Eastern Region Technical Attachment
No. 2010-01
April, 2010

Application of The KINEROS2 Site Specific Model to South-Central NY and Northeast PA: Forecasting Gaged and Ungaged Fast Responding Watersheds

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Editor's Note*: The original version of this Eastern Region Technical Attachment, published in March of 2010, contained an inadvertent error in Table 2 (p. 35) relating to local time for some river stages. The time(s) and associated text have been corrected in this updated version of the original Technical Attachment.*

ABSTRACT

Fast responding headwater river basins and small streams pose a significant threat to life and property throughout the eastern United States. This paper presents the results from the application of the real-time distributed model KINematic runoff and EROSion model (KINEROS2) to the complex terrain of the Binghamton County Warning Area. In operations, KINEROS2 uses the highest resolution radar data available, in both space and time, with the intent to improve flash flood warning lead time. KINEROS2 was originally developed for use in urban and semi-arid climates. This study demonstrates a proof of concept for applying KINEROS2 to a more humid regime. Key model parameters needed for manual calibration of peak flow generated by KINEROS2 in humid climates were identified. Saturated hydrologic conductivity of hillslopes had the greatest influence on the peak flow rate and channel length on the timing of the peak flow rate. It was found that optimal parameter values varied significantly between storms with respect to both basin average rainfall and maximum basin average rainfall intensity. This uncertainty in parameter estimation is addressed by running KINEROS2 with parameter sets that reflect the range obtained by calibration. An additional source of uncertainty is the selection of an appropriate Z-R relationship. KINEROS2 can be run for ungaged watersheds assuming some information can be collected on the timing and magnitude of several flow events. Running a distributed model on the small basin scale provides information on the magnitude and timing of a flash flood event which is not currently available using current NOAA/NWS flash flood forecasting methodologies.

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1. INTRODUCTION

This paper presents an overview of the KINematic runoff and EROSion model (KINEROS2), its use in real time forecasting for fast responding watersheds of the Binghamton Hydrologic Service Area, comparison to preexisting NWS methods for site specific modeling and flash flood forecasting, and future work with the model. In the mountains of the eastern United States, flash flood occurrence is typically concentrated in small headwater watersheds where steep terrain and higher terrain control both watershed time of concentration and higher annual rainfall totals as compared to lower elevation locations. KINEROS2 provides a forecast tool for small, fast responding headwater basins using high spatial and temporal resolution radar-based precipitation data.

2. KINEROS2 MODEL

KINEROS2 is an event-oriented, distributed, physically-based model developed to simulate the runoff response in basins having predominantly overland flow (Semmens et al. 2008). KINEROS2 has been successfully applied in a number of geographies including the US desert southwest, Western Europe, the Middle East, and Southeast Asia. KINEROS2 is maintained by the USDA Agricultural Research Service:

http://www.tucson.ars.ag.gov/kineros/

KINEROS2 simulates interception, dynamic infiltration-excess and saturation-excess surface runoff, with flow routed downstream using a finite difference solution of the one-dimensional kinematic wave equations over a basin conceptualized as a cascade of planes (hillslopes) and channels (Fig. 1). The kinematic wave equation is a simplification of the Saint Venant (de Saint Venant 1871) equations that combine continuity of mass with a relation describing discharge as a unique function of water depth or cross sectional area of flow. The kinematic approach is applicable to conditions of moderate to steep slope and no backwater (Woolhiser et al. 1967).

Runoff from infiltration excess occurs when the rainfall rate exceeds the rate at which the soil can absorb water. Runoff due to saturation excess occurs when the upper soil layer becomes saturated due to a restriction, such as shallow bedrock, regardless of rainfall rate. KINEROS2 does not account for downslope movement of subsurface soil water (lateral subsurface flow). Infiltration and saturation excess are not mutually exclusive, but climate and geography will determine which mechanism is dominant at a given location and time. Short, high intensity storms typical in subhumid and semiarid zones favors infiltration excess runoff, whereas saturation excess runoff is more common in humid areas, due to lower intensities and longer storm durations. In areas where lateral subsurface flow occurs, KINEROS2 may still be useful when the watershed responds more quickly to surface runoff.

3. AGWA

The Automated Geospatial Watershed Assessment (AGWA) tool is used to develop the input parameter file for the KINEROS2 model. AGWA uses nationally available standardized spatial datasets that are readily obtained via the Internet free of charge. These include the USGS Digital Elevation Model, NALC, MLRC land cover/land use data, and STATSGO, SSURGO, FAO soils data. AGWA is also maintained by the USDA Agricultural Research Service:

http://www.tucson.ars.ag.gov/agwa/

AGWA runs on ESRI GIS software and requires the baseline series (3.x or 9.x) as well as the corresponding Spatial Analyst extension.

AGWA allows the user to delineate the watershed boundary upstream of a user defined outlet point. AGWA will also discretize the internal elements within the watershed (contributing hillslope elements and open channel elements).

4. TRANSITION TO REAL-TIME MODELING

The transition of KINEROS2 to a real-time model was funded through a COMET grant (UCAR Award Number S03-44674). This effort was the result of collaboration between the researchers at the University of Arizona (UA), Pennsylvania State University (Penn State), the National Weather Service (NWS) Weather Forecast Office (WFO) located in Tucson, Arizona, and the hydrologists of United States Department of Agriculture Agricultural Research Service (USDA ARS) located in Tucson, Arizona.

The original edition of KINEROS2 had the time-loop embedded inside the space loop, in contrast to the reverse required for real-time forecasting, and therefore required considerable re-coding. KINEROS2 was re-coded from the original Fortran 77 to the newest standard (Fortran 90/95), which provides a number of enhancements including dynamic memory allocation and encapsulation of data structures and procedures into modules. More information on the re-coding of KINEROS2 can be found in Goodrich et al. (2006).

In addition to re-coding the model, a graphical user interface (GUI) was developed specifically for use at the WFO. The GUI displays graphs of both radar-derived rainfall and predicted runoff. The rainfall graph shows both accumulation and intensity, while the runoff graph shows stage and equivalent discharge rate hydrographs. An audible alarm capability is included to alert the forecaster when the maximum predicted stage level exceeds the critical stage or stages selected by the forecaster. The taskbar button will also flash to identify which watershed is in alarm mode when multiple watersheds are running on the same PC. A snapshot of the GUI at a given instant can be printed directly or saved as a JPEG image, or JPEG images can be automatically saved at regular intervals (e.g. for real-time internet publishing).

5. RUNNING KINEROS2 AT THE WEATHER FORECAST OFFICE

Running KINEROS2 at the WFO requires a PC running a Windows operating system and a source of real-time precipitation data. The precipitation data should be available on a drive mounted to the Local Area Network. The Digital Hybrid Reflectivity Scan (DHR) product from the WSR-88D (Weather Surveillance Radar 88 Doppler) radar was selected since it provides high temporal and spatial resolution and radar beam closeness to land surface of any WSR-88D precipitation products. The DHR product provides reflectivity and radar derived estimated rainfall values approximately every 4 minutes on a polarimetric grid of 1° by 1 km. The DHR product has been historically the default precipitation input for the Flash Flood Monitoring and Prediction (FFMP) program (see http://www.nws.noaa.gov/mdl/ffmp/basicTTs.htm). The FFMP program is widely used throughout the NWS during the flash flood warning process and utilizes the DHR product for similar resolution advantages.

The DHR product is extracted for each radar bin using a modified version of the NWS FFMP DHR decoder. KINEROS2 checks for new DHR products at regular intervals. This is configurable and currently a 30 second interval is used. When a new DHR product appears, KINEROS2 applies the user selected Z-R relationship and runs the new rainfall data through the model. The model then continues to simulate into the future for a prescribed forecast interval (e.g. 2 hrs) with an assumed rainfall condition current to the last volume scan of radar data. Currently, the model assumes no additional rainfall; however there are plans to use QPF in future versions (see section 10). When new DHR data arrives, the model ‘rewinds’ back to the end of the previous DHR interval, processes the new rainfall data, and simulates a new forecast interval. By doing this, KINEROS2 produces a new forecast hydrograph about every 4 minutes or on the interval that the DHR product is received.

6. COMPARISON OF KINEROS2 TO EXISTING NWS METHODS OF FLOOD FORECASTING IN FAST RESPONDING WATERSHEDS

The NWS has two primary means of predicting watershed response in quick responding watersheds: i) FFMP and ii) site specific. FFMP overlays the DHR product to small basin shapefiles. FFMP accumulates basin average rainfall for each small basin, and is made available for varying timeframes ranging from 15-minutes to 24-hours. FFMP basins in the CONUS have a mean basin area of 3.16 mi^2. Basin average rainfall values for each small basin are compared to gridded flash flood guidance values provided by the NWS river forecast centers and in some cases to local "rules of thumb" rainfall thresholds. FFMP allows the forecaster to accurately identify areas where flash flooding is likely. The forecaster can use this information to create a polygon warning for the area of heavy rainfall and those basins downstream that are expected to be impacted by rapid rises in small creeks and streams. FFMP provides information on basin names which can be used to insert basin names into flash flood warnings. FFMP, however, does not provide any information besides the fact that flash flooding is likely in a given grouping of small basins. It does not provide information on the timing of flash flooding or on the magnitude of the flash flooding (i.e. it does not answer the questions of when will flash flooding begin, reach its maximum, and end; how high will a given small stream rise, and will this cause minor, moderate, or major flash flooding). These questions are addressed, however, with a "site specific" model.

A site specific model is the name given to a model that is run at the WFO to produce a forecast hydrograph. Depending on the support provided by the river forecast center and the preference of the WFO, two models are available within the NWS. One model is the Kansas City Antecedent Precipitation

Index (API) Model and the other is the Sacramento Soil Moisture Accounting Model (SAC-SMA). Both models are lumped models, run on hourly time steps, ingest hourly rainfall from the Multi-Sensor Precipitation Estimator product (MPE), and allow the user to manually add Quantitative Precipitation Forecast (QPF) values in hourly increments. Requirements to set up a basin in either model include a defined rating curve, an hourly unit hydrograph, and flood stage. These requirements tend to be available when there is a stream gage. As a result, site specific models are generally run only on gaged basins.

KINEROS2 can be applied to either gaged or ungaged basins. Modeling a gaged basin provides a forecast hydrograph for the outlet of the basin which corresponds to the location of the stream gage. The model will also produce a forecast hydrograph for ungaged basins, but the results will generally not be as accurate as provided from a gaged basin due to more limited data available for calibration. More details are provided below in section 9B, applying KINEROS2 to ungaged basins.

KINEROS2 can be run with essentially any time step. For real time operation the model uses the interval between rainfall inputs as its computational time step, which is typically 4-minutes. This makes forecasting possible in basins which respond too quickly to be adequately simulated by the current NWS site specific models. KINEROS2 in this way can be thought of as essentially a site specific model applicable to a smaller scale. Limitations on basin size for applying the KINEROS2 model will be discussed in more detail later in section 13.

7. ADVANTAGES OF USING DISTRIBUTED MODELING TO FORECAST FOR FAST RESPONDING WATERSHEDS

Lumped models have historically been used by the NWS and have produced good river forecasts for rainfall events that are uniform over a given watershed. Lumped models tend to show increased uncertainty as rainfall becomes more unevenly distributed in space and time over a watershed, such as during convective rainfall events. The NWS has recently begun to deploy the Hydrology Lab Research Distributed Hydrologic Model (HL-RDHM) at select river forecast centers (Smith et al. 2004). As a distributed model, HL-RDHM uses structural elements of the SAC-SMA model and a kinematic routing procedure.

KINEROS2 likewise allows an accurate distribution of rainfall over the watershed and hence should provide an improvement over lumped site specific model simulations for convective rainfall events. Being a distributed model, KINEROS2 can provide a spatially distributed set of model parameters over a watershed, whereas parameters in a site specific model are lumped for the watershed as a whole. KINEROS2 holds an advantage over HL-RDHM in forecasting in small basins in that it runs off of finer resolution precipitation data and at smaller time steps.

8. STARTING AN EVENT IN KINEROS2

KINEROS2 is an event-based model as opposed to continuous model. An event-based model does not keep a long term accounting of soil moisture and base flow states as in a continuous model. As a result, it must be initialized at the start of each event. The forecaster must enter the following:

A.) Start date and time
B.) Base flow
C.) Soil moisture
D.) Radar Z-R relationship

The default start date and time is obtained from the PC's clock. The forecaster may either leave this as is or specify a different date and time. Since the local directory could store up to a days' worth of DHR data, if the model is started after the beginning of a rainfall event, the start date and time can be set back to include the beginning of the event.

If the initial base flow rate at the forecast point is known it can be included in the simulation. Base flow rates are distributed within the stream channel network such that the flow rate is zero at the top of the headwater channels and increases linearly through the network to the forecast point. Therefore, if there is base flow at the forecast point, all channel segments will also contain base flow. Base flow for ungaged basins will have to be estimated by the forecaster. There is an allowance for a default value such as the median low flow condition. The median low flow value can be obtained from USGS regression equations. The National Streamflow Statistics (NSS) Program website can be used to obtain this information (Turnipseed et al. 2007). The NSS allows the user to estimate both high and low flow statistics for ungaged sites across the United States.

The initial soil moisture condition in KINEROS2 is categorized as very wet, wet, dry, and very dry, which is represented in the model by soil saturation levels of 80%, 60%, 40% and 20% respectively. Initial soil moisture can be estimated based on the amount of time the soil has been allowed to drain since the last rainfall event which produced saturated conditions, as indicated by rainfall records and whether current streamflow is above or below the long term median. In general, very wet conditions are where the current flow is well above the long term median flow or where a hydrologically significant amount of rain has fallen within the preceding 24 hours. Wet conditions are those where the current flow is above the long term median flow or where a hydrologically significant amount of rain has fallen within the preceding 48 hours. Dry conditions are those where the current flow is below the long term median flow or where a hydrologically significant amount of rain has not fallen for several days. Very dry conditions are those where the current flow is well below the long term median flow or where a hydrologically significant amount of rain has not fallen for a week or longer. The user is encouraged to view USGS streamflow percentiles to aid in assigning values to initial soil moisture conditions. The USGS Water Watch page (http://waterwatch.usgs.gov/) displays a graphic of all USGS streamflow gages, in the United States, that have a percentile calculated.

The model is calibrated and run operationally using an optimal Z-R relationship. This is based on the premise that radar rainfall input into KINEROS2 is the single largest source of uncertainty (Yatheendradas et al. 2008). Since the KINEROS2 model structure is fixed and studied, external inputs to the model are the primary sources of error with rainfall as the largest contributor. A comprehensive global sensitivity analysis called the 'Sobol' method (Sobol 1993) is then applied for sensitivity of the different aspects of the hydrograph to all factors varied together. The single largest source of uncertainty due to the Z-R relationship was verified. Carefully selecting the Z-R relationship should produce a more robust calibration. The Z-R relationship is selected primarily by comparing rain gage reports to radar rainfall values and secondarily through mesoscale storm analysis.

KINEROS2 allows the forecaster to run the model using any Z-R relationship that is deemed best for the situation at hand. The standard approved NWS Z-R relationships are available from Table 1. In addition, a custom Z-R called Convective-Tropical Transitional was created by WFO Binghamton for use in KINEROS2. The Z-R is the exact mid-point between WSR-88D Convective and Rosenfeld Tropical. Through the calibration of multiple warm season convective events in KINEROS2, it was determined that the WSR-88D Convective Z-R relationship can underestimate rainfall in a significant number of cases while the Rosenfeld Tropical Z-R can overestimate in many cases. The user can also select any Z and R value to create a custom Z-R relationship. Creating a custom Z-R relationship is not something that the forecaster is expected to do in an operational setting. This was placed in the model to help the user calibrate the basin in situations where any of the above mentioned Z-R relationships do not produce a precipitation estimate that represents ground truth. This would be most commonly used in convective situations where the radar precipitation estimates are overestimated using the WSR-88D Convective Z-R. While this can be common in the desert southwest (Morin et al. 2005), it has been noted during this project in a limited number of cases.

9. APPLICATION OF KINEROS2 TO THE BINGHAMTON, NY COUNTY WARNING AREA

The County Warning Area (CWA) for WFO Binghamton encompasses south-central New York State and north-east Pennsylvania. The CWA contains many headwater streams and several regions of complex terrain including the Catskill Mountains of New York State. Such complex terrain makes flash flood potential moderate to high in many watersheds and fast responding basins are commonplace.

Field work was required to define channel element parameters that AGWA does not adequately define due to the 10m resolution of commonly available USGS Digital Elevation Model (DEM) data. These include up- and down-stream channel widths and an average Manning roughness coefficient for each channel element. These parameters were generally determined at bridge crossings. Bridge crossings usually did not correspond exactly with the up- or down-stream end of a channel element. As a result, trends in channel widths and Manning roughness were estimated. Channel widths were measured perpendicular to the channel with a tape measure. Manning roughness values were selected through visual comparison to sites of verified manning roughness values by the USGS (Barnes 1967). Average Manning roughness values incorporated both the manning roughness imparted by the bed material and the vegetation along the sides of the channel that would be encountered at medium to high flows.

KINEROS2 was calibrated manually for each event to match the observed timing and magnitude of the peak flow. Channel lengths of open channel elements were modified to obtain a best fit for the timing of the peak flow. The channel length was modified as the actual channel length is almost always greater than the length derived from the 10m DEM, due to channel sinuosity not captured by the DEM. Saturated hydrologic conductivity of overland flow planes was modified to obtain a best fit for the magnitude of the peak flow. Calibration was accomplished by adjusting global parameter multipliers. A parameter multiplier allows the user to proportionally adjust the parameter for all elements without having to edit the parameter value for each element individually. For example, a multiplier of 2 for the saturated hydrologic conductivity would double the original parameter value for each overland flow plane. This is based on the assumption that the soils and DEM data used to derive the initial model parameters are spatially consistent in a relative sense. In order to preserve the elevation drop when the length of a channel element is adjusted by a multiplier, the channel slope is also adjusted accordingly. If saturated hydraulic conductivity is adjusted by a multiplier, the soil capillary potential parameter is also adjusted based on a linear regression between the two parameters (Goodrich 1990).

A strategy for model calibration and the logic behind it is explained in more detail under the subsection for Platte Kill near Dunraven, NY. This was the first watershed to be calibrated and demonstrates the process. Section 16 provides a step-by-step guide to help users with their first calibration. Figure 2 shows a location map of all gaged and ungaged basins included in this study.

A. Gaged basins

A selection of gaged basins was used for calibration. Most of these were USGS stream gages. Drainage area also varied from relatively small headwater watersheds (24.7

square miles) to larger sized ones (241 square miles). Three of the basins were located in the Catskill Mountains of New York State. The Catskill watersheds are generally steep, forested, contain subordinate meadows, and have limited development.

1.) Platte Kill near Dunraven, NY

Platte Kill is a USGS gaged basin located near Dunraven in Delaware County, New York. It is a headwater basin of 34.9 square miles (Fig. 3). The watershed is largely forested along the ridges while valley bottoms contain farm land, pasture, and meadows. The watershed is minimally developed. Main areas of impervious cover are Route 28, Route 6, and the hamlet of New Kingston.

A total of ten events were selected for Platte Kill. The peak flows for these events range from a low of 648 cfs to a high of 3070 cfs. The flow corresponding to action stage (6.5 ft.) is 1940 cfs and 2430 cfs for flood stage (7.0 ft.). As stated above, calibration was performed for the timing and magnitude of the peak flow. Each event was calibrated individually. As a result, a total of ten saturated hydrologic conductivity and channel length multiplier pairs were obtained for Platte Kill. Each pair represents the best fit model parameters required to calibrate each individual event.

Figure 4 shows a plot of saturated hydrologic conductivity multiplier vs. channel length multiplier for these ten events. There is a significant amount of variation in both parameter multipliers for the ten events. No single parameter set can be applied to all events to run the model operationally. In addition, no clear trend is apparent in the model parameters.

In order to identify a trend, model parameters were examined with respect to both basin average and maximum basin average rainfall. The basin average rainfall from the start of the event to the time of peak flow was noted for each event. Events with basin average rainfall thresholds of 1.00 inch or greater were used. Basin average rainfall less than an inch of rain was considered incapable of producing a peak flow exceeding flood stage. Figure 5 displays results for the six events exceeding 1.00 inch. The four events clustered in the lower-left hand portion of Figure 5 ranged in basin average rainfall from 1.00 inch to 1.40 inches. The single event towards the center of the figure is a 1.97 inch basin average rainfall and the event at the far upper-right is a 4.00 inch basin average rainfall. There is a trend shown of increasing saturated hydrologic conductivity multiplier and channel length multiplier with increasing basin average rainfall. Plots of model parameter multipliers vs. basin average rainfall can be viewed in Figures 6 and 7. In summary, the multipliers are a function of rainfall. The greater the rainfall, the larger a multiplier that must be applied to saturated hydrologic conductivity or channel length in order for the model to produce an accurate peak flow simulation. The multipliers are used during the model calibration process and run in the background when the model is run operationally.

A representative hydrograph for modeled and observed flow can be seen in Figure 8. The simulation takes longer before it begins to respond to rainfall and must increase in discharge at a more rapid rate in order to reach the timing and magnitude of the peak flow in the stream gage record. The simulation results were in line with the timing and magnitude of the primary peak flow. The simulation failed to replicate the two smaller secondary peak flows. The ability of the model to replicate the primary peak flow is specifically due to the fact that it was calibrated for the magnitude and timing of the peak flow for each flow event included in the calibration. The model has reduced skill with simulating smaller secondary peak flows since it was not calibrated for such flows.

The characteristics of the simulated hydrograph are not unexpected, as the KINEROS2 model was primarily designed to treat surface runoff generation common in the southwest. The earlier rise in the observed hydrograph rise is likely due to lateral subsurface flow that is common in humid basins like the Platte Kill. The authors believe that these shortcomings can be overcome by adding a lateral subsurface flow component to KINEROS2.

