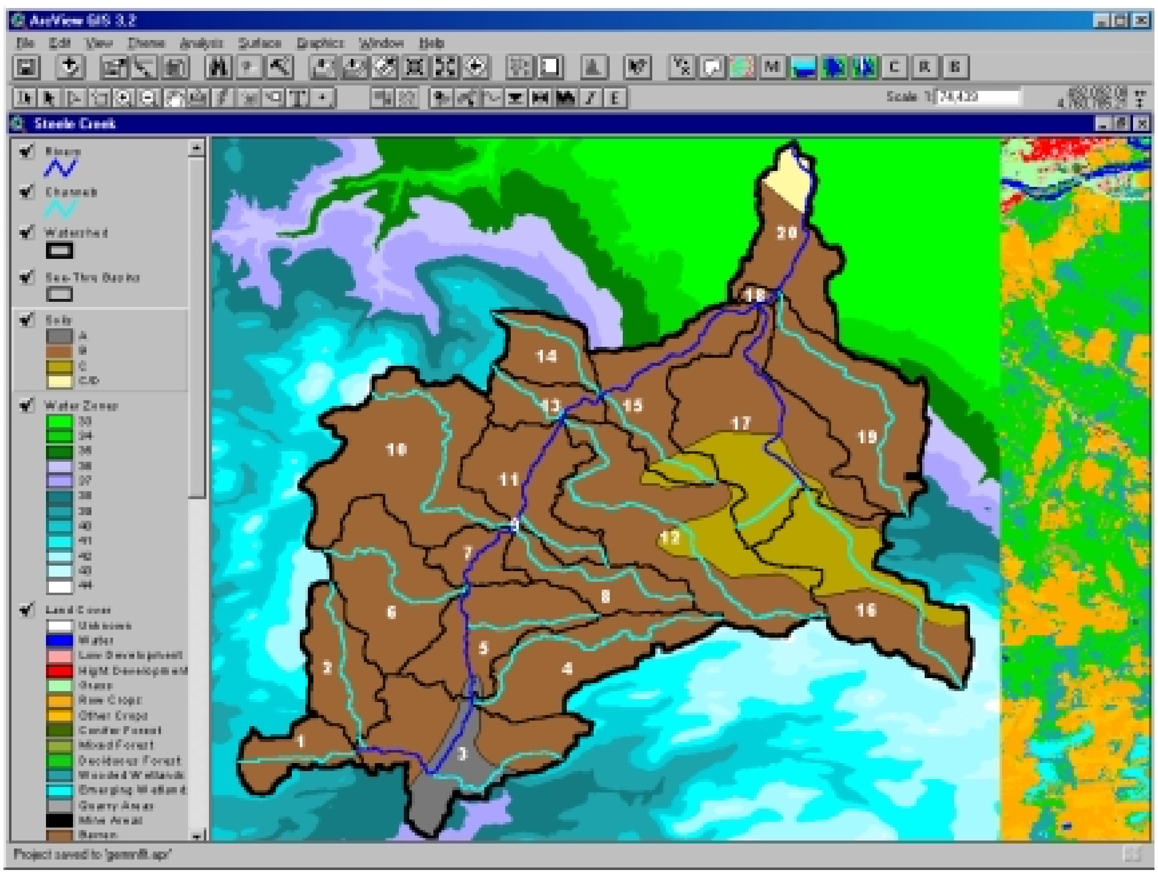

Figure 6   Steele Creek basin showing subbasin discretization

For the non-snowmelt conditions, the precipitation applied to the entire basin was uniform and taken from the Rainfall Frequency Atlas of the U.S, TP-40 (NWS, 1961). Type 2 SCS curve numbers reflect wet antecedent soil moisture conditions but allow for unimpeded infiltration and some detention storage. For the snowmelt conditions, the elevation vs. water delivered to the ground relationship was used to determine the amount of water applied to each subbasin dependent on the average elevation of the subbasin. For example, the 100-year return interval, 24-hour rainfall event is 5 in (12.7 cm) while the 100-year return interval, 24-hour snowmelt event ranged from 3.66 – 4.72 in (9.3 – 12.0 cm) depending on subbasin elevation. Type 3 SCS curve numbers reflect limited infiltration due to frozen or partially frozen ground and very limited detention storage. Figure 7 shows the distribution of the total precipitation amounts over the 24-hour period for both the rain only and the snowmelt modeling. The rain only distribution follows a classic 3rd quartile storm. The snowmelt distribution varies with and lags the temperature variation over the course of the day as reported in the SSARR model Users Manual (U.S. Army, 1991). Table 2 gives the calculated discharges for the rain only and snowmelt events for a variety of return periods.

