Adding Radar Rainfall and Calibration to the TR-20 Watershed Model to Improve Dam Removal Flood Analysis

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Abstract: In communities where flood frequency data are unavailable, rainfall-runoff-routing models can estimate flood impacts of dam removal. We used the federal TR-20 model with PEST calibration software and NEXRAD radar rainfall data to study dam removal in the 186 km^2 section of New York's Onondaga Creek. The NEXRAD calibrated TR-20 simulated dam controlled flow for 100-year frequency 24-h duration rainfall, and the predicted peak discharge of 97 $\mathrm{m}^3\,\mathrm{s}^{-1}$ was within 1% of flood frequency estimates. TR-20 predicted a peak discharge of 270 $\mathrm{m}^3\,\mathrm{s}^{-1}$ for the same 100-year, 24-h rainfall with the dam removed, which was 4% higher than regional regression estimated peaks for an unregulated watershed. HEC river analysis system analysis of TR-20 floods showed naturalized flood peaks for events of 10 years or greater would leave the channel. This note reports on how radar rainfall and automated calibration are incorporated into TR-20 by managers and planners to enhance watershed restoration analysis.

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CE Database subject headings: Floods; Flood plains; Flood routing; Frequency analysis; Dams; Decommissioning.

Introduction

This research examines enhancement to a federal rainfall-runoff-routing model that included constrained calibration and spatially distributed radar rainfall data inputs. The dam examined for removal is drained at its base, removing concerns of sediment release and dam breach flood waves, and is located on Onondaga Creek, upstream of the City of Syracuse, N.Y. (see Fig. 1). Simulation was performed using the U.S. Department of Agriculture TR-20 (SCS 1992) model for observed rainfall-runoff events. This study demonstrates how managers can integrate public calibration software and readily available spatially distributed radar rainfall inputs to constrain parameter adjustment.

TR-20 as Watershed Peak Discharge Computation Method

Peak discharge computations for 24-h rainfall events are often performed with the Natural Resources Conservation Service Curve Number (CN) method in TR-20 (SCS 1992). The Federal Emergency Management Agency (FEMA) recognized TR-20 as an acceptable and widely used model in estimating future condition peak flood flows (FEMA 2004). Model improvements have focused on spatially distributed application of TR-20 for land use development and highway culvert design, which is facilitated with a geographic information system (GIS) interface (Moglen 2005).

Missing from TR-20 are advances in using (1) readily available radar rainfall data inputs, which spatially richer than gauge data; and (2) publicly available model calibration software. These radar-rainfall and calibration tools are features that are increasingly common in more recently developed hydrologic models, such as HEC-HMS (USACE 2004). Given TR-20 input data structure, incorporating radar rainfall is primarily a challenge of preprocessing the NEXRAD Digital Precipitation Array (DPA). Given TR-20 may be executed from the DOS command prompt using ASCII based input and output files, automated calibration is possible using the Parameter ESTimation (PEST) software (Doherty 2005). In the following sections, we illustrate how NEXRAD data and PEST calibration are used by TR-20 model simulation.

Collection and Processing of Input Data

Model simulation and flood analysis were performed for an upper part of the 301 km^2 Onondaga Creek Watershed, which ranges in elevation from 587 to 110 m. For this upper watershed, 30 subarea watersheds were delineated (see Fig. 1) based on tributary confluences and had an average area of 5 km^2, which is within 25% of the 4 km^2 NEXRAD bin size and captures rainfall spatial patterns. Watershed points of interest include the U.S. Geological Survey (USGS) gauges at Cardiff #04237962, 7.5 km above the dam on the South Branch, and Dorwin #04239000, 9 km below the dam on the North Branch, and the flood control dam separating these stations. At the Dorwin Gauge, Onondaga Creek has been widened and bounded with levees to contain 100-year flood flows. Below the Dorwin Gauge the Onondaga Creek flows through the City of Syracuse and enters into Onondaga Lake.