The model for Platte Kill is run operationally using a parameter multiplier set approach to account for the trend in model parameters with changing basin average rainfall. The user will select the model parameter multiplier set corresponding to the basin average rainfall expected to produce the forecasted peak flow. Most of the time this will approach the storm total rainfall for the event, excluding some light rainfall at the end of the event. Each parameter multiplier set is a unique saturated hydrologic conductivity multiplier and channel length multiplier corresponding to a given basin average rainfall. As mentioned above, it is important to keep in mind that this is the basin average rainfall from the start of the rainfall event to the time of peak flow. If there is uncertainty in what is the most appropriate parameter multiplier set to select, the user could select multiple parameter multiplier sets that correspond to the most likely range of expected basin average rainfall values. If the final basin average rainfall deviates from those selected, the user can simply re-run the model using the most appropriate parameter multiplier set. Figure 9 shows KINEROS2 model output of two model parameter sets.

In addition to calibrating Platte Kill to basin average rainfall, the authors later evaluated if rainfall intensity was important. The authors found that there was a relationship of saturated hydrologic conductivity multiplier to the maximum basin average rainfall intensity (Fig. 10). A linear regression curve fit the data with a coefficient of determination (R^2= 0.99) higher than was observed when using basin average rainfall (Fig. 6). Figure 11 plots the relationship of channel length multiplier with respect to maximum basin average rainfall intensity.

Strictly speaking, the channel length and saturated hydraulic conductivity parameters describe invariant physical attributes that should not be a function of rainfall characteristics. However, the authors justify varying the parameters from the standpoint of obtaining a better operational result, with the understanding that they are accommodating an as yet unknown misrepresentation of either the underlying processes by the model and/or the by an inaccurate description of the physical system by the input parameters. Some possibilities include:

1. No lateral subsurface flow component in the model.
2. Small-scale topographic effects. The micro-topography model in KINEROS2 did not address the variation in saturated hydraulic conductivity between events, but it may not be an appropriate model for this geographic area.
3. The positive relationship between the channel length multiplier and event size as measured by basin average rainfall or maximum basin average rainfall intensity may indicate increasing hydraulic roughness with increasing stage as more vegetation is inundated. While there is some ability to model this within KINEROS using a compound channel representation it was not practical to explore at this time.
4. Important spatial variations in saturated hydraulic conductivity and/or other parameters that were not captured in the parameterization, so that the model does not respond appropriately to differences in spatial rainfall distributions between storms.

One goal of the calibration process is to identify and address these. In the meantime, since it appears that the accuracy of the model can be significantly improved by externally varying one or two key parameters, it makes sense to do so.

2.) East Brook near Walton

East Brook near Walton is a 24.7 square mile USGS-gaged basin located just upstream of the Town of Walton (Fig. 12). Walton is one of the largest communities in the Catskills (about 2,800 residents); therefore the amount of impervious cover within the gaged basin is minimal. East Brook has historically flooded portions of Walton just downstream of the stream gage. The most recent historical floods were in June 2006 and January 1996. East Brook is composed of a main channel and a series of tributary streams that are generally symmetric about the axis of the channel. A total of 25 open channel elements and 63 overland flow units make up the model (Fig. 12).

In addition to modifying channel widths and Manning roughness coefficients from data collected in the field, it was noticed that one open channel element located in the headwaters of the watershed contained two ponds or small lakes according to the land use cover (Fig. 13). However, upon closer inspection using detailed aerial imagery, it could be seen that this channel segment contained additional bodies of water that were too small to be identified by the spatial resolution of the land use cover (30 meters). Areas of what appeared to be in-channel wetlands were also noted. To account for the increase in flow lag time through the wetlands, channel roughness was further increased for this particular open channel element. Upon field inspection it may be possible to model these wetlands or impoundments as a detention pond but additional information on pond geometry and outflow ratings would be required.

A total of ten events were selected to calibrate East Brook. These ranged from the flow of record on June 2006 of 7110 cfs to low flow events in the 200 to 900 cfs range. Only three of the events available for calibration were either considered to be high-water events near bankfull flow or above flood flow. Figures 14 through 17 show the relationship of model parameter multipliers with respect to basin average rainfall and maximum basin average rainfall intensity. Model parameter multipliers displayed a better relationship with respect to maximum basin average rainfall intensity than to basin average rainfall.

3.) Beaver Kill at Cooks Falls, NY

Beaver Kill at Cooks Falls is a USGS gaged basin located along the southern terminus of the Catskill Mountains in Ulster, Delaware, and Sullivan counties New York. Beaver Kill is a 241 square mile watershed. It is composed of a North Branch which intersects steeper terrain and the Willowemoc Creek which can be thought of as the southern branch of the watershed. Each branch makes up roughly half of the drainage area (Fig. 18).

Eight events were available to calibrate Beaver Kill. One event had enough uncertainty as to the correct Z-R relationship that two Z-R relationships were applied to this event resulting in a total of 9 data points for calibration. Unlike the calibration of smaller basins (e.g. Platte Kill near Dunraven), no clear trend in model parameters was seen with respect to basin average rainfall (Figs. 19 and 20). A trend was noted, however, when comparing saturated hydrologic conductivity with maximum basin average rainfall intensity, but not with respect to the channel length multiplier (Figs. 21 and 22). Because there was no clear trend in the channel length multiplier, an average value of 1.66 was selected.

As with Platte Kill, KINEROS2 for Beaver Kill is run using parameter multiplier sets. Parameter multiplier sets in this case will be run based on maximum basin average rainfall intensity.

4.) Callicoon Creek at Callicoon, NY

Callicoon Creek at Callicoon is a USGS gaged basin located in Sullivan County, NY. It is a 110 square mile watershed. It is composed of an East Branch and a North Branch (Fig. 23). Both the East and North Branch contain man-made lakes. Additional lakes and ponds are located on tributary streams to the East and North Branch. As was described in the section for East Brook near Walton, the Manning roughness coefficient was increased for each open channel element containing one or more bodies of water to help account for the peak flow attenuation. The USGS stream gage is a stage-only site and no longer maintains a discharge to stage relationship. In 1999, the weir at the site was destroyed by a flood. Since then the USGS Office of the Delaware River Master takes occasional low flow measurements. NWS has taken these more recent low flow measurements and the historical high flow measurements (1941 – 1999) to create a rating curve for the site. This curve agrees well with the USGS rating curve in effect in the late 1990's prior to the loss of the weir. Since KINEROS2 is not planned to be used for low flow prediction, this rating curve is considered by the authors to be appropriate for forecasting moderate to high flow events.

No good trend was seen with respect to model parameter multipliers with respect to basin average rainfall (Figs. 24 and 25). A trend however is present with respect to saturated hydrologic conductivity multiplier and maximum basin average rainfall intensity (Fig. 26). The channel length multiplier with respect to maximum basin average rainfall intensity displays significant scatter and no clear trend (Fig. 27). An average of channel lengths will be selected with respect to running the model operationally.

B. Ungaged basins

It's common that flash flooding events will occur in small streams that are ungaged. It is not practical to gauge every small watershed that is flash flood prone. There tends to be a bias for a higher density of stream gaging in small watersheds with higher populations, more proactive local interests, or some combination thereof.

While flash flood guidance and the FFMP program answer the questions of where (the flash flood will occur), they cannot answer the questions of when, how high, and what will be impacted (i.e. minor, moderate, and major flash flooding). If a model can be calibrated with limited data and applied to ungaged basins, it would provide a tool to answer these unanswered questions.

KINEROS2 has been applied to two ungaged basins situated in the Catskill Mountains. Both basins are small headwater basins contained within the Beaver Kill at Cooks Falls basin (Fig. 28). These watersheds were impacted by a record flash flood on June 19, 2007. This flash flood resulted in four fatalities, homes being washed off of foundations, and reports of a "wall of water" in the lower portion of Spring Brook. The magnitude of peak flow was documented by the NWS through a single cross section slope conveyance method performed along Berry Brook. The timing of the flow event was documented from accounts from local residents who were home at the time of the flash flood. The timing of both the onset of rising water along Berry Brook and the peak flow were documented. Additional information was collected on the ground truth rainfall from the event and timing of the onset of flash flooding. These details as well as an analysis of the atmospheric conditions for this flash flood event can be found in NWS Eastern Region Technical Attachment 2008-05 (Schaffner et al. 2008). An online copy of the technical attachment can be viewed at:

http://www.erh.noaa.gov/er/hq/ssd/erps/ta/ta2008-05.pdf

In addition to the flash flood of record for these two watersheds, a second and smaller flash flood impacted both basins on July 23, 2008. Once again, information on the timing of the event was obtained from local residents for Berry Brook and from the county office of emergency management for Spring Brook. An estimate of the peak flow relative to June 19, 2007 was obtained for both watersheds. These two events serve as the starting point to perform a rough calibration on a small ungaged basin. Unlike a gaged basin where KINEROS2 can be calibrated to predict both the magnitude and time of a peak flow, KINEROS2 is more limited when run on ungaged basins.

It is envisioned that KINEROS2 can be used operationally for "categorical forecasting" for ungaged basins. Categorical forecasting involves predicting a category of flash flooding (i.e. minor, moderate, or major) as opposed to an exact discharge/gage height that the peak flow will rise to. Categorical forecasting is commonly done by NWS river forecast centers for river forecast points along mainstem rivers in situations where a stream gage is no longer available. If the timing of the peak flow is known (as was the case for these two basins), KINEROS2 can be used to provide the time of peak flash flooding for ungaged basins.

1.) Spring Brook near Roscoe

Spring Brook near Roscoe is an ungaged basin located in the Catskill Mountains. It has a drainage area of 9.0 square miles at the landing strip near its outlet with the Beaver Kill. It is composed of a main branch and a smaller Little Spring Brook (Fig. 29). The vast majority of the watershed is forested. Areas near the valley bottoms are the only portions of the watershed to contain much in the way of development. The most pronounced development is along Route 206 which runs the length of the main branch from near the outlet up-valley to the watershed divide. Approximately 120 free-standing structures were identified within the watershed by the NWS using high-resolution aerial imagery.

Calibration of the model using the June 19, 2007 and the July 23, 2008 events resulted in a trend similar to Platte Kill of increasing the saturated hydrologic conductivity multiplier with respect to increasing basin average rainfall (Fig. 30) and maximum basin average rainfall intensity (Fig. 31). The small number of data points does not permit a regression analysis.

The calibrated June 19, 2007 event produced a model result that corresponded well to the timing and magnitude of the onset of both moderate and major flooding and the peak flow (Fig. 32). The rising limb experienced a later response than reported, but this was not unexpected as noted earlier in the discussion of the Platte Kill model performance.

2.) Berry Brook near Roscoe

Berry Brook near Roscoe is an ungaged basin located in the Catskill Mountains. It has a drainage area of 4.6 square miles just below the old landing strip. It is composed of a main branch and a smaller Hendricks Hollow (Fig. 33). The vast majority of the watershed is forested like Spring Brook. Likewise development is largely confined along the main watercourse. Approximately 25 free-standing structures were identified within the watershed by the NWS using high-resolution aerial imagery.

Calibration of the model using the June 19, 2007 and the July 23, 2008 events resulted in a trend similar to both Platte Kill and Spring Brook of increasing saturated hydrologic conductivity multiplier with respect to increasing basin average rainfall (Fig. 34) and maximum basin average rainfall intensity (Fig. 35).

The relationship of saturated hydrologic conductivity multiplier with respect to maximum basin average rainfall intensity can be viewed in Figure 36. Both Spring Brook and Berry Brook displayed significant variation in the saturated hydrologic conductivity multiplier with little variation in maximum basin average rainfall intensity.

Platte Kill in contrast showed a nice trend of increasing saturated hydrologic conductivity multiplier over a wide range of maximum basin average rainfall intensity values. East Brook showed less variation though the range of rainfall intensity values, available from the calibrated events, was capped at 2 inches per hour. It is unclear if the pattern shown by Spring Brook and Berry Brook is indicative of the small size of the sample set or is an accurate portrayal of the watersheds rainfall intensity response within KINEROS2. Until this is known, it is wise to use basin average rainfall as opposed to maximum basin average rainfall intensity for input to parameter multiplier sets for these two smallest basins.

10. EFFECT ON WARNING LEAD TIME FOR PEAK FLOW AND USE OF QUANTITATIVE PRECIPITATION FORECASTS

A model using observed precipitation cannot provide warning of an impending flood crest at a time earlier than the lag time of that watershed. Lag time is defined as the time measured between the center of a mass of rainfall and the center of a mass of runoff at the outlet of a watershed. Lag time for a watershed is largely a function of the geometry of the watershed and does not change appreciably through time unless development takes place. Development of the watershed by increasing impervious cover and paving channel bottoms or reducing channel meanders tends to decrease lag time. An example of lead time using KINEROS2 vs. current lumped modeling is provided for the Beaver Kill at Cooks Falls, NY in Table 2. While both KINEROS2 and the River Forecast Center under-simulated the peak flow, KINEROS2 provided a forecast closer to flood stage and with additional lead time.

Using observed precipitation, a model can provide the maximum warning when the highest resolution rainfall (temporal and spatial) input is used as is the case for KINEROS2. If KINEROS2 was required to provide warning of an impending flood crest with a greater lead time than the watershed lag time, the model must also use a quantitative precipitation forecast (QPF). Warning lead time of peak flow would then equal watershed lag time plus the timeframe covered by QPF. For example if a given watershed has a lag time of 2 hours and 1 hour of QPF is added, the resultant warning lead time for the peak flow should equal 3 hours. With the addition of model QPF, KINEROS2 accuracy will not only be a function of radar rainfall estimation accuracy, but will also depend on the accuracy of the QPF forecast. QPF has the potential to be a large source of error. The forecaster can use precipitation NOWCASTING or QPF available from local models. To minimize model overestimation due to selecting too large a QPF value, the user may want to consider using a likely QPF as opposed to a worst case scenario QPF.

At the time of writing, QPF is not available in KINEROS2. Adding QPF is a planned enhancement to the model and is slated to be available by the middle of 2010. QPF will be entered manually with a temporal resolution of 30 minutes and rainfall will be assumed to be evenly distributed over the watershed.

11. PARAMETER MULTIPLIER SELECTION

The largest source of error is the selection of the appropriate Z-R relationship. This is followed by the selection of an appropriate parameter multiplier set. For the case of multipliers based on maximum basin average rainfall intensity, as long as the maximum basin average rainfall intensity does not increase significantly from that assumed by the forecaster, the result will still be valid. If the maximum basin average rainfall intensity does increase significantly, the model should be restarted from the beginning of the event with another ensemble based on a revised assessment of the anticipated maximum intensity.

For parameter multipliers based on basin average rainfall, the forecaster must select an ensemble corresponding to the expected accumulation of rainfall prior to the peak flow. If rainfall accumulation appears to be diverging from the forecaster's expectations, the model can be restarted from the beginning of the event with a more appropriate parameter multiplier set. A proposed best practice is for the forecaster to place added confidence in the modeled solution when the basin average rainfall is approaching the average of the gridded flash flood guidance for that watershed.

Both basin average rainfall and maximum basin average rainfall intensity should be evaluated during the calibration process. If both produce robust parameter multiplier sets, either or both can be implemented operationally. Otherwise, the parameter multiplier set that produces the better regression should be used.

The authors are planning to automate the process of selecting and updating parameter multipliers. The program will monitor the appropriate storm metric (basin average rainfall or maximum basin average rainfall intensity) and update the parameter multipliers when pre-determined thresholds are crossed. Basin average rainfall would be the sum of the rain already fallen (according to given Z-R relationship) plus the current QPF. Due to the difficulty in forecasting maximum basin average rainfall intensity, multipliers will be updated using the maximum intensity that has occurred prior to the current time. After revising the multipliers, the program will recompute the entire hydrograph, from the beginning of the storm, using the new multipliers. Which storm metric is used for a particular basin can be specified in the configuration file, along with a table defining the thresholds and associated parameter multipliers.

12. FUTURE WORK

As mentioned above, the authors plan to add QPF to the model in the near future and the ability to automate multiplier selection and recomputation of the hydrograph. The authors also plan to test the model at another NWS WFO in the eastern US. In particular, watersheds with a high degree of urbanization are being sort out. Three steep urbanized basins in the WFO Pittsburgh area have been selected for this purpose. In addition, KINEROS2 is to be tested under the HOSIP process at a minimum of one WFO per region of the NWS. This would result in testing the model at a minimum of 4 WFOs in addition to WFO Binghamton. The WFOs would be representative of various regional differences in climate, terrain, and land use.

The authors also recognize the inherent limitations of running an infiltration excess runoff model in a humid climate regime. The authors have been awarded a COMET grant (UCAR Award Number S09-75794) for a proposal entitled "NWS Flash Flood Forecasting in Two Hydrologically Distinct Regions Using an Improved Distributed Hydrologic Model." The project is under the direction of the University of Arizona (UA) Surface Hydrology Group. A graduate degree candidate at UA began working on the project during the fall 2009 semester. Also involved are researchers from Pennsylvania State University and USDA-ARS. NWS involvement will be from WFO Binghamton and WFO Tucson. WFO Binghamton has been assigned the role of principal investigator from the NWS. The project seeks to couple a subsurface flow model with KINEROS2. The researchers in the same effort would couple an energy balance snow model with KINEROS2. Such a model would allow KINEROS2 to function as a full four season model and not be restricted to only warm season rainfall events as is the current limitation. Such a model would be expected to handle both rain-on-snow and rapid snowmelt scenarios.

13. SUMMARY, DISCUSSION AND CONCLUSIONS

The KINEROS2 model has been successfully applied to the humid climate and complex terrain of the Binghamton WFO for the forecasting of peak flood flows in fast responding watersheds. A summary of basins used in the study with results can be located in Table 3. Forecasters running the KINEROS2 model do so using a parameter multiplier set approach. The parameter multiplier(s) selected should be based on the expected amount of rainfall that will create the peak flow. Parameter multiplier sets can be based on basin average rainfall and/or maximum basin average rainfall intensity for small basins (4 - 50 square miles). In general, parameter multiplier sets based on maximum basin average rainfall intensity provide a more robust calibration as indicated by the coefficient determination (R^2) and regression line fit to the data. Parameter multiplier sets were based exclusively on maximum basin average rainfall intensity for basins larger than 50 square miles.

A trend of increasing saturated hydrologic conductivity with increasing rainfall has been seen, with respect to an increase in quantity of rainfall (i.e. basin average rainfall) for small basins, or intensity of rainfall (maximum basin average rainfall intensity) for large sized basins.

Each watershed must be calibrated individually from the default model parameters provided by AGWA. Field work to determine an accurate representation of channel roughness and widths is required for both gaged and ungaged basins. Calibration must include use of a reasonable Z-R Relationship for that event as a whole. Likewise, the model is to be run in real-time using a Z-R Relationship that is representative of ground truth rainfall reports available at the time and mesoscale analysis of the storm event.

KINEROS2 provides a unique tool for site specific forecasting not formerly available with the NWS. The model allows the WFO to provide warning services for both gaged and ungaged watersheds as small as 4 square miles and up to 250 square miles. The ability to run KINEROS2 on either gaged or ungaged basins are a benefit over existing NWS site specific models which can only be run on gaged basins.

The distributed model framework with the highest temporal and spatial resolution rainfall possible produces a robust modeling framework to handle any watershed whose reaction time is all but instantaneous. KINEROS2 compliments FFMP and RFC Flash Flood Guidance by providing information beyond simply when to issue a flash flood warning, but how high will the water get, when will the worst flooding take place, and what will be impacted. The models' use of geographic datasets allows watersheds of virtually any combination of land use, soil type, and topographic steepness and shape to be effectively modeled. The models' use of distributed rainfall input allows storm motion to be taken into account. Particularly dangerous storm tracks such as storms propagating from upstream to downstream which accentuate peak flow height are accounted for using KINEROS2. Likewise back building of storms which tend to concentrate rainfall over a limited number of sub basins is accurately represented using distributed models versus lumped models which do not account for convective rainfall.

14. ACKNOWLEDGEMENTS

The authors would like to acknowledge the hard work and dedication of our research partners who have been involved over the past several years with KINEROS2. This includes Hoshin Gupta (University of Arizona), Peter Troch (University of Arizona), Thorsten Wagener (Penn State), and Soni Yatheendradas (NASA; formerly University of Arizona Ph.D. student who worked on the transformation of KINEROS2 into a real time model framework). COMET for providing the funds needed to make the transition to real-time modeling with KINEROS2 possible. Elizabeth Persichilli (SUNY Binghamton) who worked over the summer of 2007 on the calibration of the Platte Kill model. AGWA help from Shea Burns (USDA). Soni Yatheendradas for providing useful review comments. Michael Evans (NWS Binghamton SOO) for his review of this

document. Caitlan Reilly (NWS Binghamton and SUNY Binghamton) for her calibration work on East Brook and help with GIS figure preparation.

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16. CALIBRATION GUIDE

Step 1: **Setting up KINEROS2 Model with AGWA**

Setting up KINEROS2 involves both GIS work and field work. The user has to first delineate and discretize the watershed using AGWA. AGWA will write an initial parameter file for KINEROS2. The parameter file contains all model parameters for each overland flow plane and open channel element.

Step 2: **Field Verification of Open Channel Element Parameters**

The user should conduct field work to obtain representative channel lengths and channel Manning roughness coefficients. This data should be used to refine the parameter file.

Step 3: **Selecting Events**

The user should select events representative of a wide range of peak flows (half bankfull to flood of record (if available), initial soil moisture conditions (very dry to very wet), basin average rainfalls (1 inch and upwards), maximum basin average rainfall intensities (0.50 inch/hour and upwards), and mechanisms of peak flow generation (stratiform to convective). It should be noted that the lower end of selected basin average rainfalls and maximum basin average rainfall intensities may not be appropriate for all WFOs. Watersheds with a large percentage of sandy soils may require higher rainfall values to start.

A number of events to be statistically significant should be selected. This will allow a regression analysis to be performed.

If a limited number of events are available for calibration, the user could still perform an initial calibration. While not statistically significant and representative of all event possibilities, a trend in model parameters may still be evident allowing KINEROS2 to be run. Additional events should be added to the calibration as they become available.

Step 4: **Initial Conditions**

The user should select an initial soil moisture state and flow rate at the start of the simulation. The simulation start time should correspond to the start of rainfall over the modeled watershed. It is important that the entire amount of rainfall from start of event to time of peak streamflow is included in the calibration run.