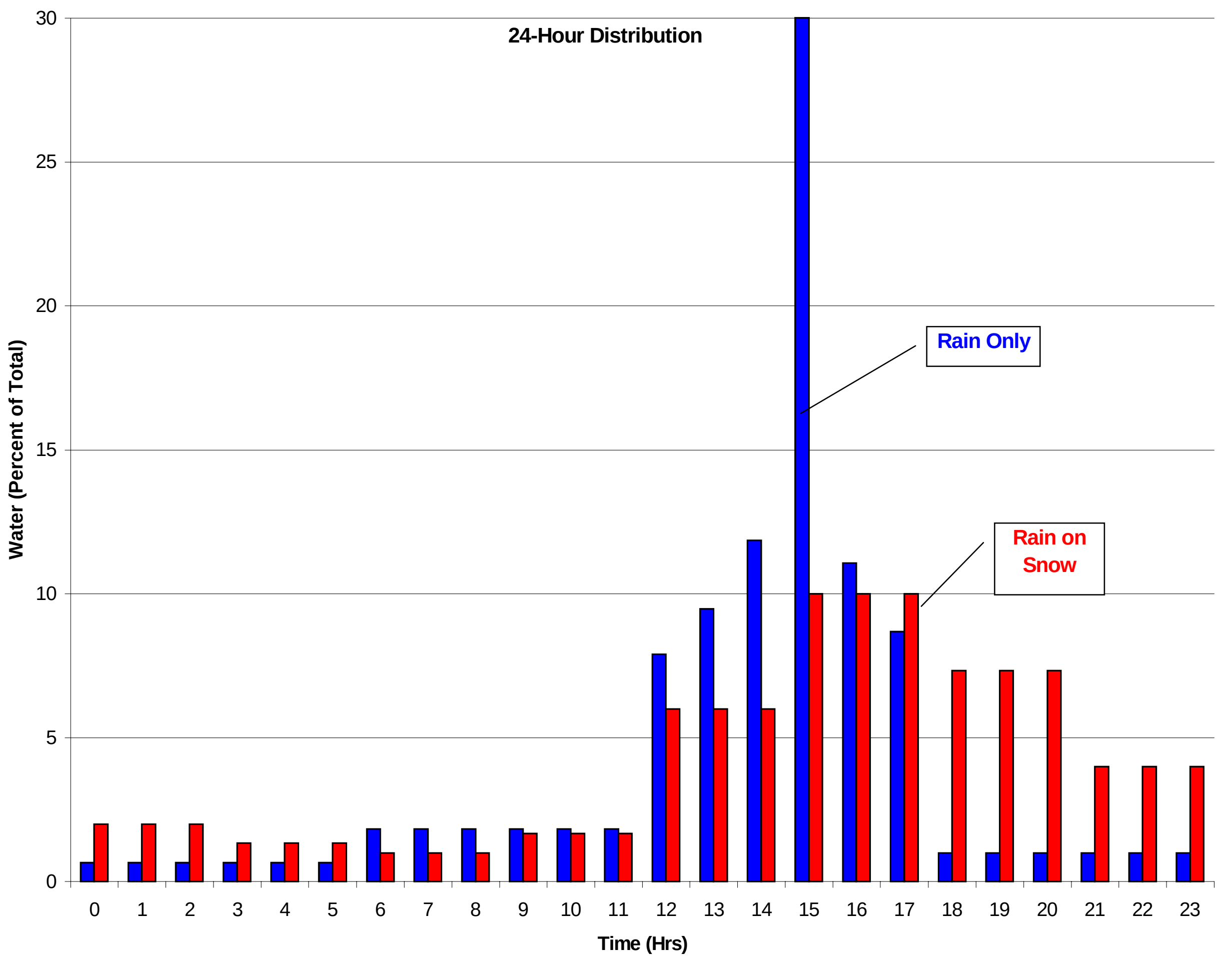

Figure 7 Distribution of total rain and snowmelt amounts over 24-hour period

Table 2 Calculated discharges for rain only and snowmelt events

Return Period	Rain only discharge	Snowmelt discharge
2-year	900	900
5-year	1475	1650
10-year	1750	2100
20-year	2350	2750
50-year	2950	3450
100-year	3350	4000
200-year	3800	4475
500-year	4350	5300