CN were obtained from a supervised classification of a 2001 Landsat TM image. This classification was superimposed with a

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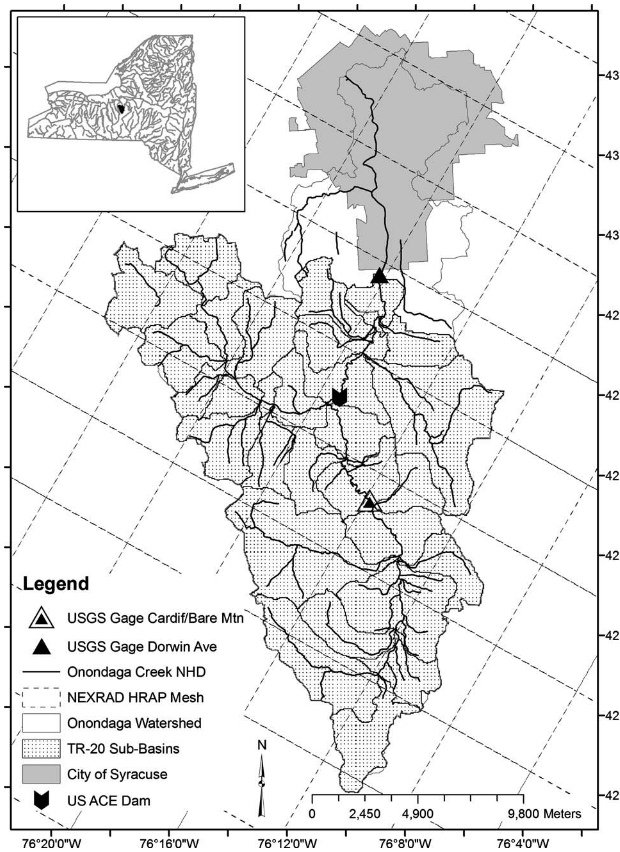


Fig. 1. Onondaga Creek Watershed, with dam, two USGS gauging stations, and City of Syracuse. Twenty-five NEXRAD HRAP bins are overlapping 30 subwatersheds. (Inset) Watershed location within New York State, and the grid around the edge has UTM zone 18 Northing and Easting coordinates.

Hydrologic Soil Group layer, which resulted in a spatially distributed database of soil and land use data. The CN database was partitioned and queried to produce a weighted CN by the watershed subarea. Dam regulation of the Onondaga Creek flow was simulated in TR-20 with a flow control device, which used as input dam-specific discharge and storage relations (USACE 1947). The outlet conduit allows flows up to 11 $m^3 s^{-1}$ to pass as open channel flow, at 16 $m^3 s^{-1}$ the conduit has filled, and when the reservoir is full, a maximum discharge of 40 $m^3 s^{-1}$.

TR-20 simulated the November 15–16 and April 2–4, 2005 rainfall-runoff events, for calibration and validation, using NEXRAD DPA from the Binghamton WSR88D station. These NEXRAD data are readily available on the Internet by the National Climatic Data Center (NCDC) (2005). These are not raingauge corrected radar Stage III or MPE files used by the NOAA River Forecast Centers, and those files are not as readily available. DPA files were converted from Binary to ASCII format with the NCDC NEXRAD Viewer (Ansari 2005). The ASCII DPA files were then imported to ESRI ArcGIS (Environmental Systems Research Institute, Redlands, Calif.) and overlain with the Onondaga Creek Watershed Shape file. Twenty-three DPA Hydrologic Rainfall Analysis Project (HRAP) bins overlapped the watershed, each bin 4-km^2 in area. A composite rainfall sum for each subwatershed was constructed by sampling the appropriate fraction from the overlapping HRAP bins. The sampling algorithm wrote out each subwatershed time series rainfall in the format required for input by TR-20.