Step 5: **Z-R Selection**

Model calibration runs must be made using a representative Z-R relationship. There are a variety of ways to select an appropriate Z-R relationship. One method is to compare ground truth rain gage reports to radar precipitation estimates to determine the best Z-R relationship for the event as a whole. This was the method used in this study. Another method would be to examine perceptible water values with respect to normal and warm cloud depths to determine if the atmosphere had tropical character. The later method is likely more appropriate in an operational setting as opposed to during calibration work unless rain gage reports are absent from in/nearby the modeled basin.

Step 6: **Calibration Model Runs**

The user should run the model for each event. For each event, the model output should be compared to that of the stream gage record. The goal of calibration is to determine those model parameters that will allow the timing and magnitude of the peak flow to be reproduced through KINEROS2 simulations. If the model output is over simulating the peak flow, the user should increase the saturated hydrologic conductivity multiplier and rerun the model. On the other hand if the model output is under simulating the peak flow, the user should decrease the saturated hydrologic conductivity multiplier and rerun the model. Increasing the saturated hydrologic conductivity multiplier will increase the amount of infiltration on model overland flow planes thus decreasing the resultant magnitude of peak flow the next time the model is run. Conversely, decreasing the saturated hydrologic conductivity multiplier will decrease the amount of infiltration on model overland flow planes thus increasing the resultant magnitude of peak flow the next time the model is run. This process is continued till a reasonable match of the magnitude of peak flow. The model should reasonably match the timing of the peak flow as well. This is accomplished by adjusting the channel length multiplier. Increasing the channel length multiplier will push forward in time the timing of the peak flow while decreasing the channel length multiplier will push backward the timing of the peak flow. A reasonable match would be within 5 percent of peak flow magnitude and within 30 minutes of peak flow timing. It should be noted that the user will have to generally adjust both the saturated hydrologic conductivity multiplier and the channel length multiplier simultaneously. The reason behind this is that adjusting one multiplier will have an effect on the other. For example, decreasing the saturated hydrologic conductivity multiplier in order to increase the peak flow magnitude will result in a later peak flow time.

Step 7: **Interpretation of Results**

Once calibration runs have been completed for each event modeled, the user should have the following data assembled in a spreadsheet:

1.) Start date and time of simulation.
2.) Initial flow rate.
3.) Initial soil moisture state.
4.) Z-R relationship used for calibration model run.
5.) Basin average rainfall from start of simulation to time of peak flow.
6.) Maximum basin average rainfall intensity from start of simulation to time of peak flow.
7.) Date and time of peak flow (from gage data).
8.) Peak flow (from gage data).
9.) Date and time of peak flow (from calibration model run)
10.) Peak flow (from calibration model run)
11.) Saturated hydrologic multiplier used in that particular calibration model run.
12.) Channel length multiplier used in that particular calibration model run.

A plot should be created of each model parameter multiplier vs. basin average rainfall and maximum basin average intensity. This will result in a total of four plots. In general, the user should look for trends of saturated hydrologic conductivity multiplier with increasing basin average rainfall as well as increasing maximum basin average rainfall intensity. If a trend exists and enough points exist to make it statistically significant, a regression line (usually linear) should be fit to the data. The R^2 value can be used as an overall indicator of how well the modeled is calibrated assuming the events selected are representative. Trends often exist with channel length multiplier increasing with increasing with increasing basin average rainfall as well as increasing maximum basin average rainfall intensity. If such a trend is not present, the user should look for an average channel length multiplier.

Step 8: **Parameter Multiplier Sets**

The final step in setting the model up so it can be run operationally is to create parameter multiplier sets. A parameter multiplier set is simply the parameter multipliers which correspond to a given basin average rainfall value or a given maximum basin average rainfall intensity value. In this case, the saturated hydrologic conductivity multiplier and channel length multiplier corresponding to a given basin average rainfall value or a given maximum basin average rainfall intensity value. KINEROS2 allows up to 8 parameter multiplier sets. The sets used in a model should correspond to the range of basin average rainfall values or maximum basin average rainfall intensities used in the calibration. For example, if basin average rainfall totals ranged from 1 inch to 4.5 inches, the user might want to have parameter multiplier sets corresponding to 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 inches.

TABLES

Table 1: List of Z-R Relationships available in KINEROS2. KINEROS2 also allows the user to select a custom Z-R (i.e. user defined).

Z-R Relationship	Z	R
WSR-88D Default Convective	300	1.4
Convective-Tropical Transitional	275	1.3
Rosenfield Tropical	250	1.2
Marshall Palmer	200	1.6
East-Cool Stratiform	130	2.0
West-Cool Stratiform	75	2.0

Table 2: Event timeline for minor flood event along Beaver Kill at Cooks Falls, NY. Included are forecast results from KINEROS2, forecasts originating from MARFC using their lumped continuous API model, and observations from USGS stream gage at Cooks Falls.

Event Date	Event Time, EDT	Event Description
July 29, 2009	6:45 PM	KINEROS2 simulation started.
July 30, 2009	12:35 AM	MARFC issues first river forecast product for the event for Cooks Falls. Crest forecast of between 8.00 and 10.00 feet during the morning hours. Remarks indicate 2-3 inches of rain has fallen over the watershed with up to an additional inch possible.
July 30, 2009	1:20 AM	KINEROS2 forecasts bankfull stage to be exceeded.
July 30, 2009	1:45 AM	KINEROS2 forecasts a peak flow of 9.64 feet / 9089 cfs at the future time of 6:08 AM. This forecasted peak flow is just below Flood Stage of 10.00 feet.
July 30, 2009	3:25 AM	MARFC issues second river forecast product with a crest of 8.80 feet and mentions need to monitor the river as it approaches flood stage.
July 30, 2009	5:11 AM	MARFC issues third river forecast product for flood stage to be exceeded momentarily with a crest of 11.00 feet.
July 30, 2009	5:17 AM	River Flood Warning issued by NWS Binghamton.
July 30, 2009	5:30 AM	Flood Stage of 10.00 feet exceeded at USGS stream gage.
July 30, 2009	6:45 AM	Beaver Kill at Cooks Falls USGS stream gage crests at 10.60 feet / 11500 cfs.

Table 3: Basin and simulation summary table.

Basin	Drainage area (mi^2)	Outlet type	Flood Flow (cfs)	Number of events in linear regression analysis	R^2 for linear regression analysis (basin average rainfall/ rainfall intensity)	Minimum /maximum flow (cfs) used in calibration	Minimum/ maximum rainfall intensity (in/hr) used in calibration
Platte Kill	35	Gage	2430	6	0.80	648	0.55
					0.96	3070	3.60
East Brook	25	Gage	3580	10	0.19	255	0.20
					0.57	7110	2.00
Beaver Kill	241	Gage	9930	9	NA	7510	0.55
					0.93	62400	2.60
Callicoon Creek	110	Gage	6900	14	NA	1100	0.50
					0.47	12503	1.70
Spring Brook	9.0	Ungaged	2000	2*	NA	3544	3.45
					NA	5469	4.05
Berry Brook	4.6	Ungaged	1250	2*	NA	1605	3.40
					NA	2792	3.55

*No regression analysis performed for Spring Brook or Berry Brook due to a small number of events.

Figures

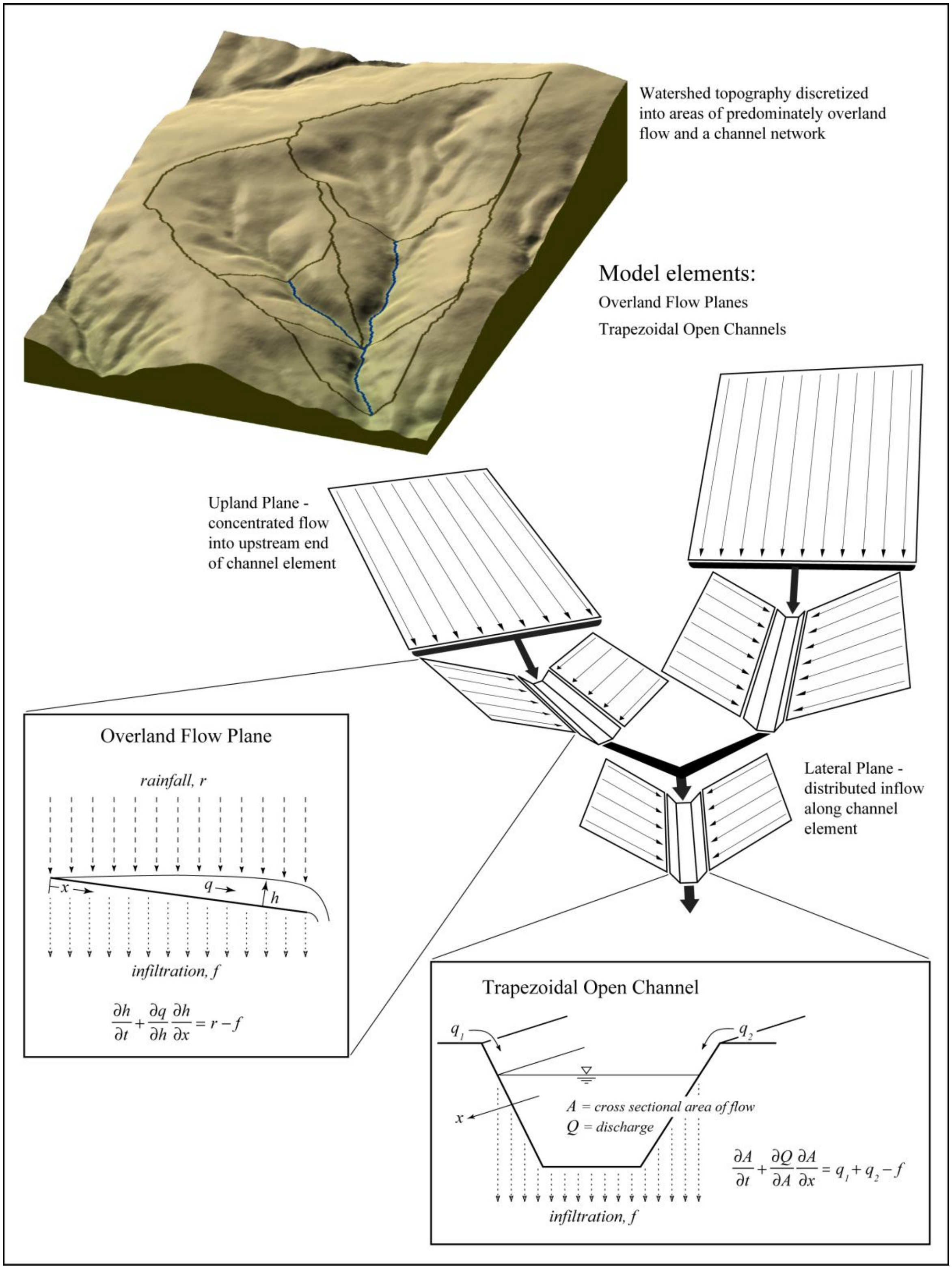

Figure 1: Schematic diagram of KINEROS2 (provided by USDA-ARS).

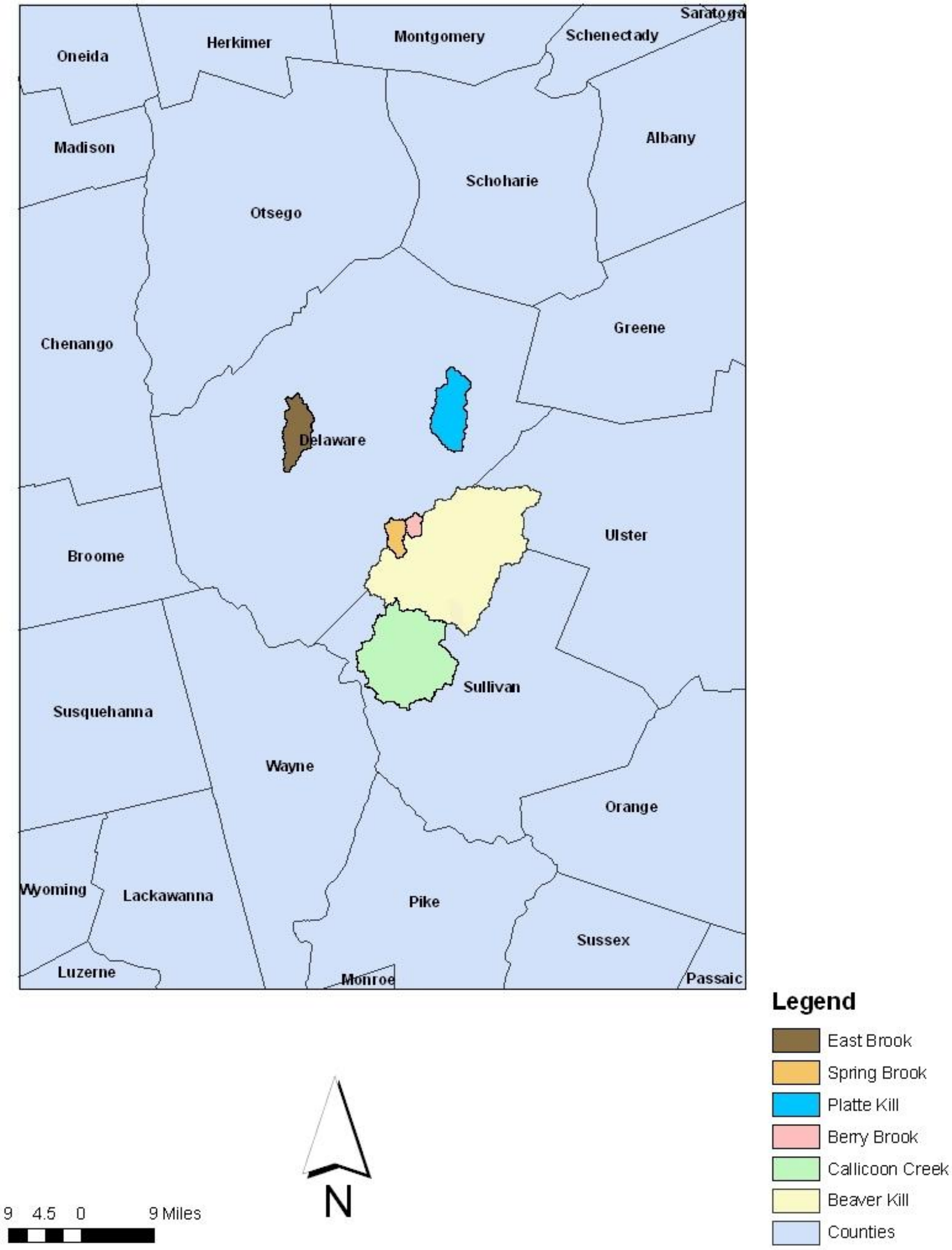

Figure 2: Map of east-central New York State showing locations of study basins located in Delaware, Sullivan, and Ulster counties. It should be noted that both Spring Brook and Berry Brook are located within the larger Beaver Kill basin.

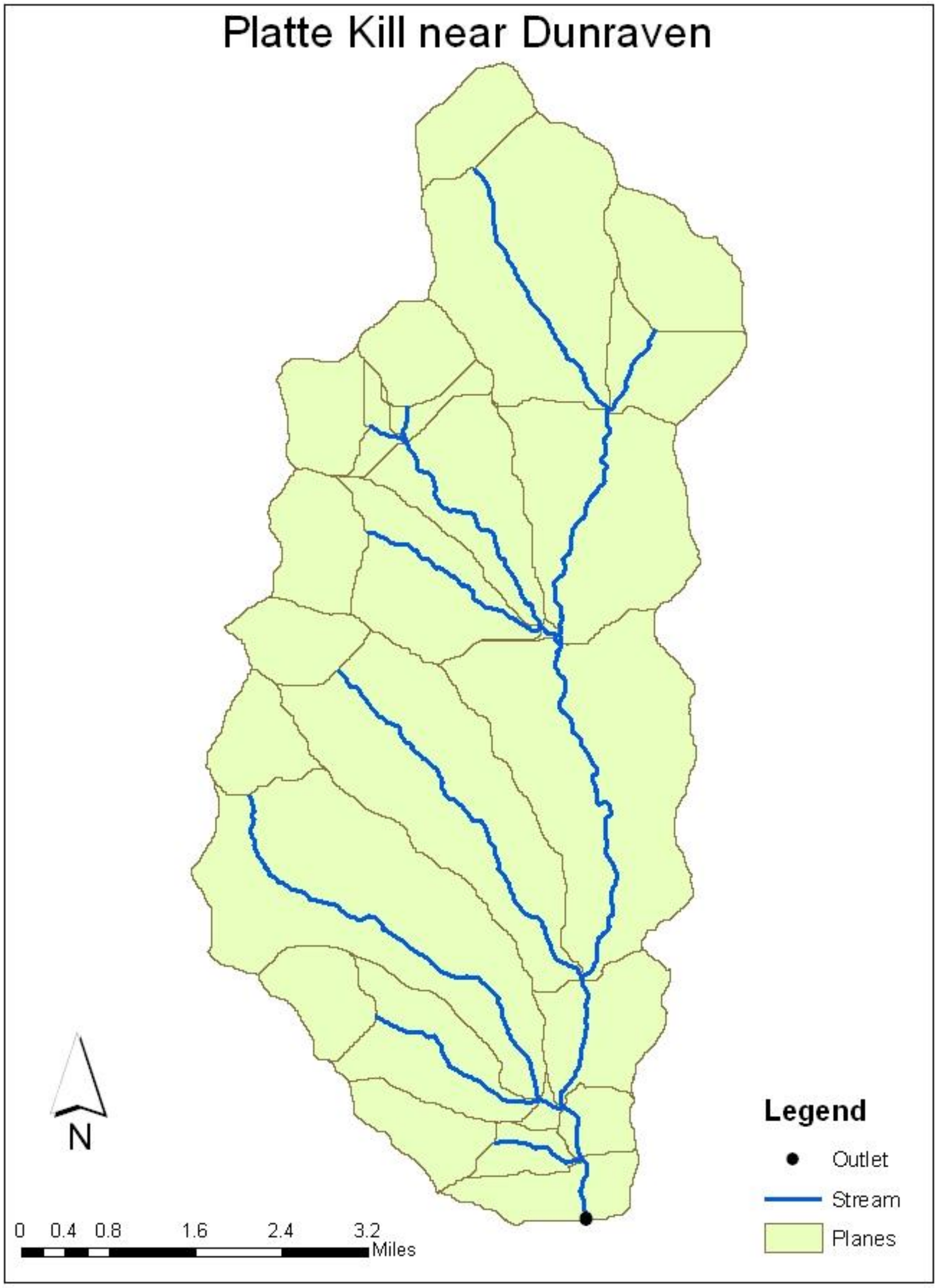

Figure 3: Plan view of KINEROS2 model elements for Platte Kill near Dunraven, NY. The basin outlet is represented by the small circle at the south end of the basin and corresponds to the location of a USGS stream gage. Overland flow planes are represented by polygons. Open channel elements are represented by blue line segments. This particular basin is composed of 41 overland flow units and 17 open channel elements.

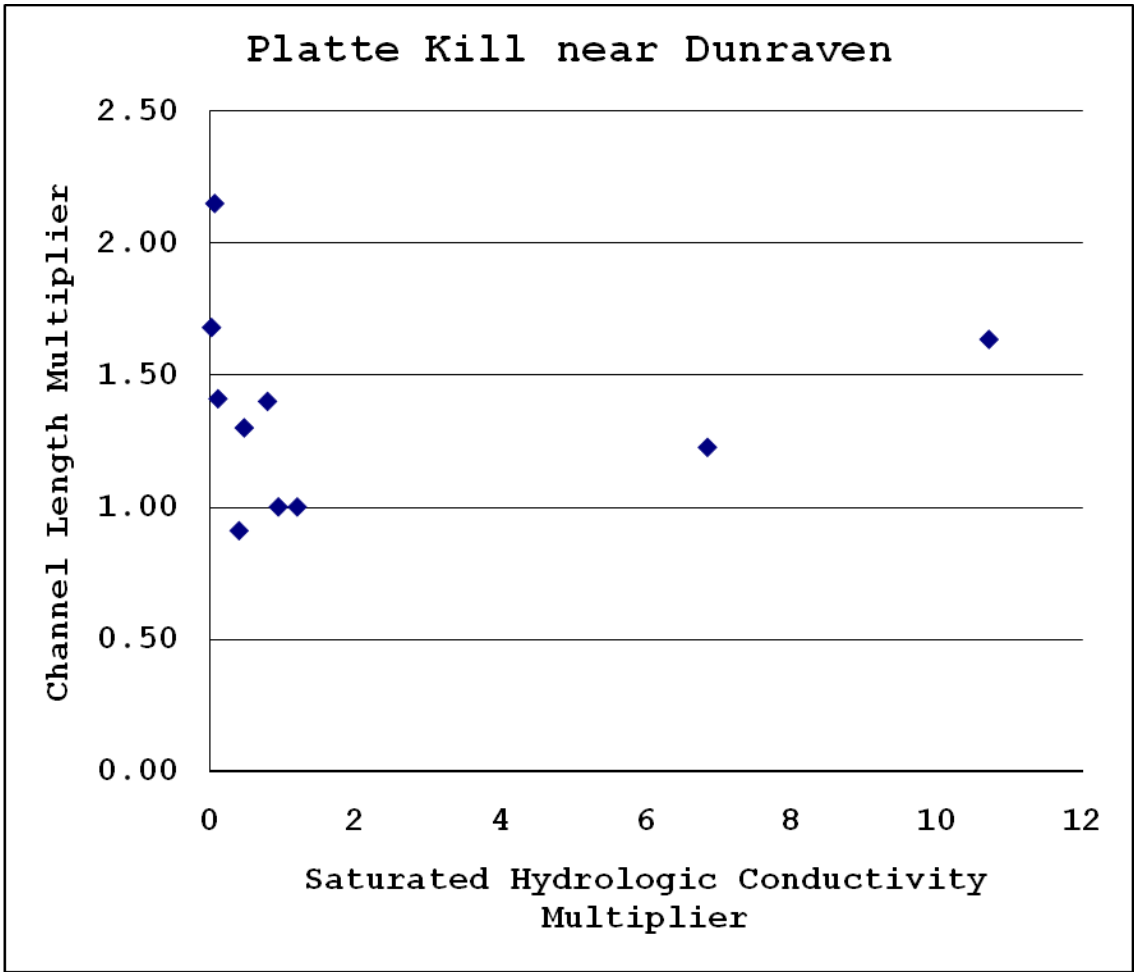

Figure 4: Plot of saturated hydrologic conductivity multiplier vs. channel length multiplier for ten events for Platte Kill near Dunraven, NY.