Figure 8 shows the final discharge frequency plots for the Steel Creek basin. As can be seen on the figure, the rain only frequency distribution compares very closely to the NFF Region 5 (regression equation) and also to the Log-Pearson Type III distribution based on the 18 years of peak data for the discontinued gage (FFA). The snowmelt discharge frequency curve exceeds the others and approaches the upper error bound of the NFF Region 5 curve. This shows that snowmelt is important for these basins and that the NFF Region 5 equations should not be used for determining discharge frequency.

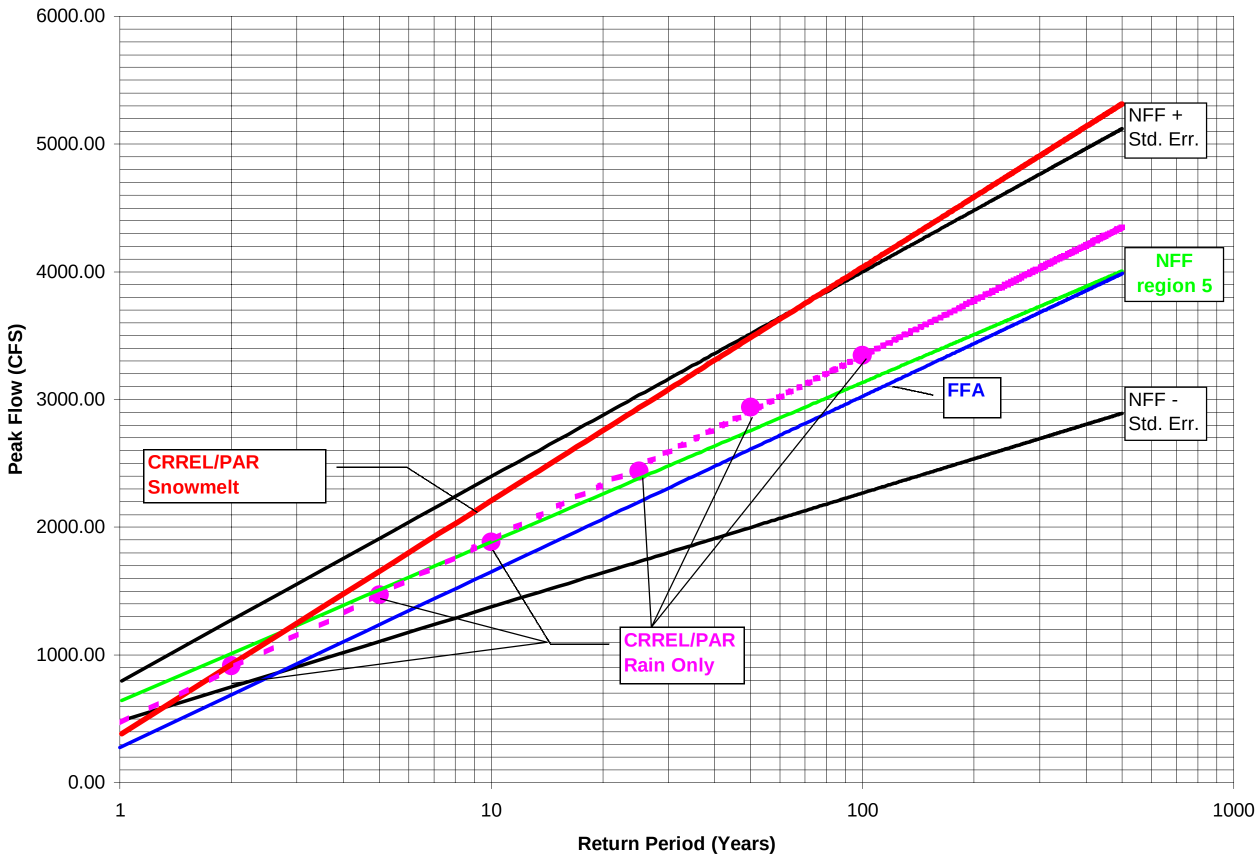

Figure 8 Discharge-frequency plot for Steele Creek

5. Climate trends in Central New York State

An analysis of the Syracuse data from 1922 to 1997 was conducted to determine if any definitive statements could be made concerning general trends in either air temperatures or precipitation. The Cox and Stuart test for trend was applied to monthly mean and standard deviation of the average daily air temperatures for January, February, and March. The trend test was also applied to the maximum daily and total monthly precipitation data for January, February, and March. While there appear to be some cyclic variations in both air temperatures and precipitation, there were only statistically significant trends in a few instances. The total monthly precipitation for both January and February show a downward trend. The standard deviation of the daily air temperature (from the monthly mean) showed an increase for January. Figure 9 shows the plot of total monthly precipitation for January, February, and March. A cyclic variation can be seen over time and that we are currently entering a period of increasing precipitation.