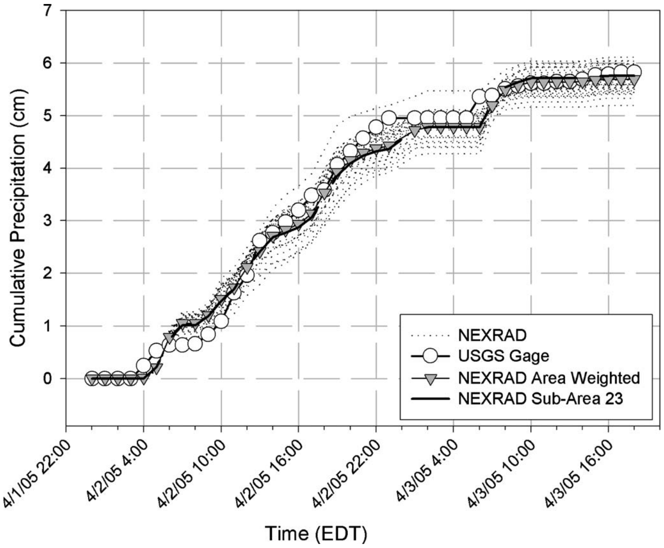


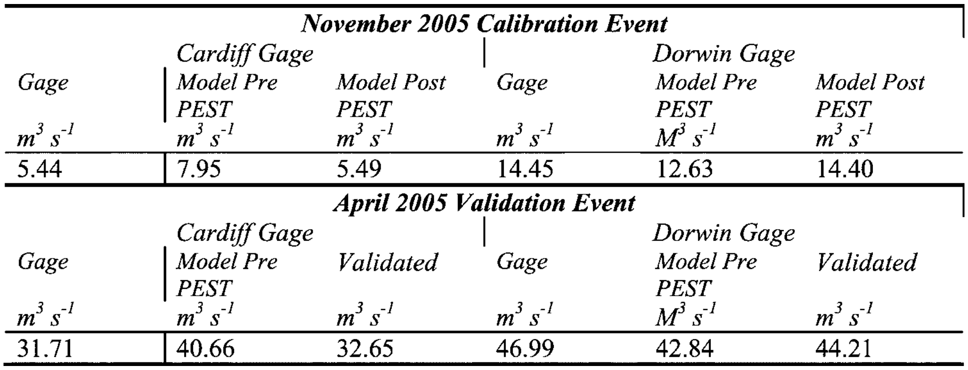
Fig. 2. Hourly cumulative rainfall (cm) time series for (a) November 2005; (b) April 2005 events used in calibration and validation. Each reports rainfall from the 30 subwatersheds recorded by NEXRAD, from the USGS gauge, and median values for NEXRAD. The November event also reports the ESF gauge value.

NEXRAD rainfall used for the calibration November 15–16, 2005 storm event had a median depth of 2.7 cm, whereas the validation April 2–4, 2005 storm event had a median depth of 5.7 cm, both events characterized by two pulses of rainfall (see Fig. 2). Important features captured by NEXRAD for the November and April 2005 rainfall involved storm intensity and movement. The November storm had greater intensity and depths in the northern section of the watershed, moving west to east. The April storm moved from the northwest to the southeast, and depths have a spatial arrangement that reveals this storm trajectory.

Initial model runs used unique cross sections for each stream reach, which required energy slope values at different water stages, from low flow to extreme floods. These energy slope values were determined through hydraulic simulation of each reach set in HEC river analysis system (RAS) with a mixed flow regime, look-up values of roughness, and boundary conditions of stage (USACE 2002). Reach cross sections were obtained from USGS records for Onondaga Creek.

Preliminary Calibration and Validation of TR-20

TR-20 was run for the November 15–16, 2005 storm, with 38 h of rainfall. Analysis of the calibration and validation storms is documented and available in our technical reports. CN inputs to TR-20 are nonmeasurable, subbasin average, values that were estimated using standard procedures, yet CN values typically increment by 2–4 units and provide some room for fine-tuning the model. No other model parameters were adjusted. Forcing the November 15–16, 2005 heterogeneous rainfall across the watershed enabled a spatially unique adjustment of CN values, which was completed by the PEST software (Doherty 2005). The final CN values within the Onondaga Creek Basin underwent a mean absolute adjustment of 1.8 units, with 20 subwatersheds CNs adjusted upward by an average of 1.1 units, 10 subwatersheds CNs adjusted downward by an average of 0.7 units.