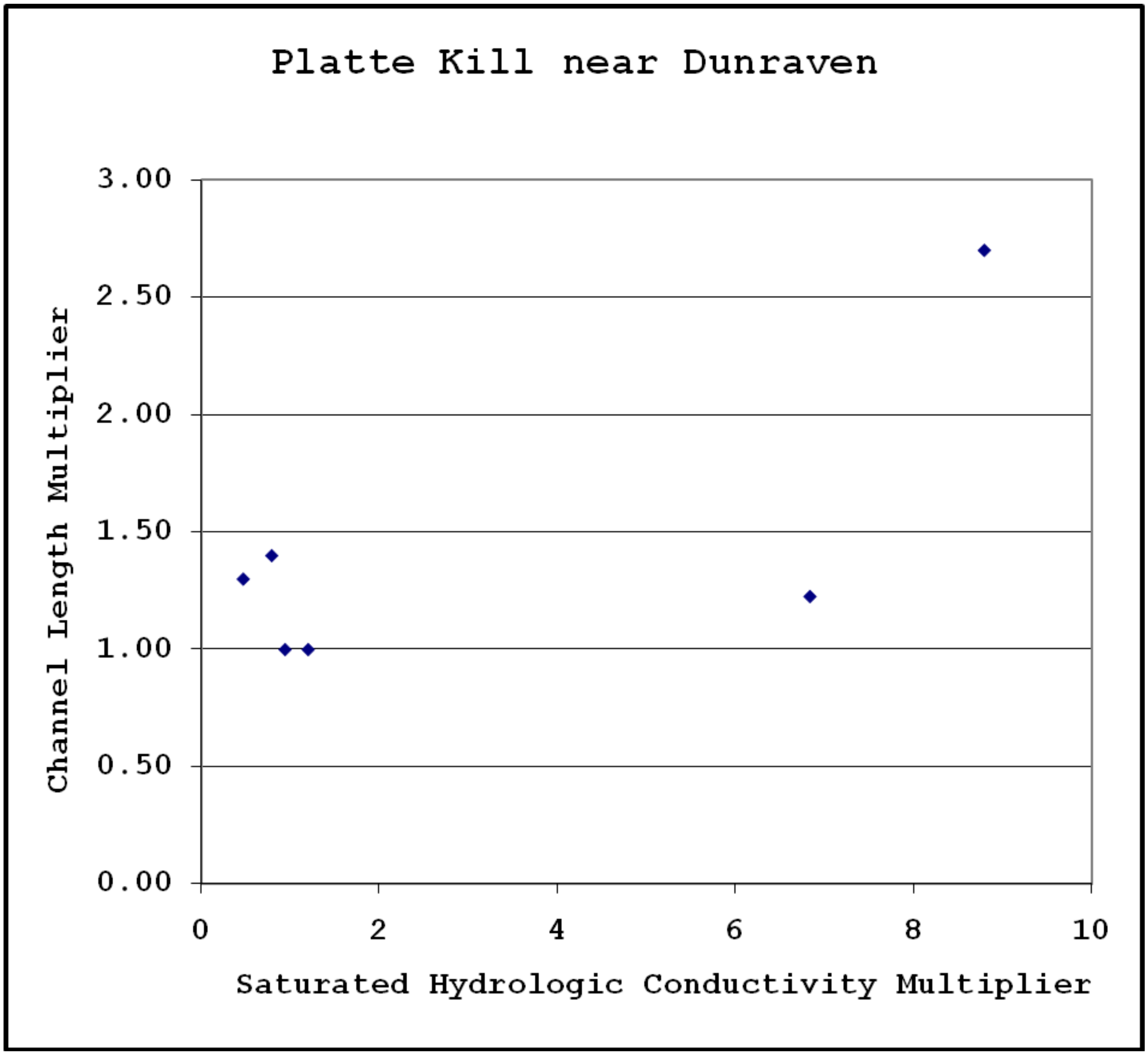

Figure 5: Plot of saturated hydrologic conductivity multiplier vs. channel length multiplier for six events for Platte Kill near Dunraven, NY. Events plotted are a sub-set of those from Figure 4 (those that exceeded 1.00 inch of basin average rainfall).

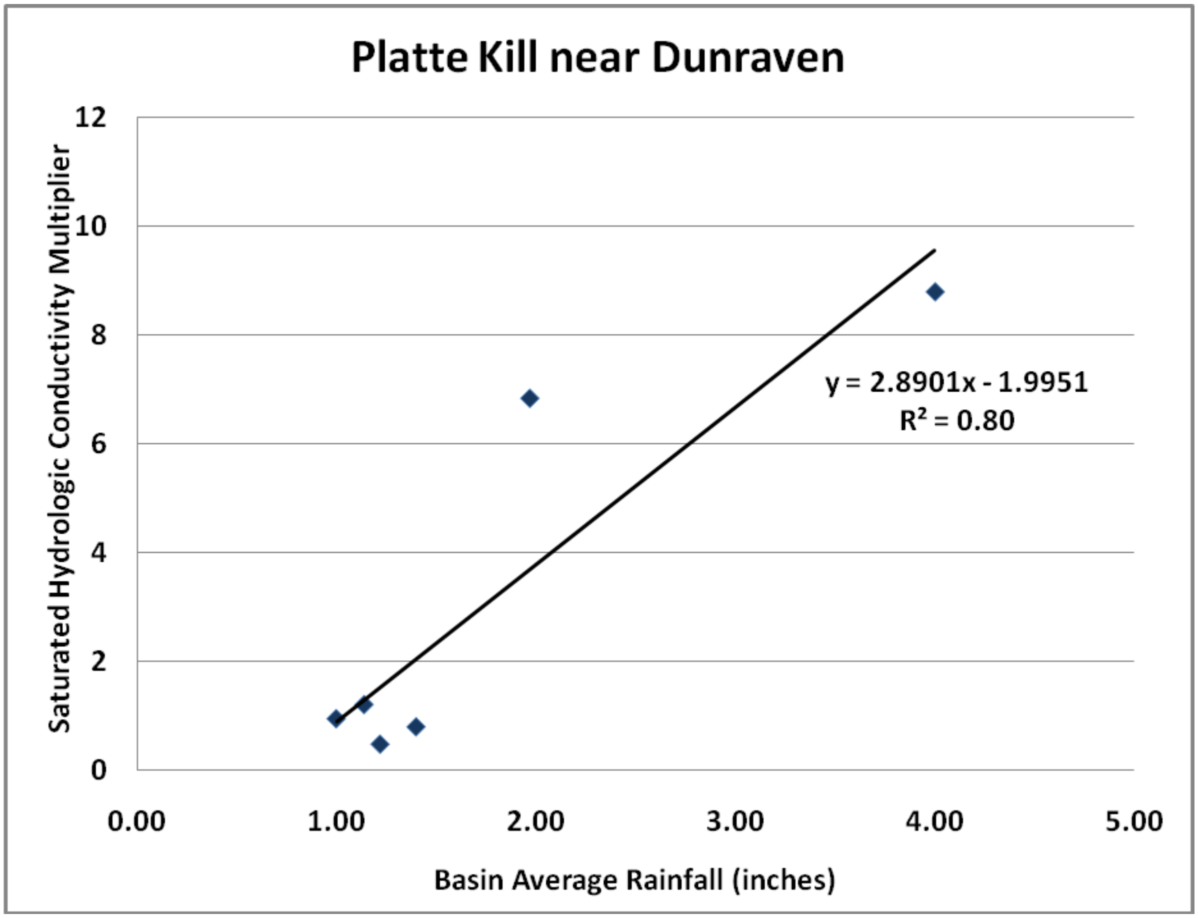

Figure 6: Plot of basin average rainfall vs. saturated hydrologic conductivity multiplier for six events for Platte Kill near Dunraven, NY.

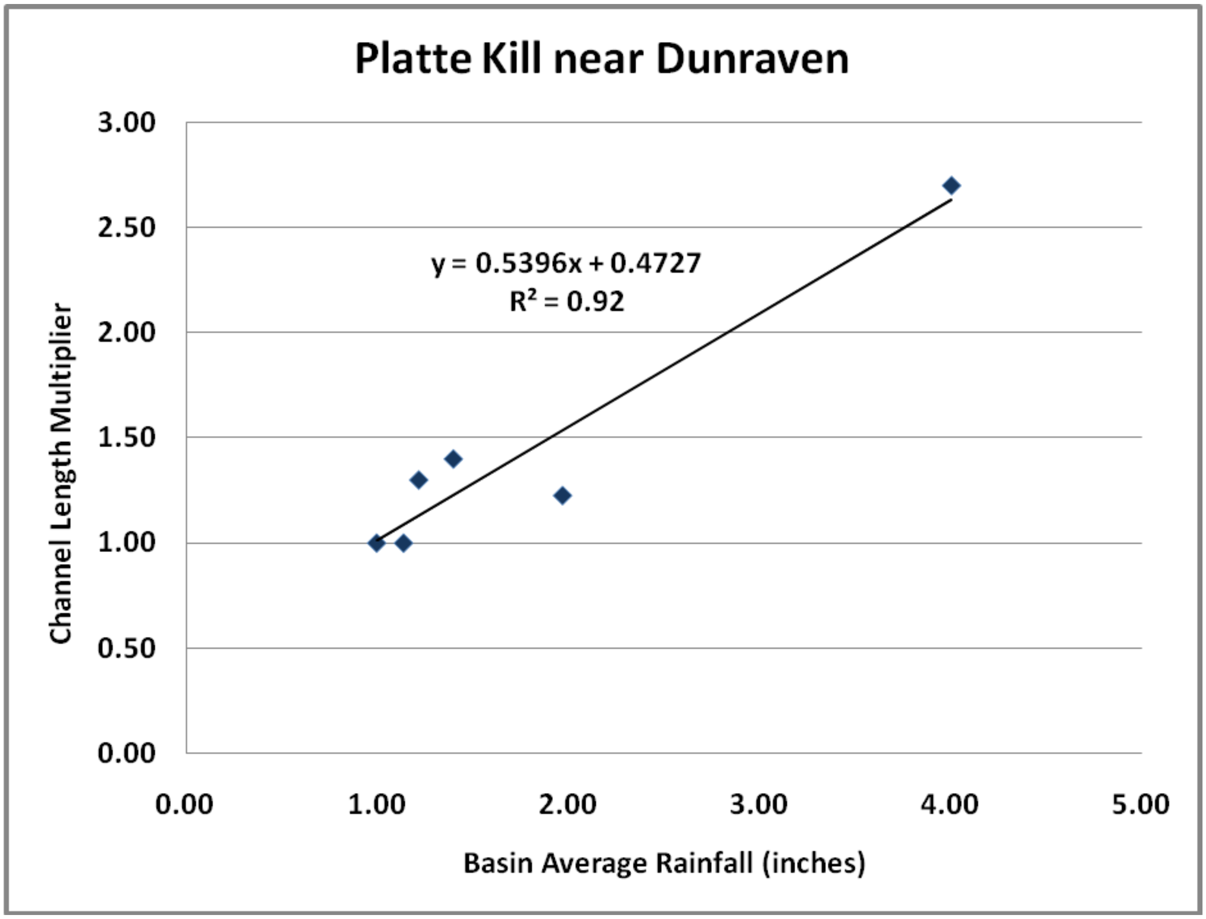

Figure 7: Plot of basin average rainfall vs. channel length multiplier for six events for Platte Kill near Dunraven, NY.

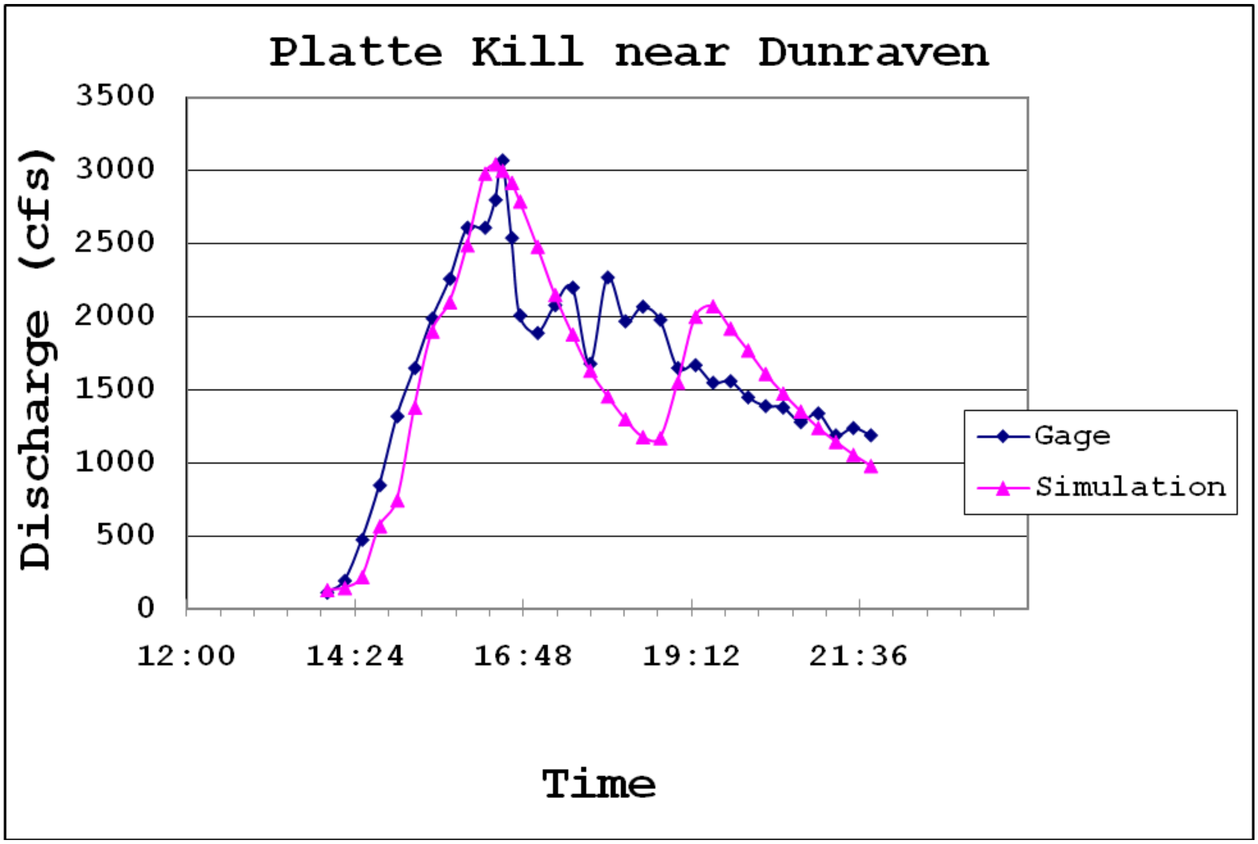

Figure 8: USGS stream gage data vs. modeled results for Platte Kill near Dunraven, NY for the July 23, 2008 event. Time on the 23rd is in local time.

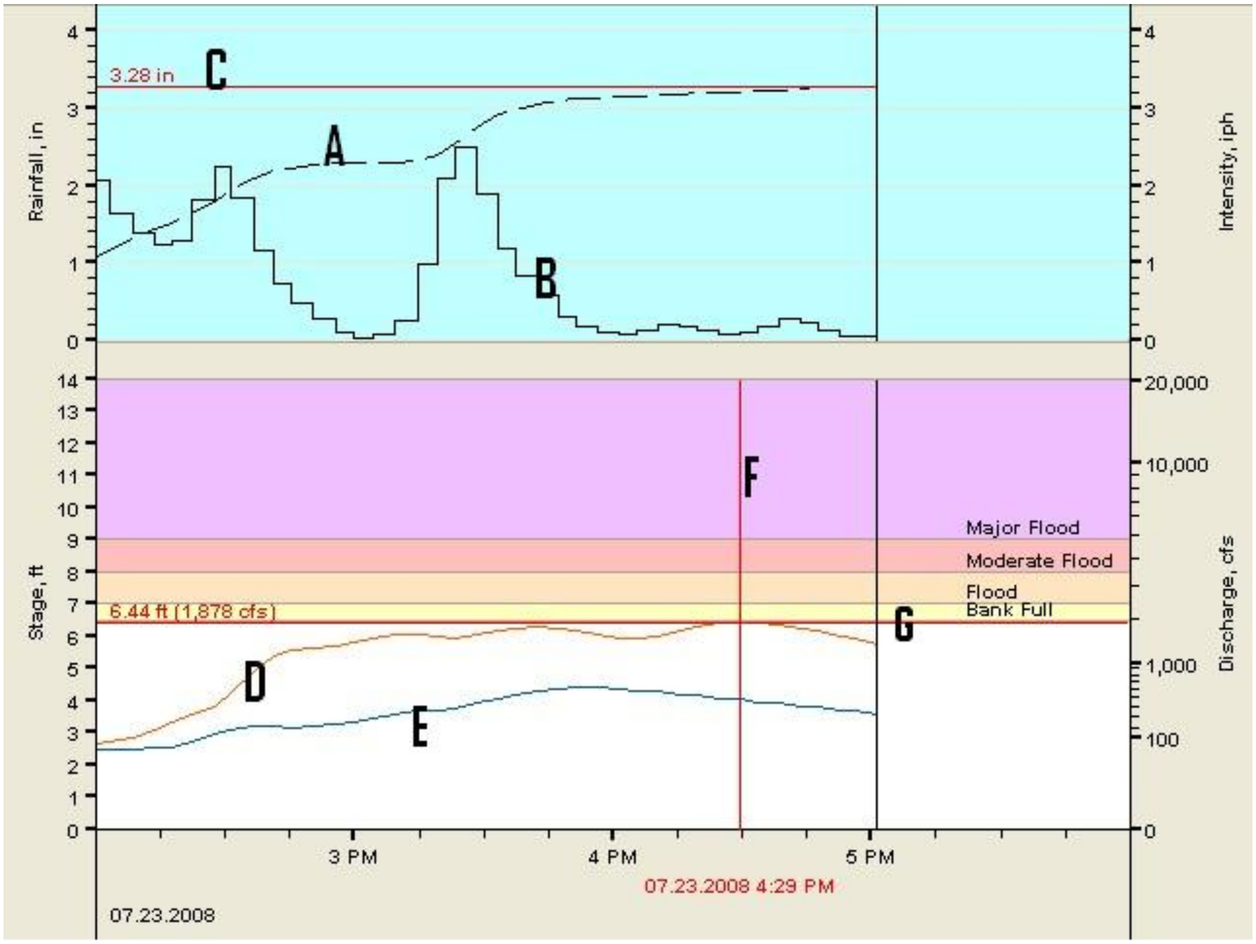

Figure 9: Dynamic KINEROS2 display showing output range of model parameter ensembles. One the top third of the display is the accumulated basin average rainfall (dotted black line/labeled A), instantaneous basin average rainfall (solid black line/labeled B), and total basin average rainfall at the time the image was captured (solid red horizontal line with corresponding total basin average rainfall value in red/labeled C). The bottom two thirds of the display shows the two forecast hydrographs corresponding to the two parameter multiplier sets (labeled D and E). Both stage and discharge can be read. The vertical red line represents the date and time of the peak flow (labeled F). The horizontal red line (G) marks the magnitude of the peak flow (in stage and discharge).

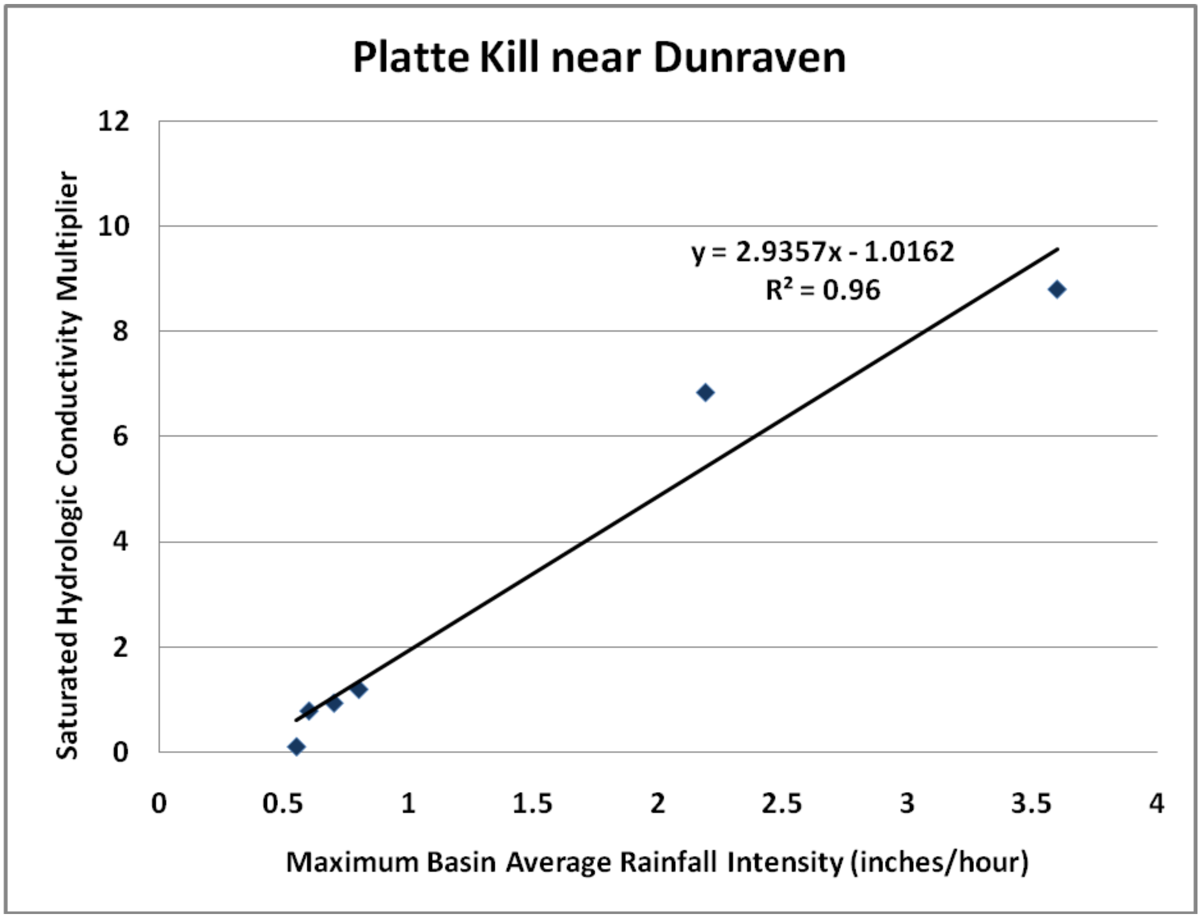

Figure 10: Plot of maximum basin average rainfall intensity vs. saturated hydrologic conductivity multiplier for six events for Platte Kill near Dunraven, NY.