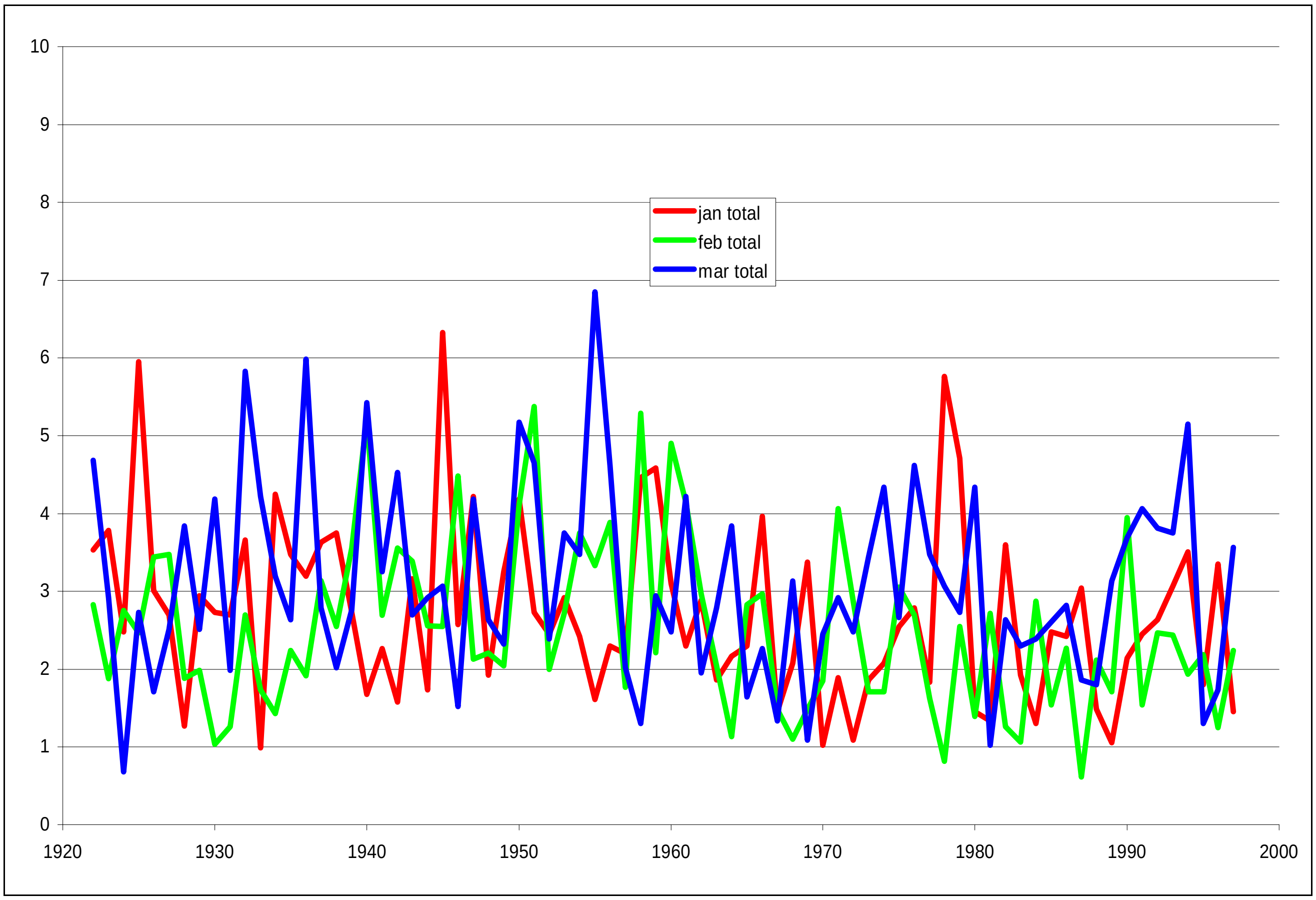

Figure 9 Total monthly precipitation for Syracuse, NY

The effects of the decreasing precipitation trends might lead one to expect that the snowmelt runoff is also decreasing. The increase in variability of January temperatures, or the occurrence of "January thaws", would increase the likelihood of snowmelt runoff events in January. It is possible that these two coincidental processes may indeed cancel each other out. Figure 10 shows the annual peak runoff due to snowmelt for Syracuse, NY separated into month of occurrence. It can be seen that significant January snowmelt events have not occurred since about 1970 and that significant February snowmelt events are quite