November 2005 Calibration Event					
	Cardiff Gage			*Dorwin Gage*	
Gage $m^3 s^{-1}$	*Model Pre PEST* $m^3 s^{-1}$	*Model Post PEST* $m^3 s^{-1}$	*Gage* $m^3 s^{-1}$	*Model Pre PEST* $M^3 s^{-1}$	*Model Post PEST* $m^3 s^{-1}$
5.44	7.95	5.49	14.45	12.63	14.40
April 2005 Validation Event					
	Cardiff Gage			*Dorwin Gage*	
Gage $m^3 s^{-1}$	*Model Pre PEST* $m^3 s^{-1}$	*Validated* $m^3 s^{-1}$	*Gage* $m^3 s^{-1}$	*Model Pre PEST* $M^3 s^{-1}$	*Validated* $m^3 s^{-1}$
31.71	40.66	32.65	46.99	42.84	44.21

Fig. 3. Calibration and validation discharge values ($m^3 s^{-1}$) for the Onondaga Creek Watershed at the USGS Cardiff and Dorwin Gauges

Using PEST calibrated CN values, the observed and modeled peak discharge at the Cardiff and Dorwin Gauges differed by less than 1%, as reported in Fig. 3. When uniform average rainfall was used, a similar model fit was only obtained by allowing CN values to adjust by 5 units, and 12 basins were at the 5 unit limit. TR-20 was next run with the adjusted CN values for the April 2–4, 2005 storm, with 34 h of rainfall, with an observed peak discharge at Cardiff Gauge was 31.7 $m^3 s^{-1}$. Predicted peak discharges from the validation model runs were 3% larger at the Cardiff Gauge and 6% lower at the Dorwin Gauge. To quantify the impact of the calibrated parameters on the April event, TR-20 was run with the uncalibrated CN and peak discharge was recorded for the Cardiff and Dorwin Gauges. When using the unadjusted CN values, TR-20 overpredicted peak discharge by 28% at the Cardiff Gauge and underpredicted it by 8.4% at the Dorwin Gauge. Fig. 3 summarizes these values.

Estimation of Peak Flow for Design Storms with Dam Removal

Following PEST based adjustment of TR-20, flood estimation at USGS Dorwin Gauge with design rainfall considered two scenarios, dam present and dam removed, and historical records were used in both cases to compare with model predictions. Dorwin Gauge provided historical flow records and permitted comparison of TR-20 results with two other methods of flood analysis, frequency analysis, and regional regression.

Flood frequency analysis (FFA) was conducted with an annual series in a Log Pearson Type-III FFA (USWRC 1981). FFA used station skew and historical peak streamflow data from the USGS Dorwin Gauge, postdam construction, from 1952 to 2004. A set of predam flows (1902–1943) were obtained from City of Syracuse and U.S. Army Corps of Engineers (ACE) reports (Syracuse Intercepting Sewer Board 1927), however FFA estimates from these flows were less certain, with observations from multiple sites, and with nonstationarity in watershed land cover. Regional regression was conducted with equations developed for unregulated basins in the larger Oswego River Watershed, Region 7, by the USGS (Lumia 1991), which contains the Onondaga Creek Watershed. Coefficients in the regression are watershed parameters of area, main channel slope, basin storage, annual precipitation, main channel average elevation, and basin shape, and values were extracted from GIS layers.

TR-20 was run with TP40 design rainfall (Hershfield 1961) 24-h rainfall storm depths, with the Type II rainfall hyetograph distribution. This 24-h duration exceeded the 11-h time of concentration for our watershed, enabling runoff response from the entire watershed. Table 1 lists for recurrence intervals between 2 and 100 years the TP40 24-h design rainfall depths, the FFA predicted peak discharges pre- and postdam, the TR-20 predicted peak discharges with dam present and dam removed, and the regional regression peak discharges.