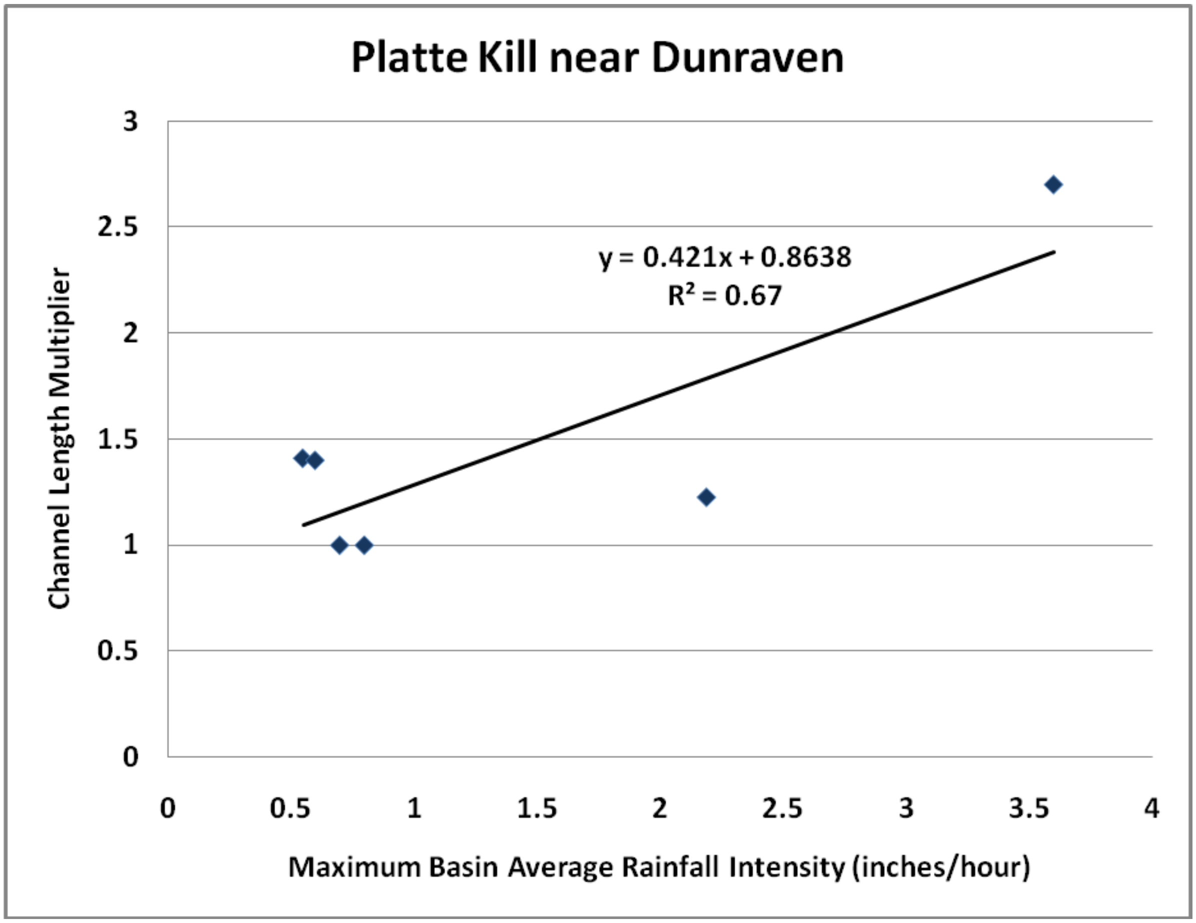

Figure 11: Plot of maximum basin average rainfall intensity vs. channel length multiplier for six events for Platte Kill near Dunraven, NY.

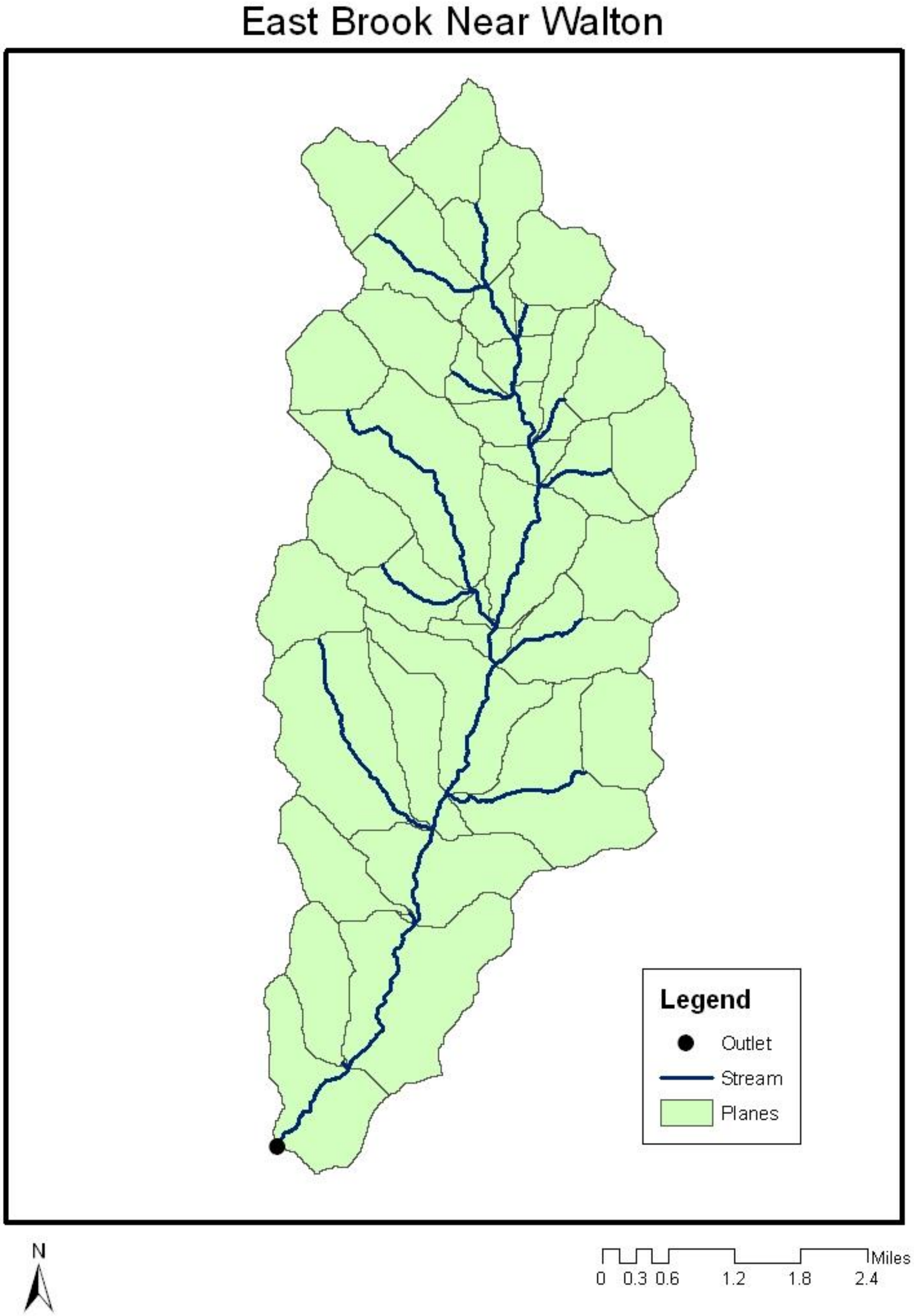

Figure 12: Plan view of KINEROS2 model elements for East Brook near Walton, NY.

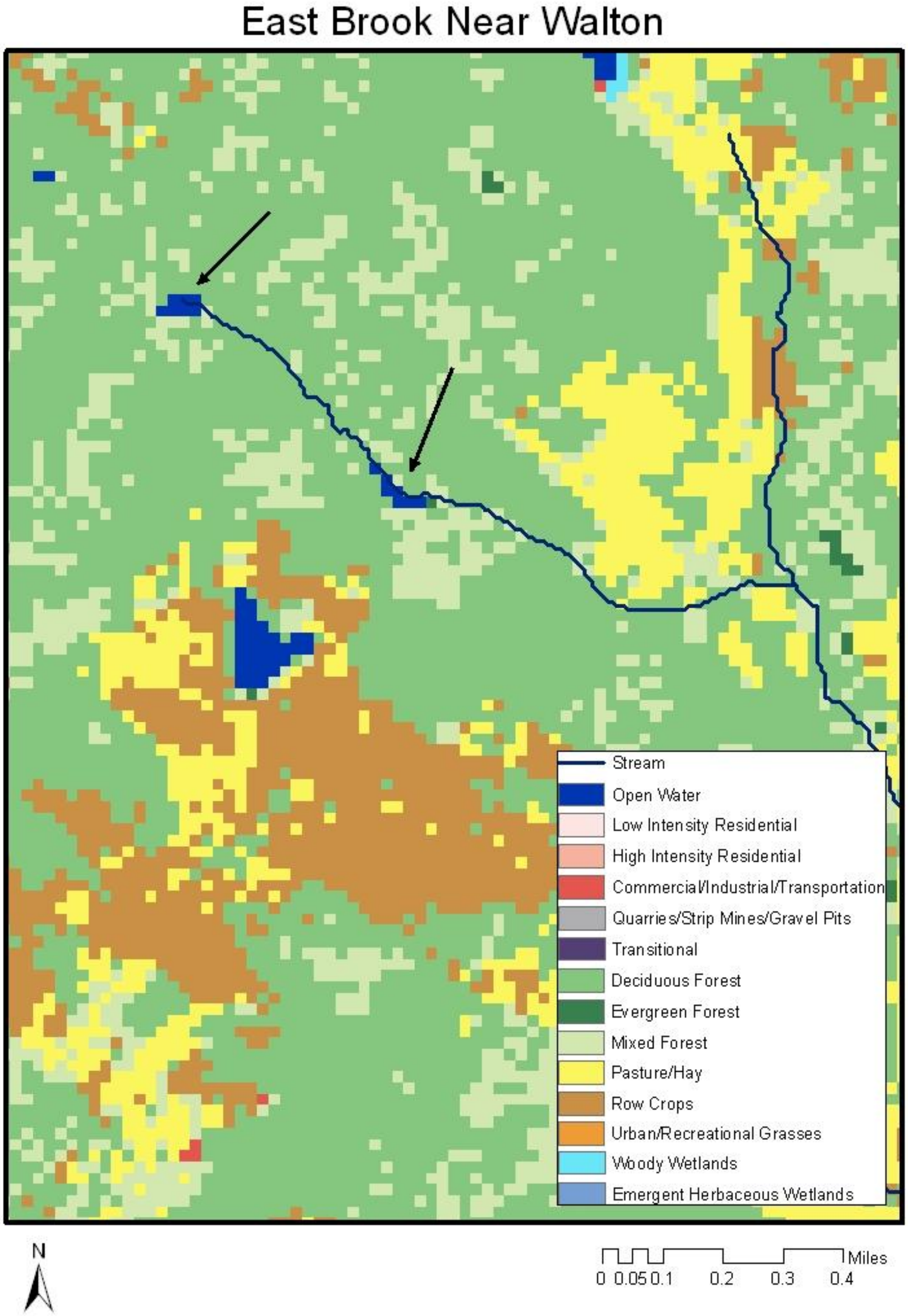

Figure 13: Close up of open channel element modified for the presence of several bodies of water and wetlands. Arrows point two larger bodies of water visible from land use cover.

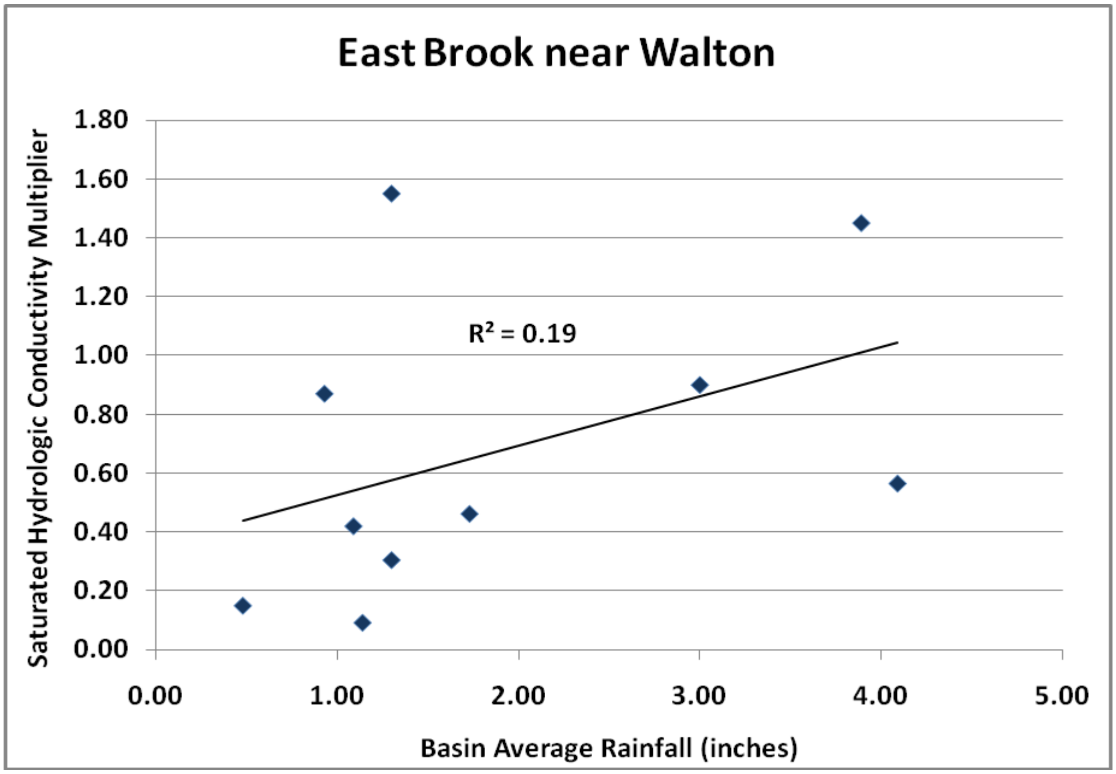

Figure 14: Plot of basin average rainfall vs. saturated hydrologic conductivity multiplier for nine events for East Brook near Walton, NY.

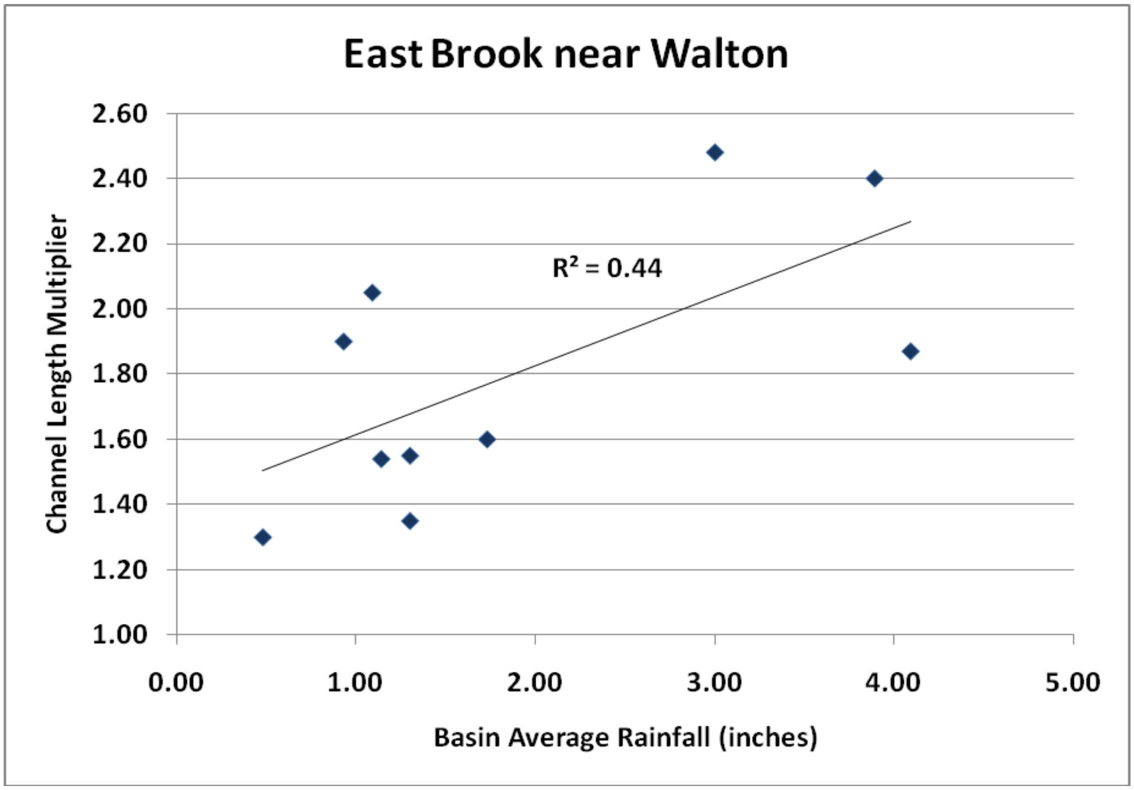

Figure 15: Plot of basin average rainfall vs. channel length multiplier for nine events for East Brook near Walton, NY.

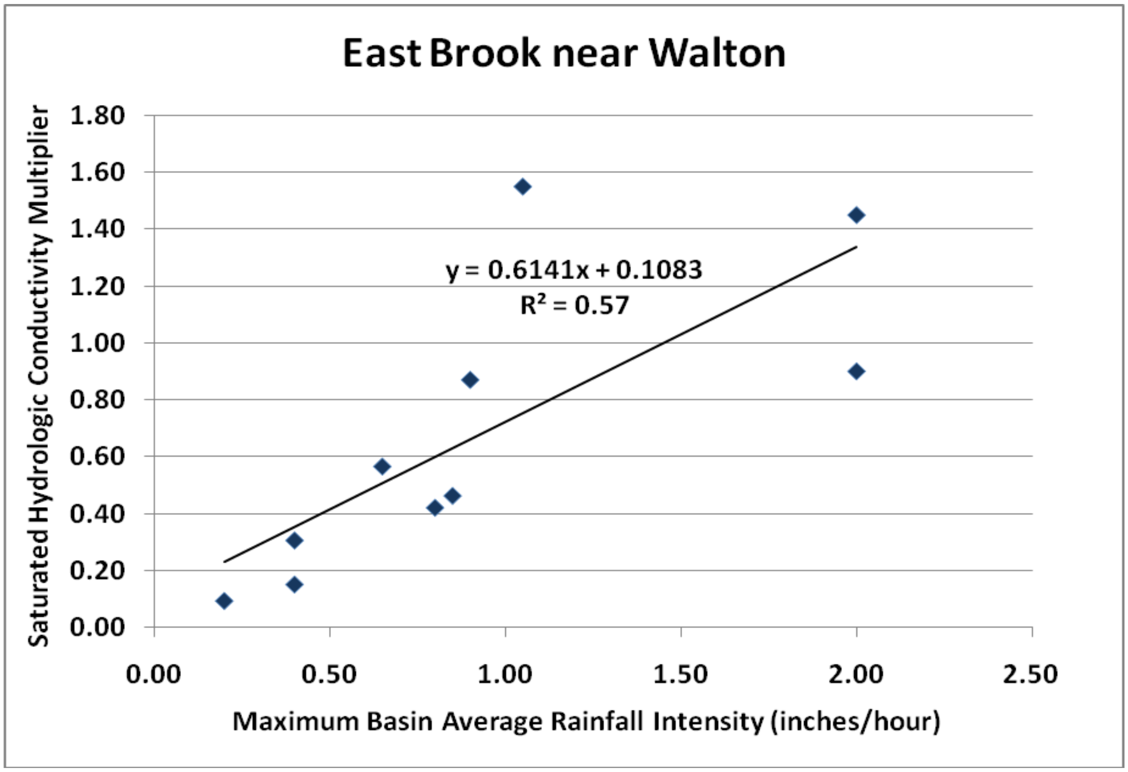

Figure 16: Plot of maximum basin average rainfall intensity vs. saturated hydrologic conductivity multiplier for nine events for East Brook near Walton, NY.