rare. Since the early 1980's, runoff from snowmelt has been rather mild and appears to be decreasing, possibly from the effect of reduced precipitation amounts in January and February. A significant snowmelt event did occur, however, further to the east in January 1996 with 2.62 inches occurring at Albany, NY. That event caused ice jams and flooding throughout the mid-Atlantic coast and Northeast U.S. This points out the problem of using one weather station record to make generalized statements concerning the potential climate change for an entire region.

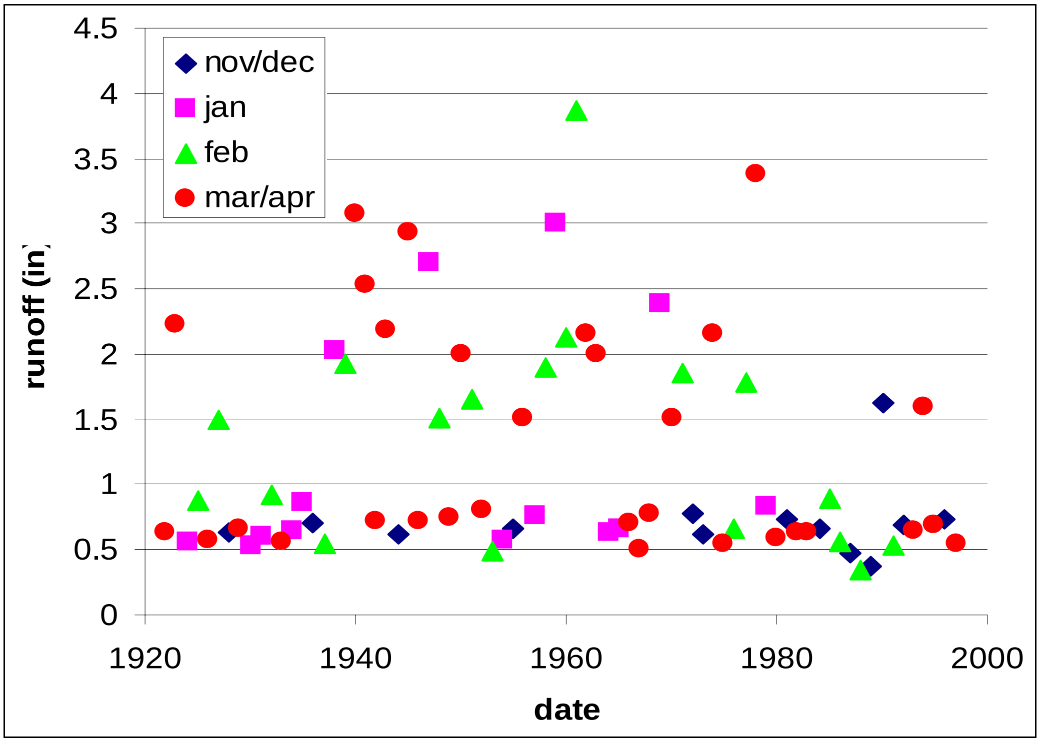

Figure 10 Maximum 24-hour snowmelt runoff depicting month of occurrence

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