Dam present TR-20 simulation had relatively good agreement with FFA predicted peaks for Dorwin Gauge for the period of record with the dam in place. The maximum difference was 14.4% for the 5-year recurrence interval, the minimum difference 0.7% at the 100-year recurrence interval, and the average difference was 6%. In all cases, except the 100-year event, TR-20 peak estimates were lower than FFA estimates. This is likely a result of TR-20 calibration to a non-rain-on-snow event, and the dominance of rain-on-snow conditions in annual peak streamflow data at Dorwin Gauge. These larger differences at shorter recurrence

Table 1. Onondaga Creek Peak Discharges ($m^3 s^{-1}$) at USGS Dorwin Gauge

Return interval (years)	Rainfall depth (cm)	FFA predam discharge ($m^3 s^{-1}$)	FFA postdam discharge ($m^3 s^{-1}$)	TR-20 with dam discharge ($m^3 s^{-1}$)	TR-20 without dam discharge ($m^3 s^{-1}$)	Regional regression discharge ($m^3 s^{-1}$)
2	6.60	35.67	63.14	34.64	56.13	88.98
5	8.13	50.96	98.53	43.62	94.63	129.03
10	9.65	61.72	124.86	55.01	136.47	159.26
25	11.43	75.31	161.38	72.92	193.52	199.05
50	12.19	85.79	190.83	81.68	219.08	230.44
100	13.21	96.55	222.54	97.18	270.20	260.80

Note: Based on Log Pearson Type-III flood frequency analysis (FFA), TR-20 model design rainfall simulation, and regional regression.

intervals may be simply a function of the relatively short 52-year gauge record.

Dam removed TR-20 simulation had relatively good agreement with regional regression peaks for the Dorwin Gauge. For 25-, 50-, and 100-year recurrence intervals the average difference was less than 4%. The 2-year event had a difference of 37%, the 5-year a difference of 27%, in both cases with TR-20 under estimating peaks. Given the regional regression equations were established with nearby gauge records, rain-on-snow phenomenon may also explain why TR-20 underestimated these regional regression peaks. Comparison to FFA applied to predam historic peaks was limited by FFA data quality. Although the 2-, 5-, and 10-year values from the two methods are within an average of 8% of each other, the 25-, 50-, and 100-year values show TR-20 overestimating the FFA by an average of 19%.

Local channel and community flooding from the calibrated TR-20 dam removed 100-year event was analyzed using the HEC-RAS water profile model along the Dorwin Gauge channel. The cross sections used by the HEC-RAS simulation were obtained using total station surveys and LiDAR data of the site. Capacity at Dorwin was estimated by the U.S. ACE at 85 $m^3\,s^{-1}$, rising to 140 $m^3\,s^{-1}$ downtown, and then returning to 85 $m^3\,s^{-1}$ further downstream. HEC-RAS estimated dam-removed 10-year floods were contained in the channel, however historical records suggest the dam-removed 5-year flood will overtop at Dorwin Gauge as it is above 85 $m^3\,s^{-1}$. These differences may be due in part to irregular levee heights along the Creek above and below the Dorwin Gauge and are receiving further study.

Given the flood risk of complete dam removal, incremental flood mitigation measures were evaluated. One option is incremental breaching of the dam, at the Creek bed, in combination with establishment of off-line storage in riparian depressions of water leaving the channel. Incremental breaching, at 25–75% of dam removal, would provide options for reduced risk partial dam removal. Another option involves additional off-channel wetland storage or in-channel compound floodplain. Wetland storage for the channel returned to a capacity of 28 $m^3\,s-1$, the regional bankfull discharge established by DeKoskie (2004), would require a 1-m deep storage area of 9.5 km^2.

Conclusions

This research recommends enhancing TR-20 to incorporate PEST calibration software and readily available NEXRAD rainfall data. These enhancements were needed to establish model credibility in analysis of flooding for a channel naturalization and dam removal proposal in the 186 km^2 Onondaga Creek Watershed. When TR-20 CN adjustments were made with gauge data, rather than NEXRAD data, and used in validation, the predicted peak was 18% of the observed peak, rather than a 4% difference using NEXRAD. TR-20 simulation of dam removed 100-year design rainfall floods was within 4% of the USGS regional regression equation estimates for an unregulated watershed. Water resource managers and planners are encouraged to realize the benefit of using these NEXRAD data and PEST calibration routines, which are readily available and integrate well with standard engineering models such as TR-20.

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