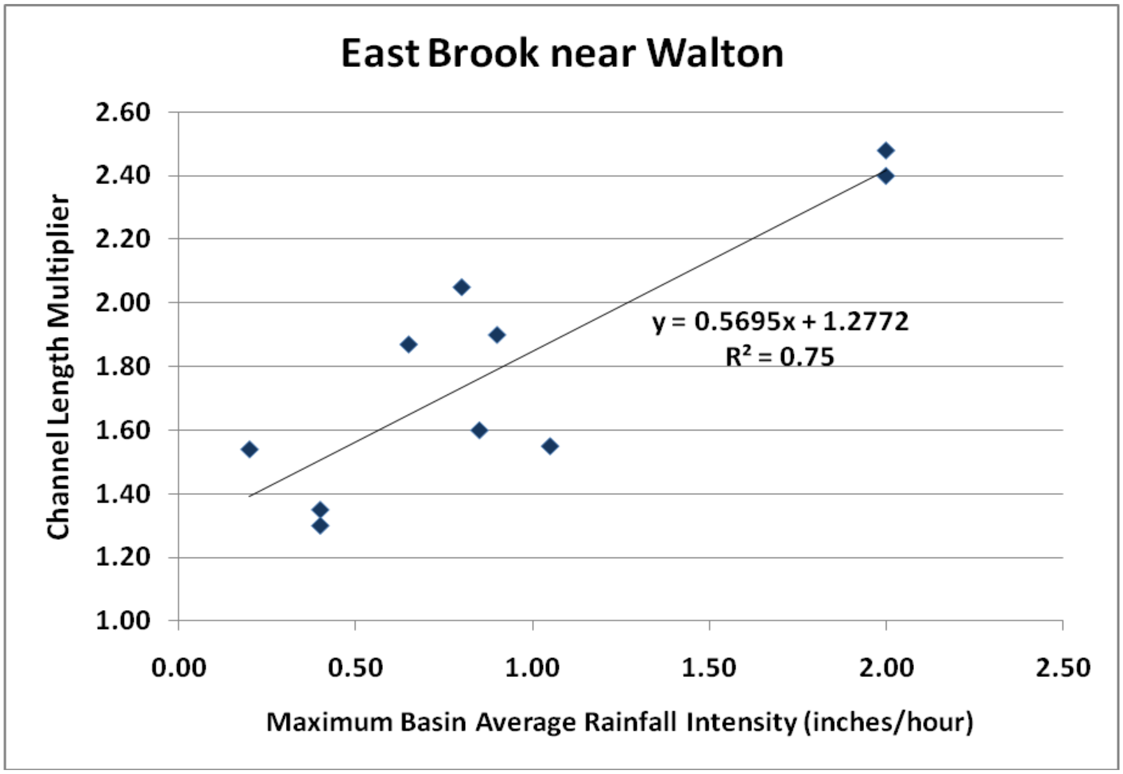

Figure 17: Plot of maximum basin average rainfall intensity vs. channel length multiplier for nine events for East Brook near Walton, NY.

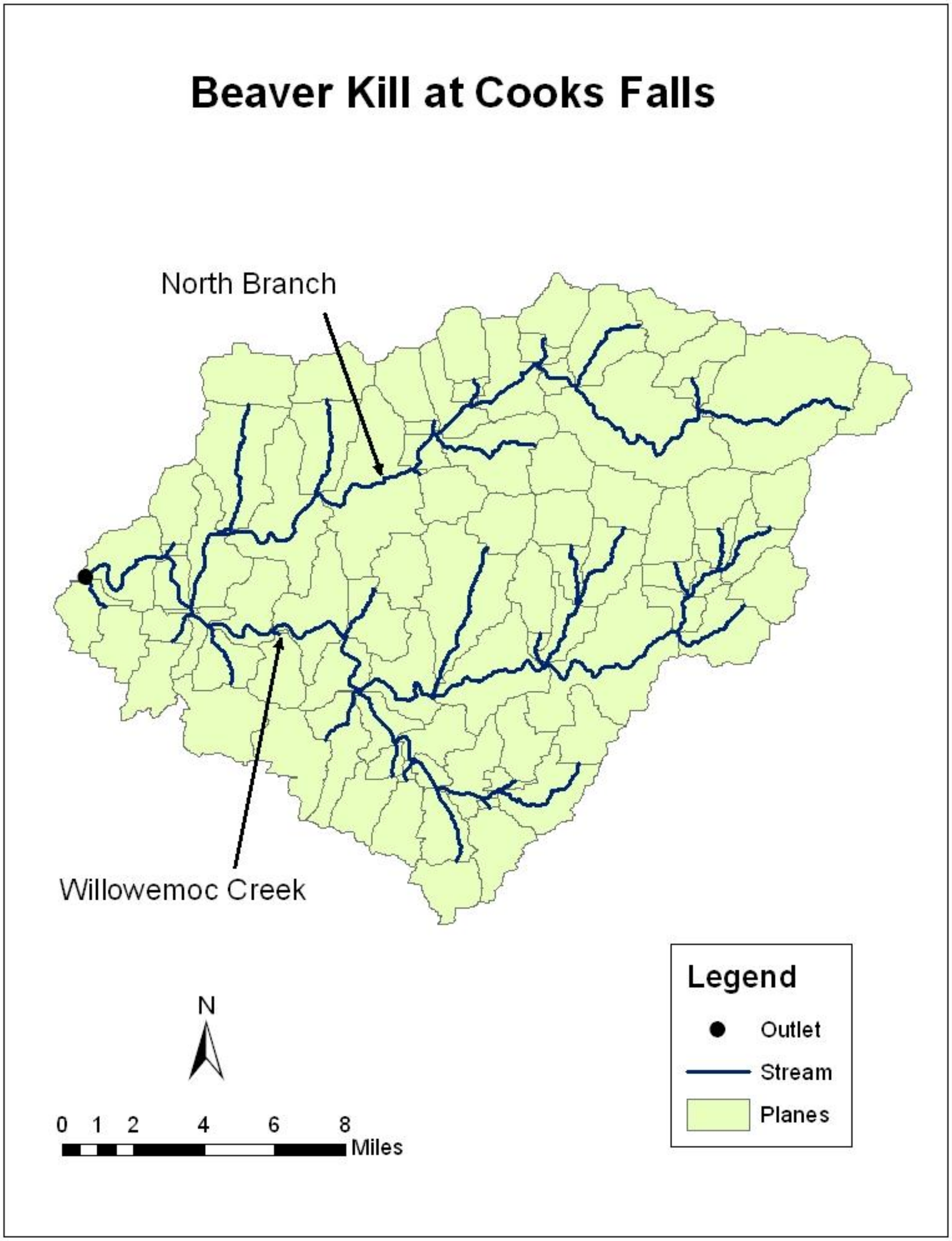

Figure 18: Beaver Kill at Cooks Falls, NY with North Branch and Willowemoc Creek labeled.

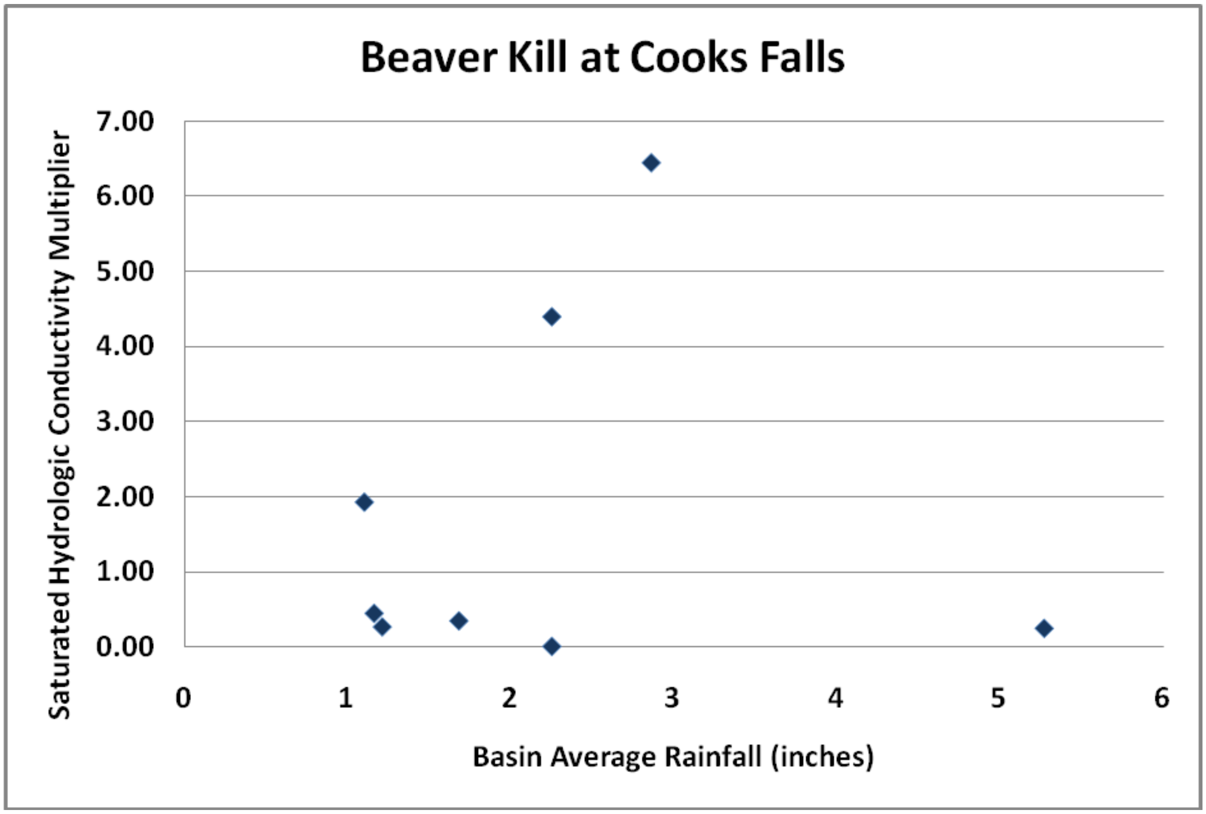

Figure 19: Plot of basin average rainfall vs. saturated hydrologic conductivity multiplier.

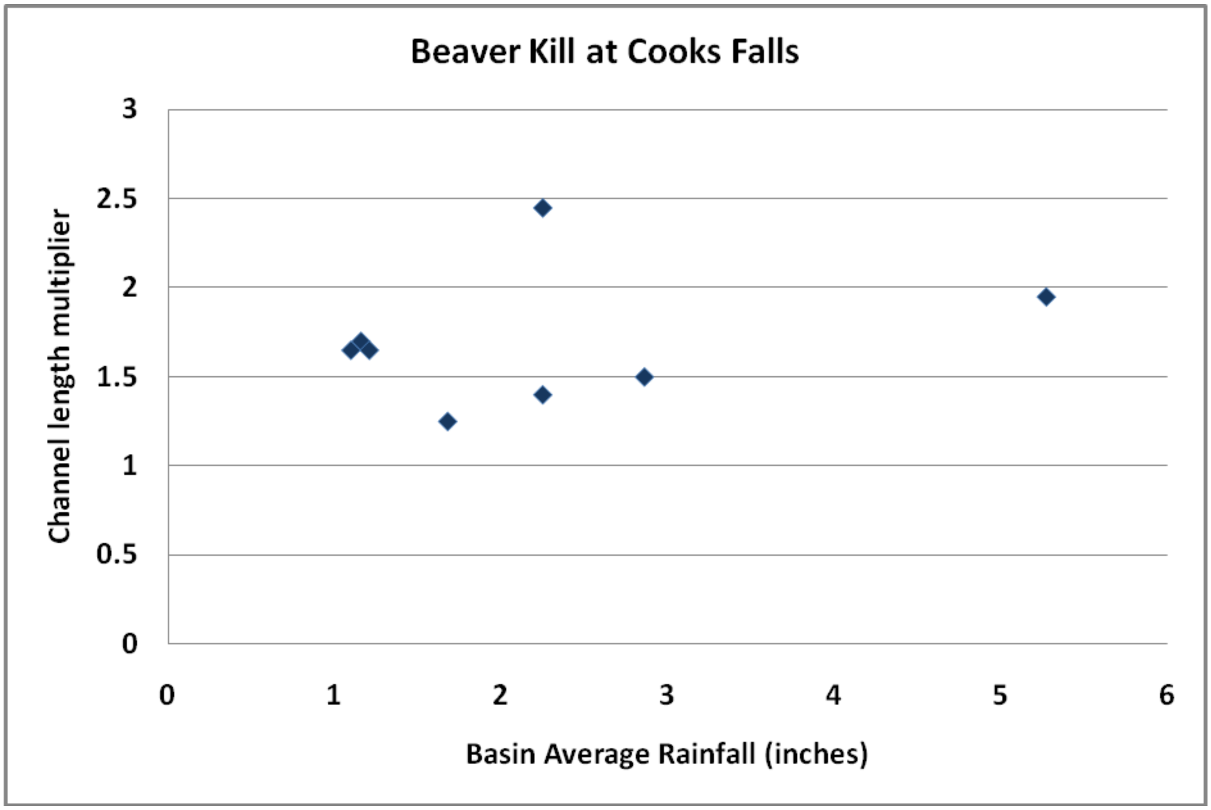

Figure 20: Plot of basin average rainfall vs. channel length multiplier.

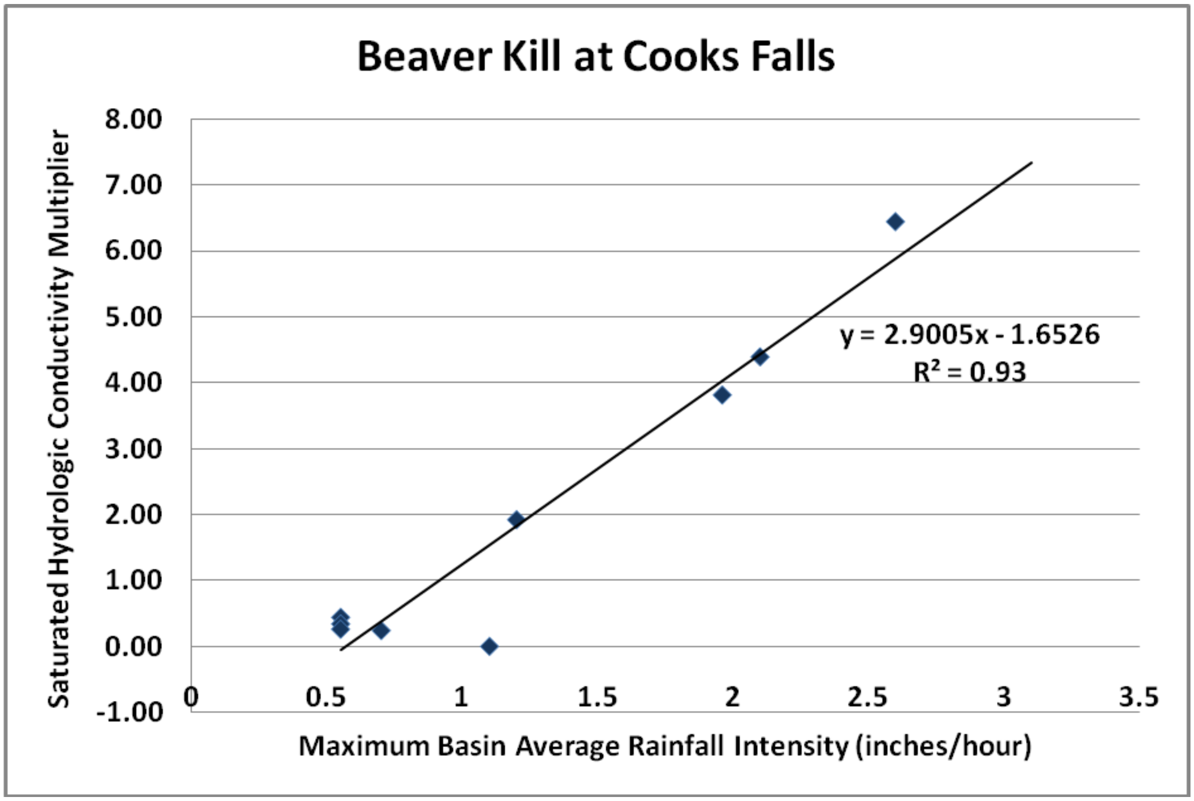

Figure 21: Plot of maximum basin average rainfall intensity vs. saturated hydrologic conductivity multiplier.

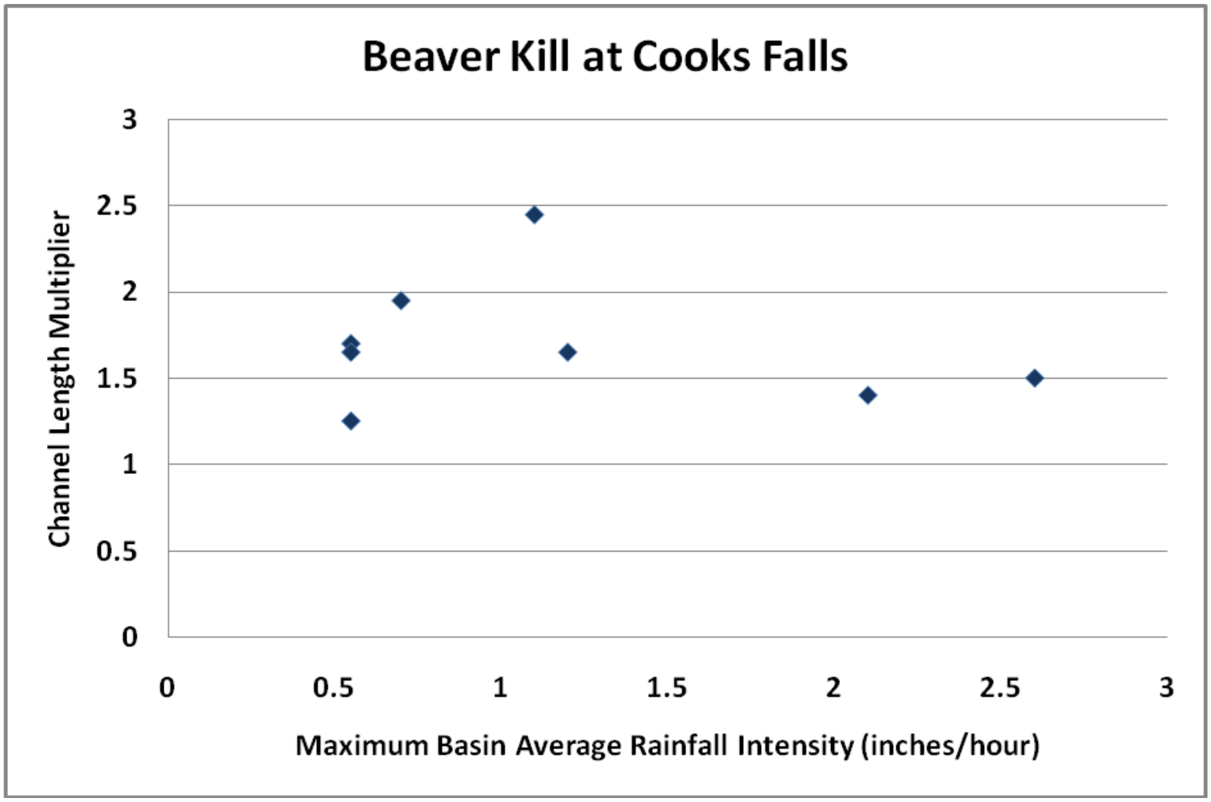

Figure 22: Plot of maximum basin average rainfall intensity vs. channel length multiplier.

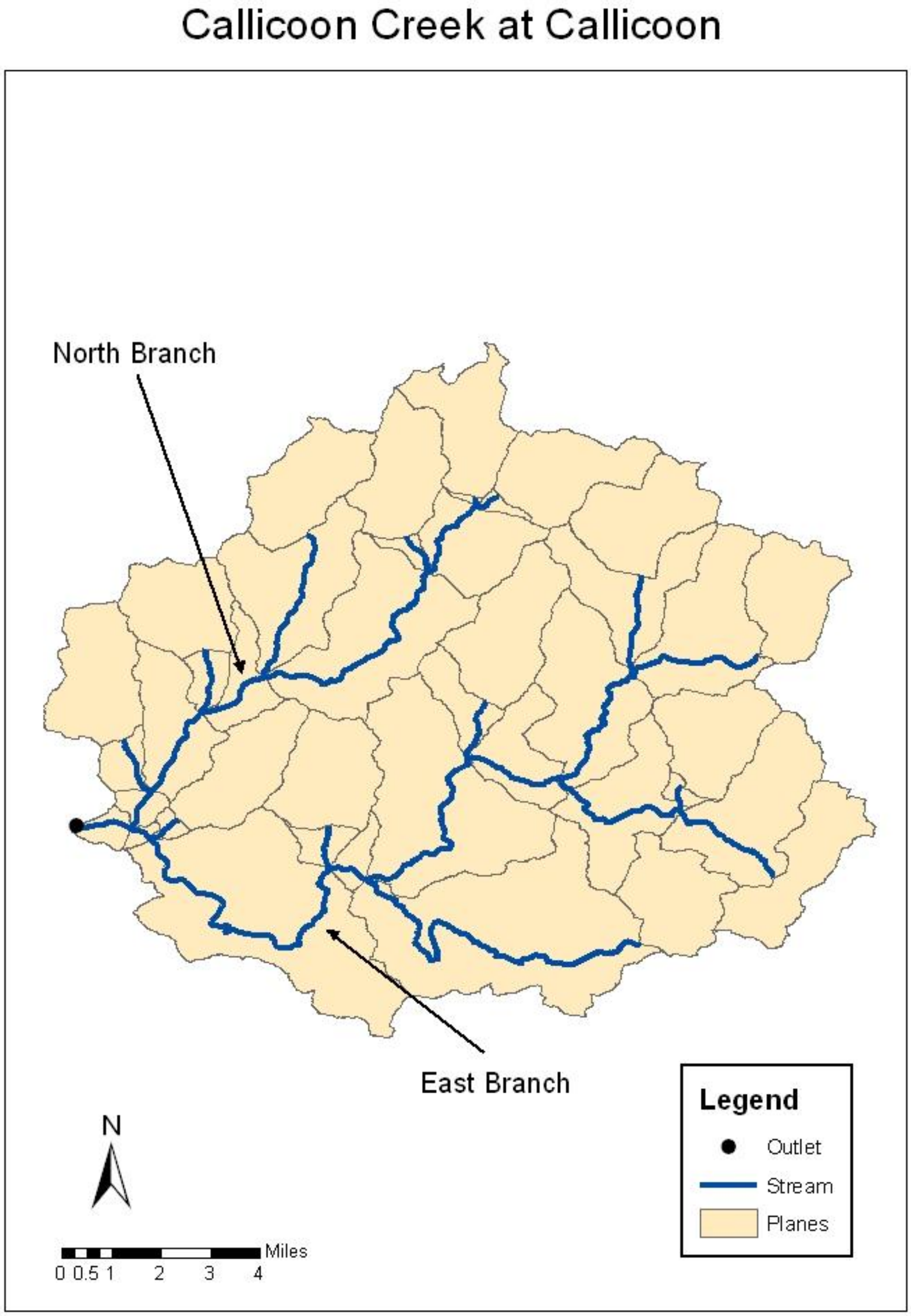

Figure 23: Callicoon Creek at Callicoon, NY with main watercourses labeled.

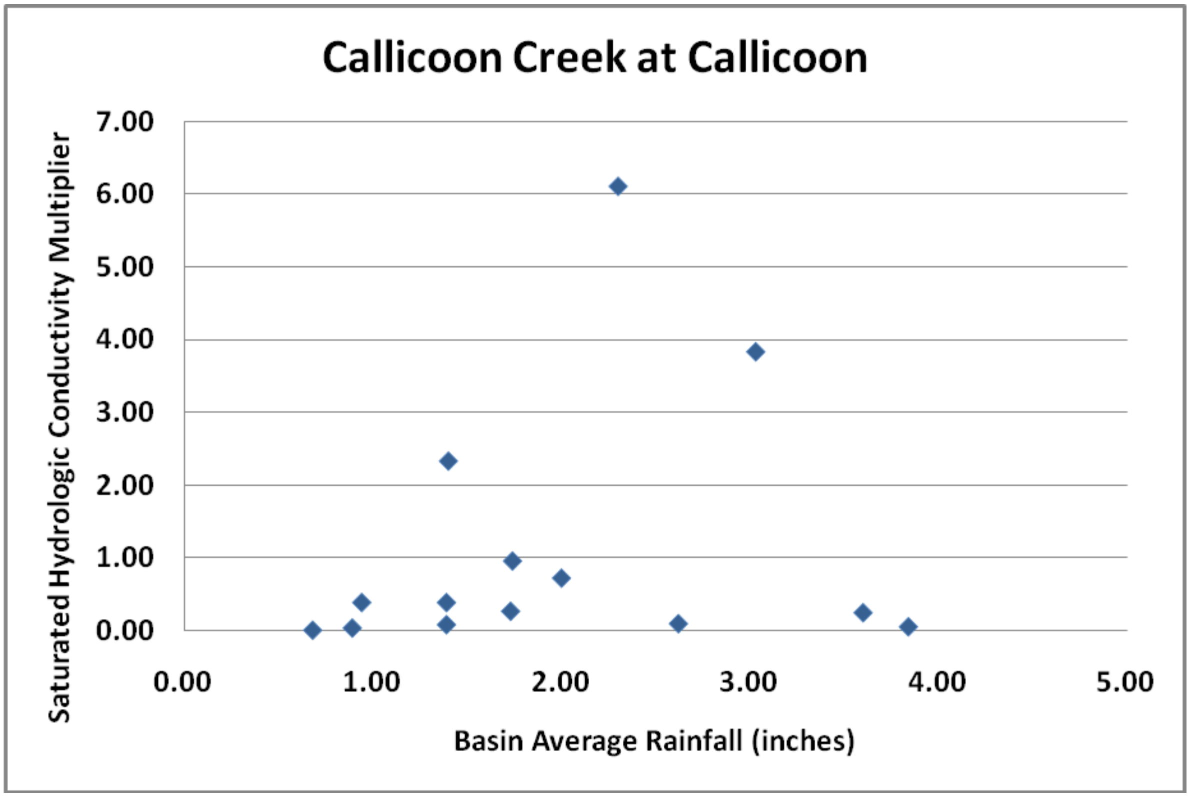

Figure 24: Plot of basin average rainfall vs. saturated hydrologic conductivity multiplier.

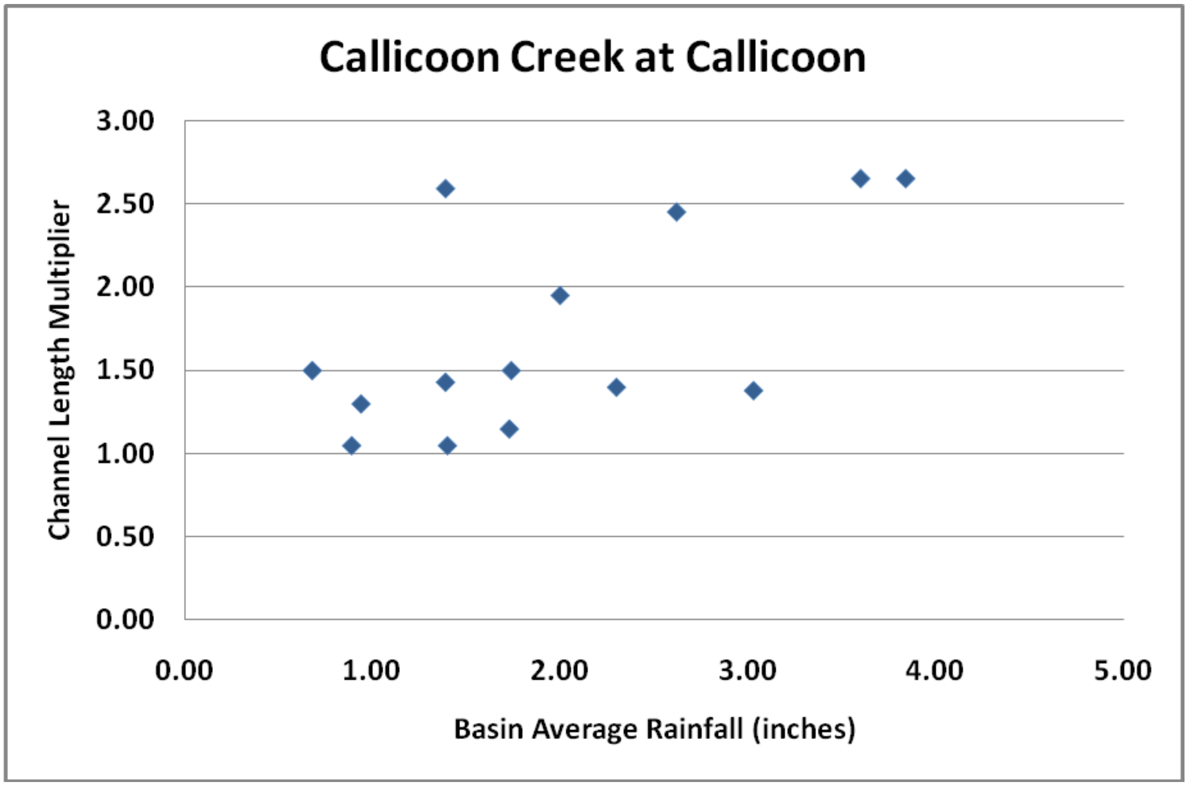

Figure 25: Plot of basin average rainfall vs. channel length multiplier.

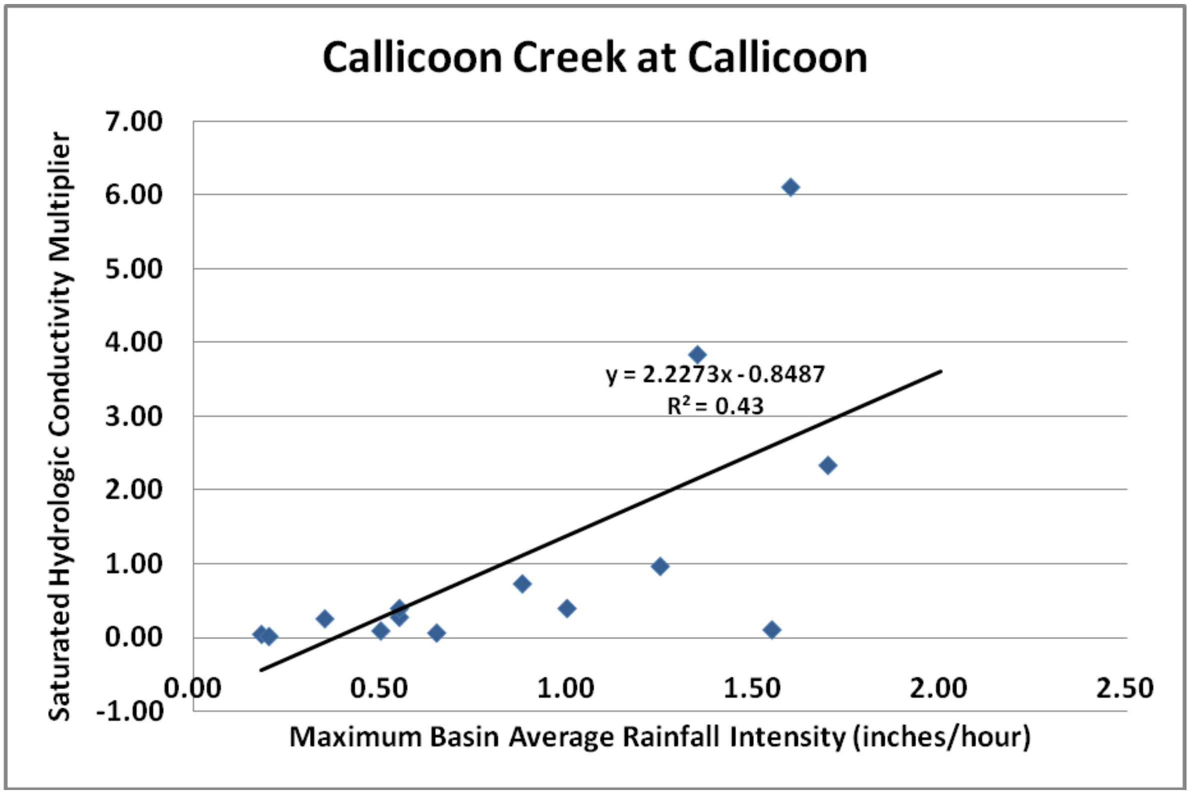

Figure 26: Plot of maximum basin average rainfall intensity vs. saturated hydrologic conductivity multiplier.

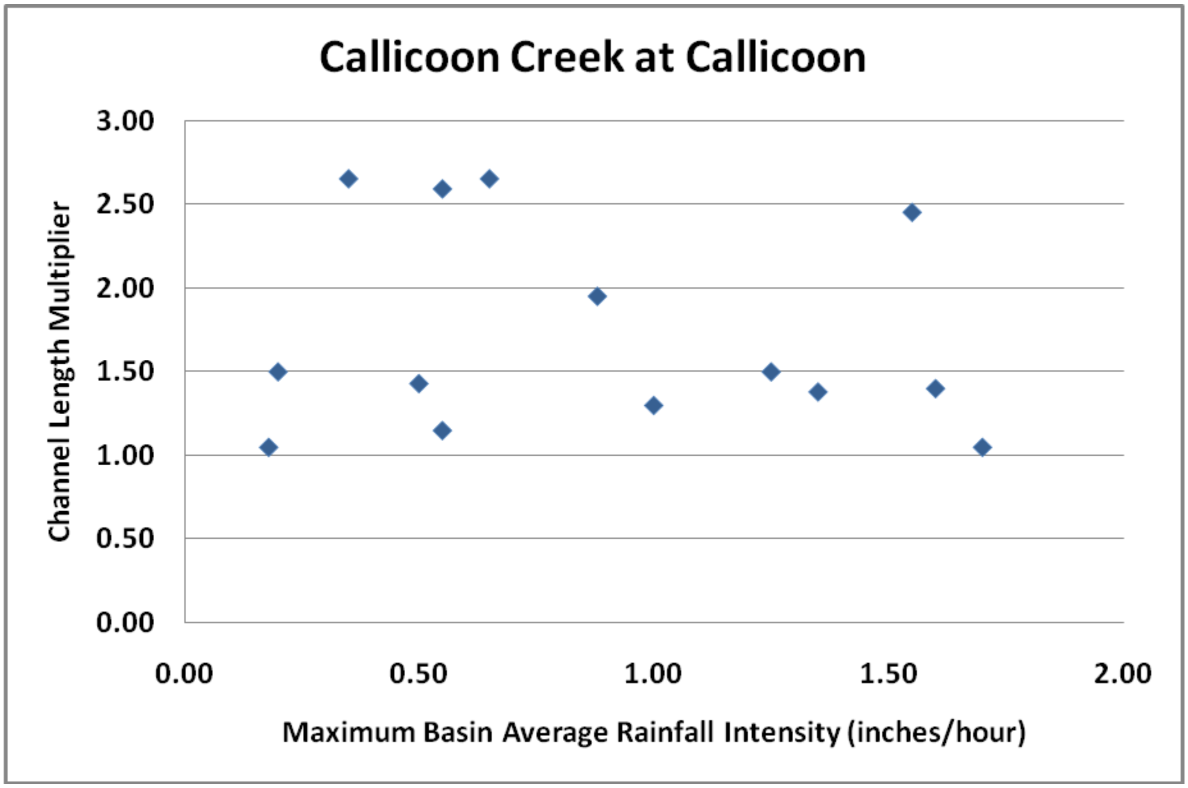

Figure 27: Plot of maximum basin average rainfall intensity vs. channel length multiplier.

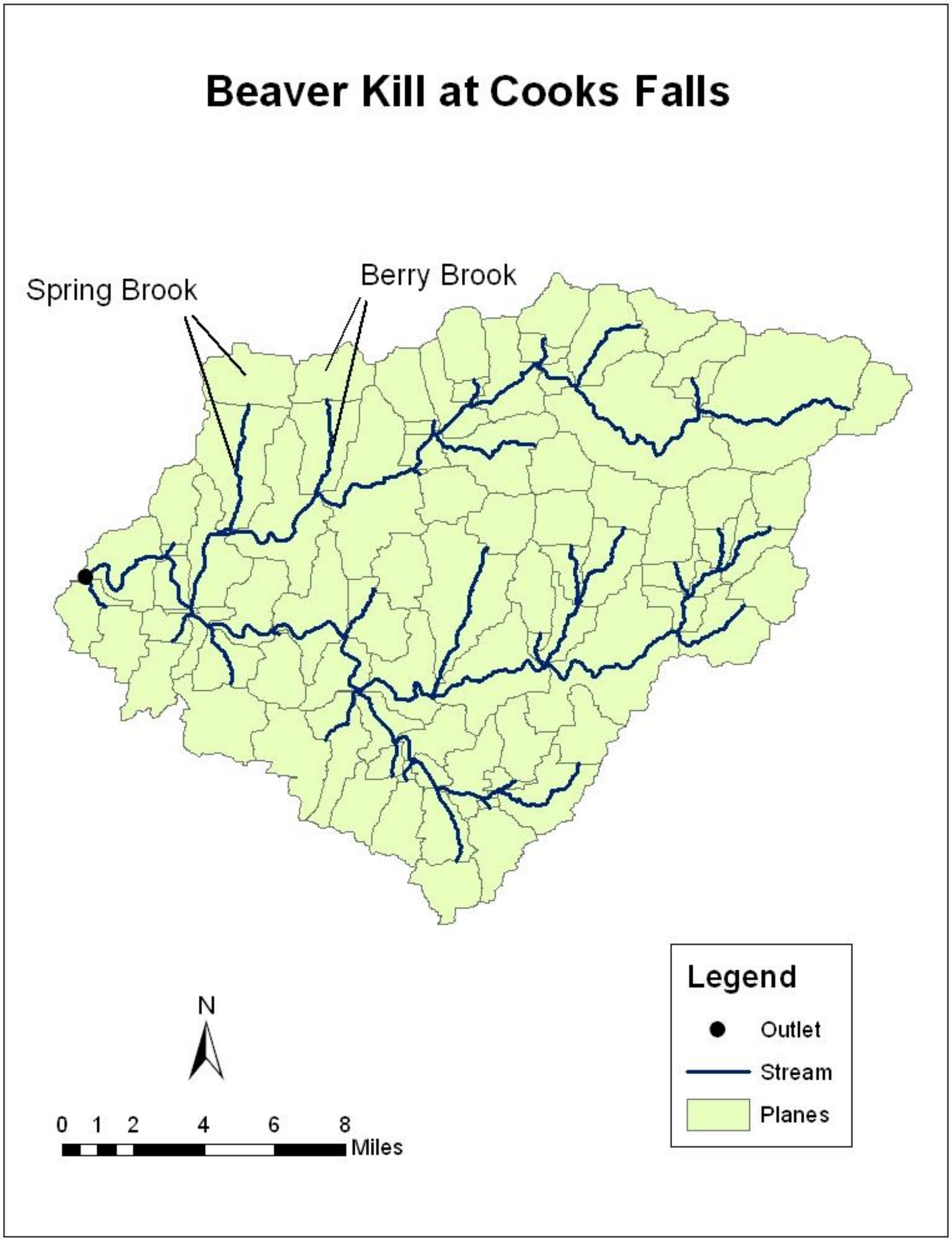

Figure 28: Beaver Kill at Cooks Falls, NY with the ungaged basins of Spring Brook and Berry Brook labeled.

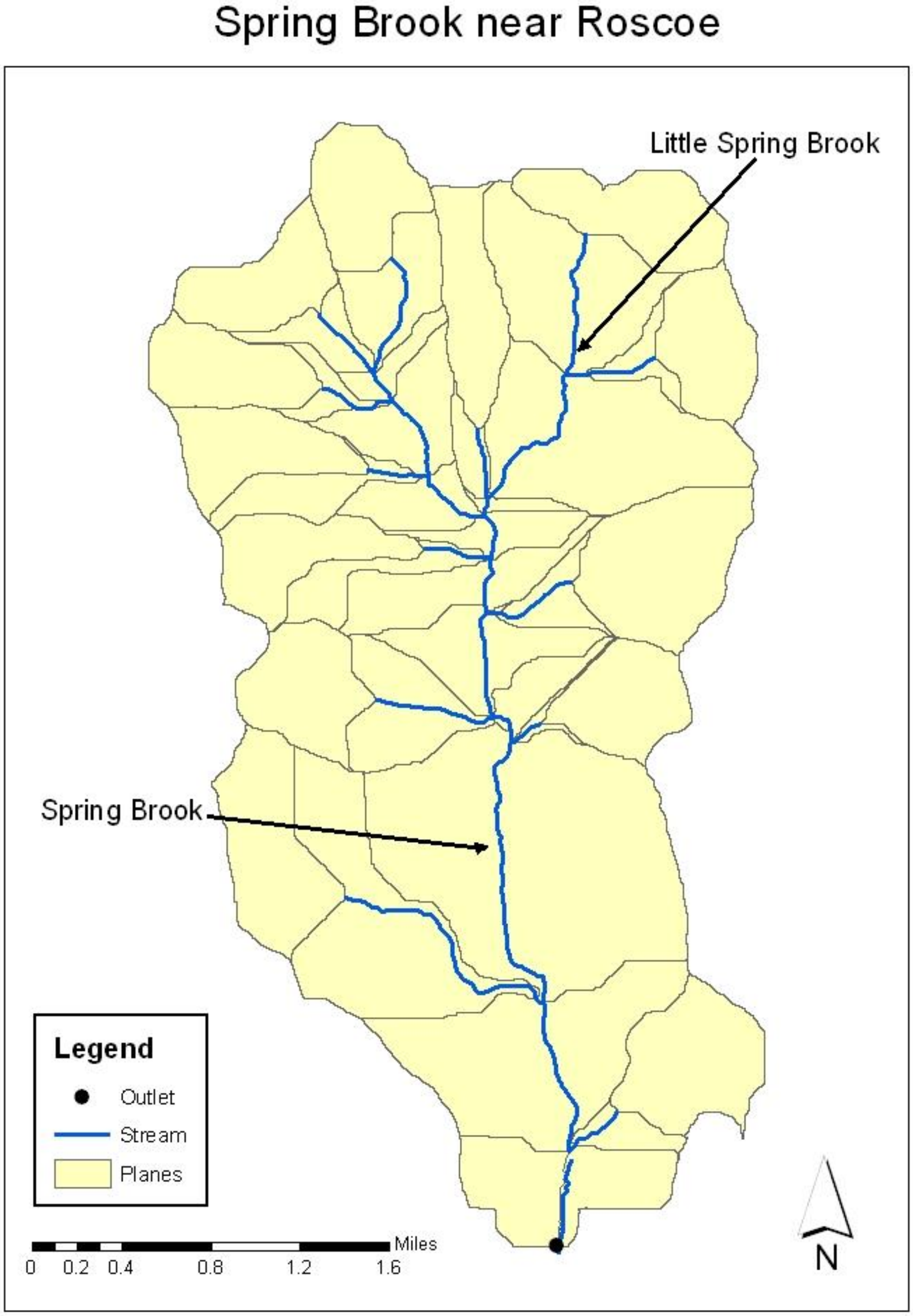

Figure 29: Spring Brook near Roscoe, NY with the mainstem Spring Brook and Little Spring Brook tributary labeled.

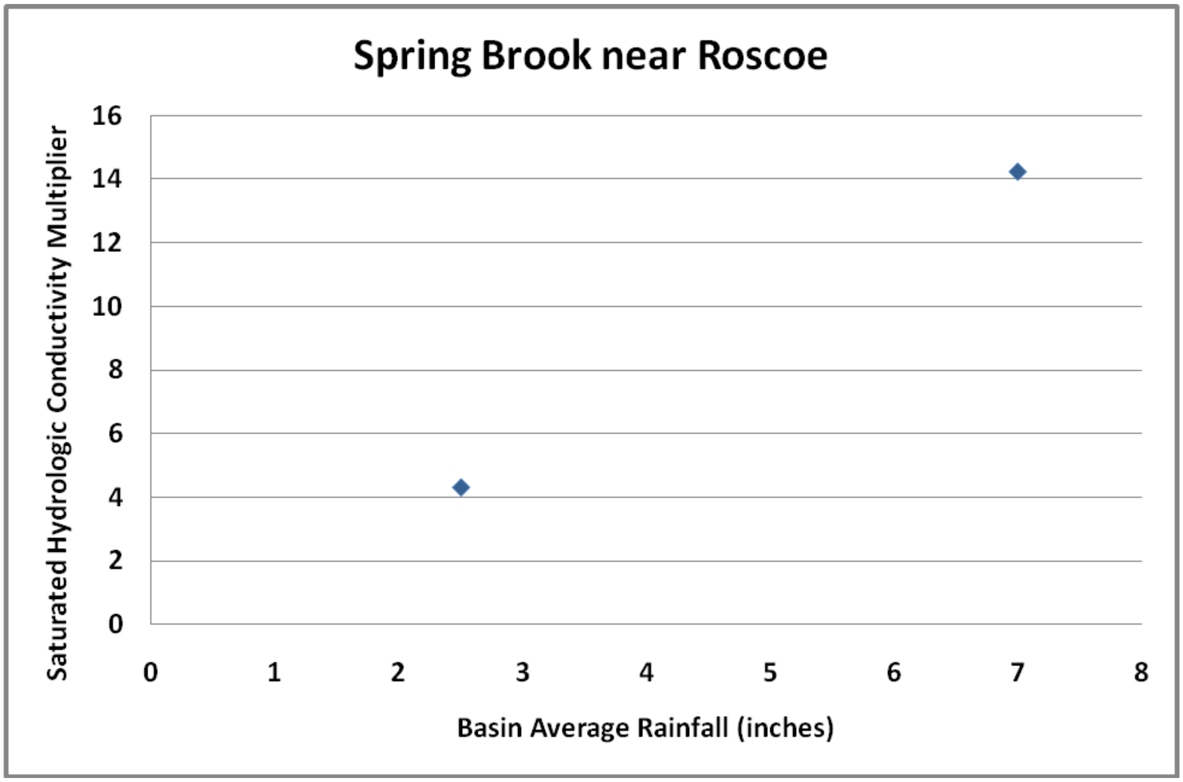

Figure 30: Plot of basin average rainfall vs. saturated hydrologic conductivity multiplier.

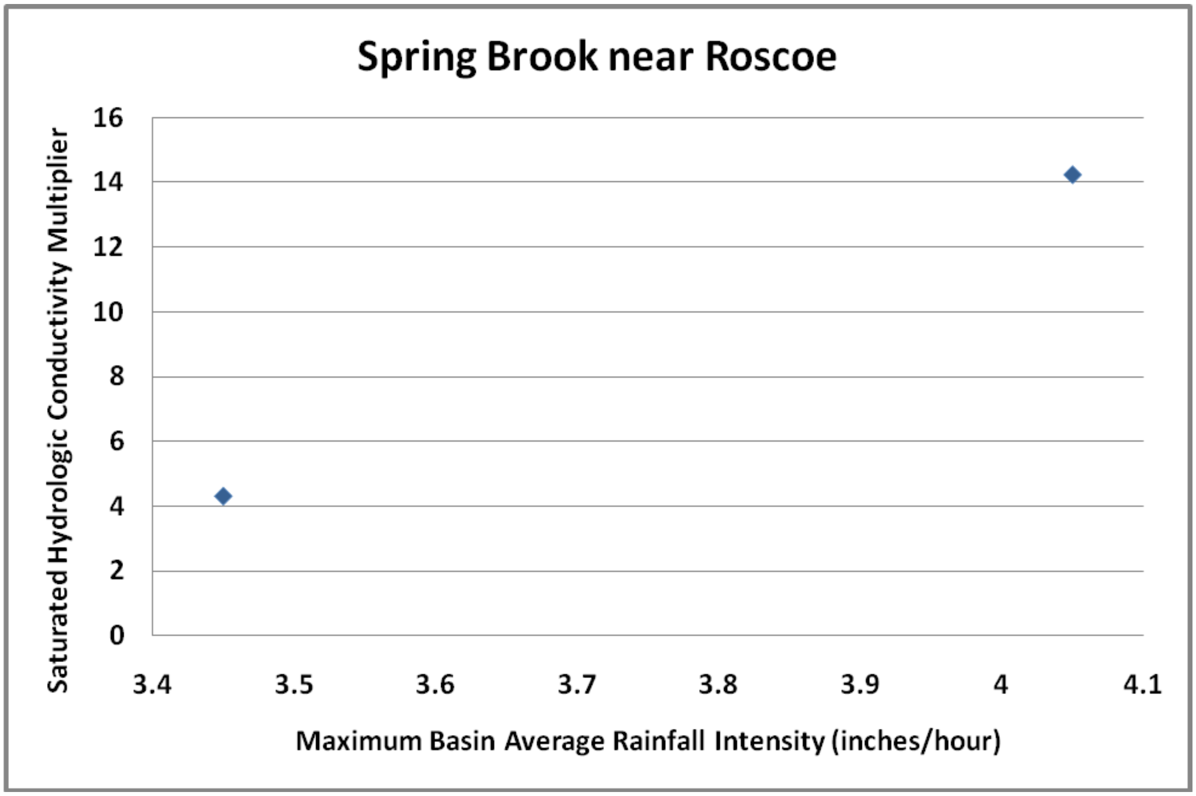

Figure 31: Plot of maximum basin average rainfall intensity vs. saturated hydrologic conductivity multiplier.

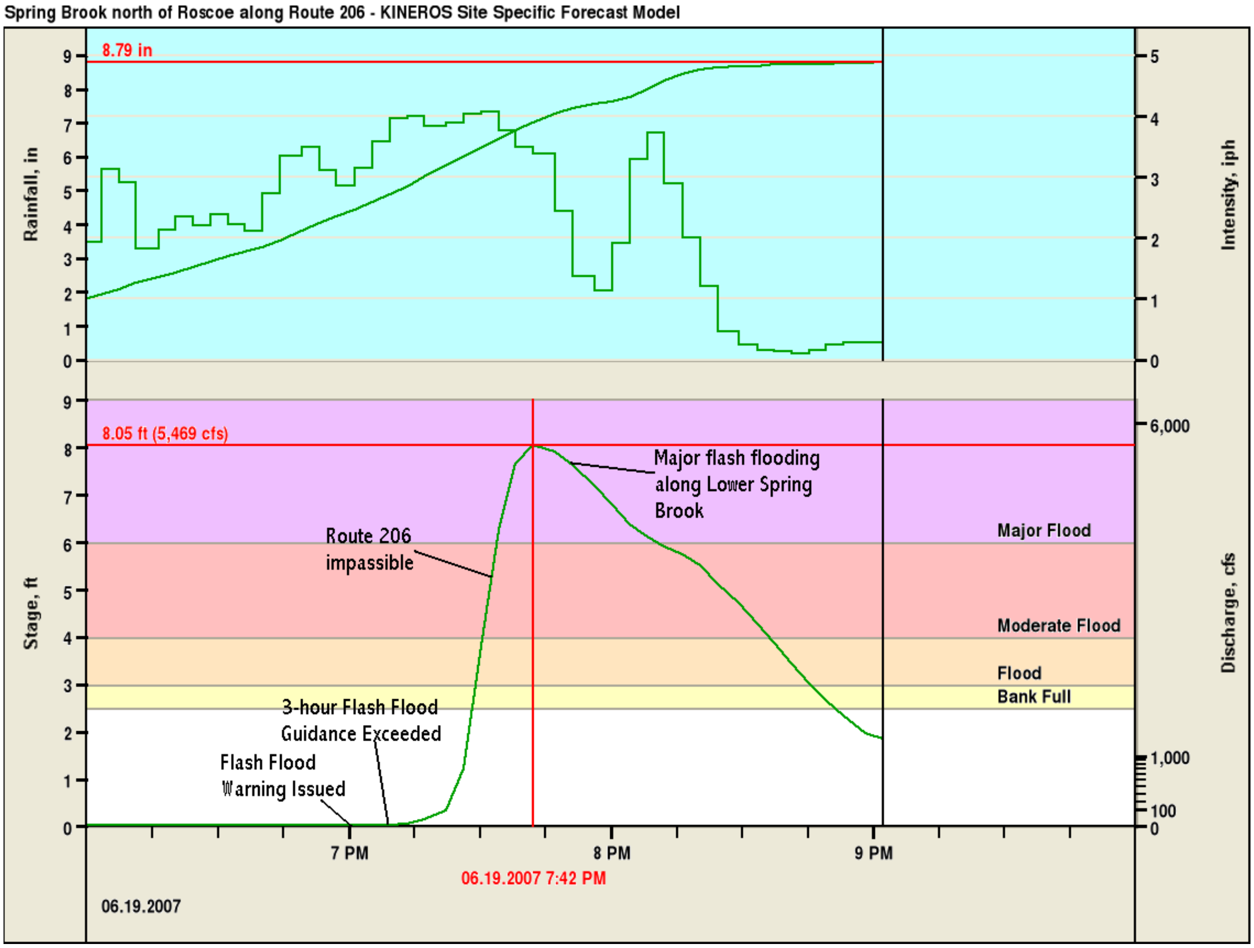

Figure 32: KINEROS2 modeled results for the June 19, 2007 flash flood event for Spring Brook near Roscoe. Reports received from the event have been overlaid on the hydrograph based on the time of occurrence.

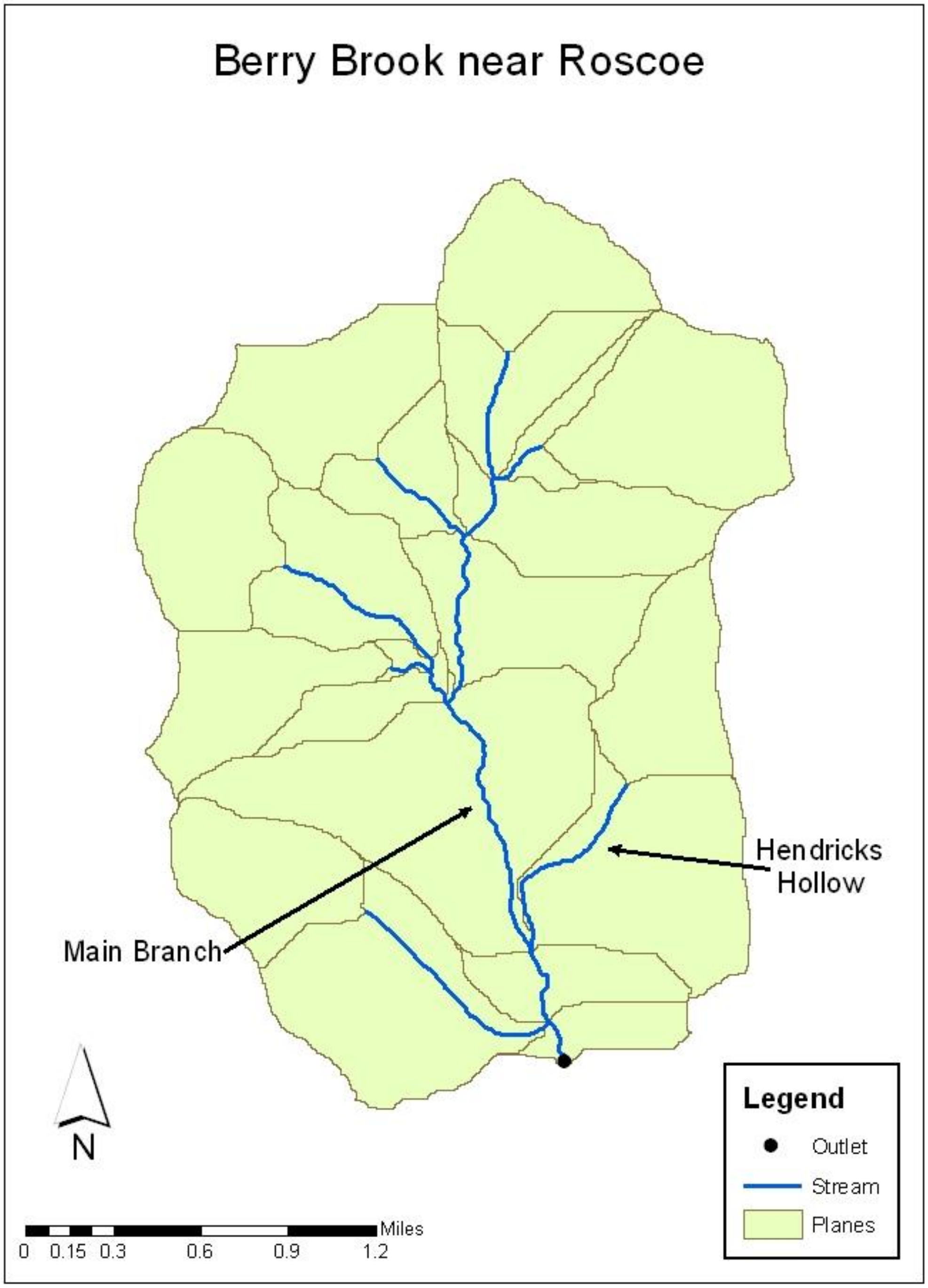

Figure 33: Berry Brook near Roscoe with the Main Branch of Berry Brook and Hendricks Hollow tributary labeled.

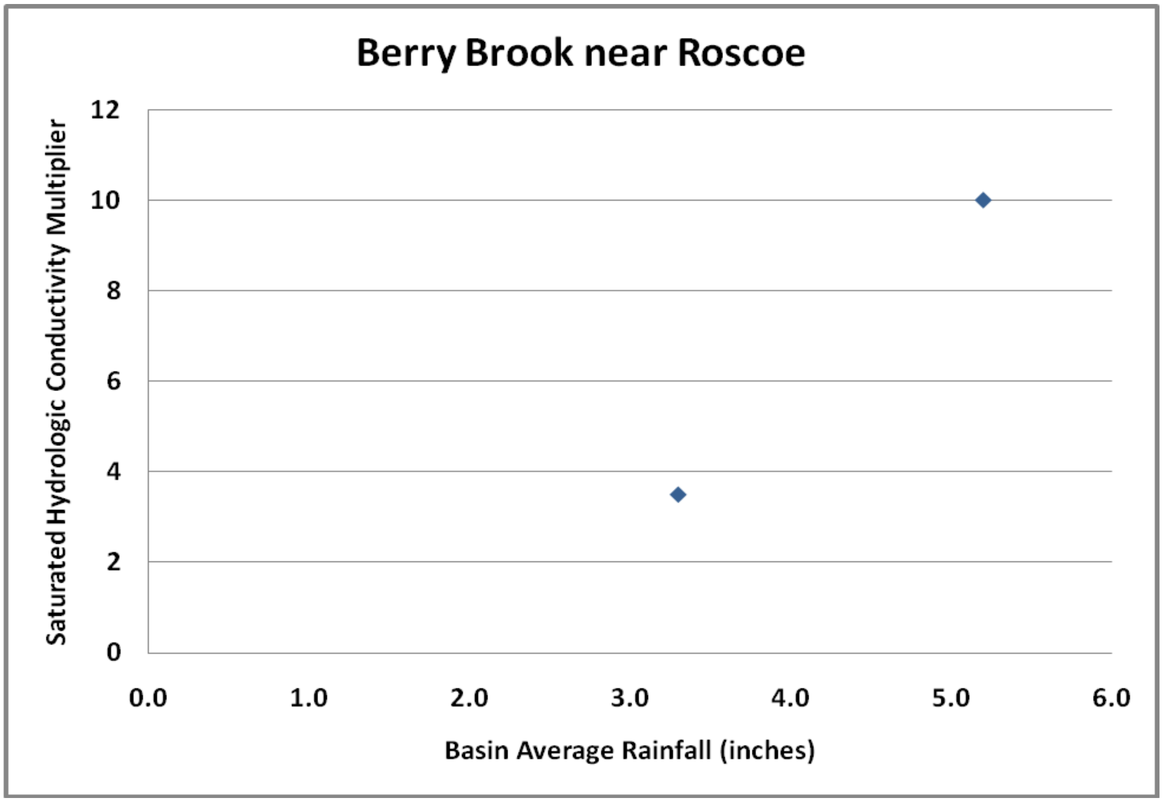

Figure 34: Plot of basin average rainfall vs. saturated hydrologic conductivity multiplier.

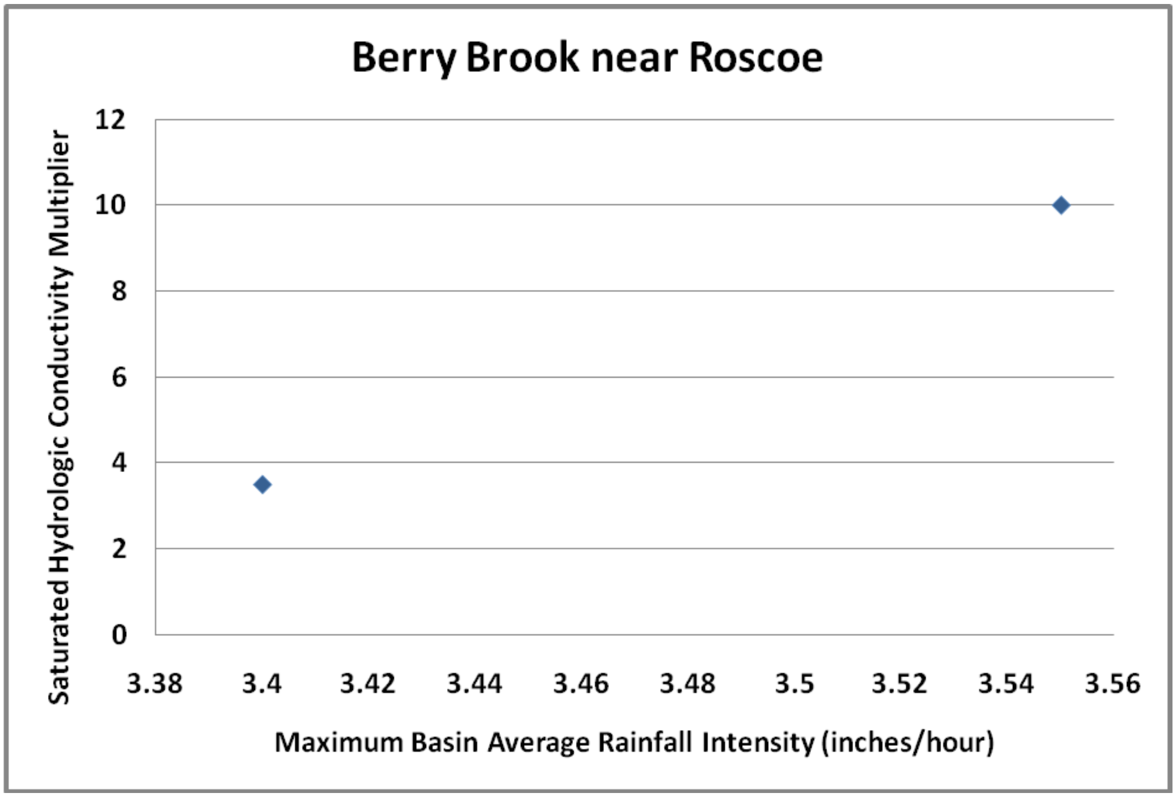

Figure 35: Plot of maximum basin average rainfall intensity vs. saturated hydrologic conductivity multiplier.

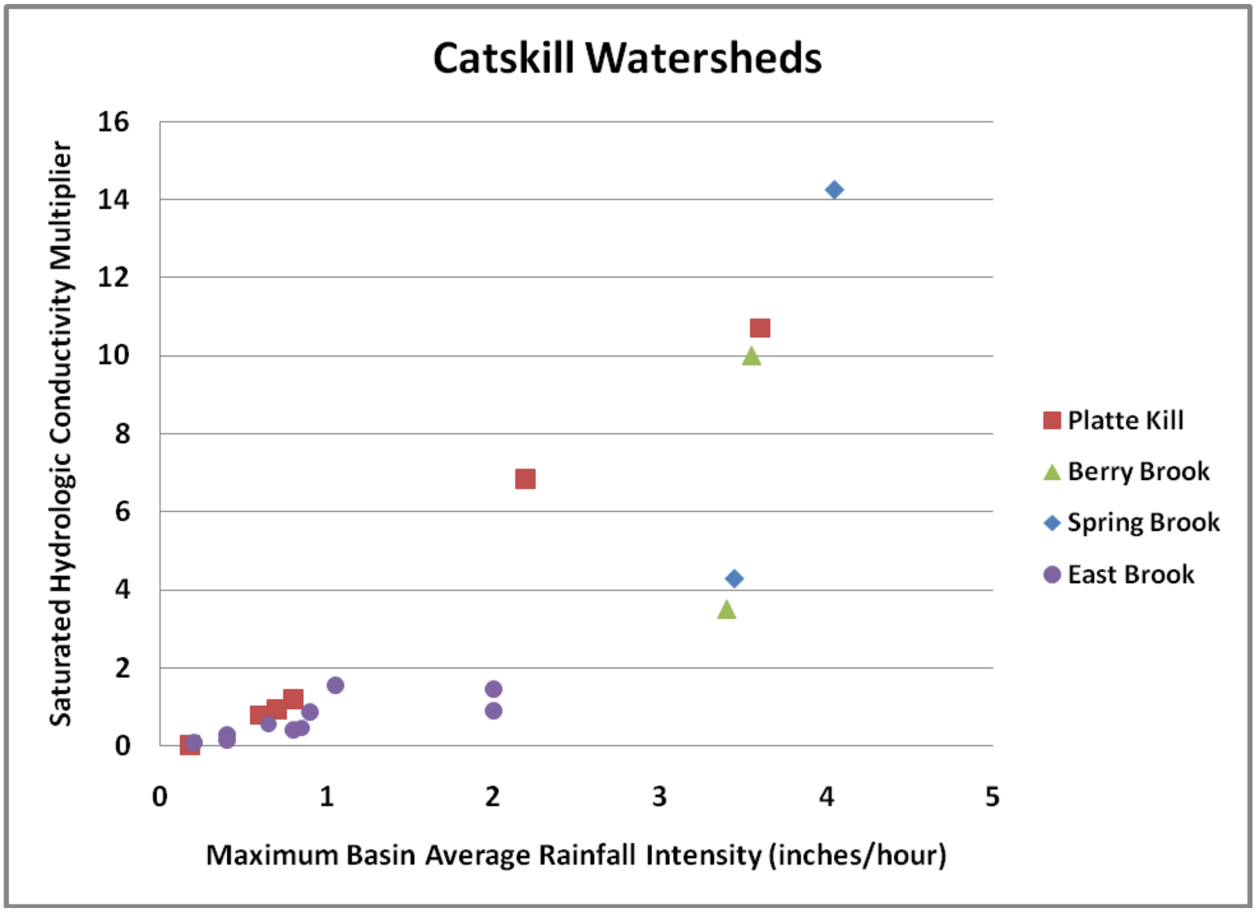

Figure 36: Plot of relationship of saturated hydrologic conductivity multiplier with respect to maximum basin average rainfall intensity for all four small watersheds calibrated in the Catskill Mountains.