Use of NEXRAD Weather Radar Data with the Storm Precipitation Analysis System (SPAS) to Provide High Spatial Resolution Hourly Rainfall Analyses for Runoff Model Calibration and Validation

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Accurate and detailed rainfall is a critical parameter for hydrologic runoff model calibration and validation. However, hourly rainfall observations are generally limited to a small number of locations, with many basins lacking observational rainfall data within the basin boundaries. NEXRAD weather radar data provides additional information over basins but the radar estimated rainfall products often overestimate or underestimate rainfall depths, due to many reasons (Hunter, 1999). Techniques have been developed to calibrate the NEXRAD weather radar data with rain gauge data to greatly improve the accuracy of the radar derived rainfall estimates, and produce high spatial and temporal resolution rainfall information for use in runoff model calibration and validation.

The Storm Precipitation Analysis System (SPAS) is a sophisticated meteorological tool used to characterize the temporal and spatial details of rainfall events (Tomlinson and Parzybok, 2004). SPAS was designed to produce storm depth-area-duration (DAD) analyses for making objective comparisons of rainfall associated with extreme storms in Probable Maximum Precipitation (PMP) studies. A SPAS analysis usually covers a relatively large area (generally >1000 square miles), consists of a full DAD investigation, extensive data mining and analysis, and includes a wide range of deliverables. However, hydrologic modeling studies have been the catalyst to use an abbreviated version of SPAS (referred to as SPAS-lite) to provide storm analyses over much smaller domains (generally <100 sq-mi) without the DAD analysis while providing a limited but sufficient set of deliverables for hydrologic modeling purposes. By incorporating NEXRAD data, SPAS-lite produces high-resolution spatial and temporal precipitation information. The resulting rainfall information are provided as hourly precipitation distributions within basin boundaries or as sub-basin averages.

The NEXRAD data provides greatly improved detailed information on the spatial variation of rainfall. Once calibrated to the available hourly rainfall rain gauge observations, the measurement accuracy of the rain gauge observations are applied to the high spatial resolution NEXRAD data to provide significant improvements in the analyses of areal variations of storm rainfall. By calibrating the NEXRAD data with the ground rain gauge observations each hour, reliable rainfall analyses are produced for each hour of the storm.

The SPAS-lite storm analyses use the NEXRAD derived hourly rainfall amounts along with the observed rainfall data to provide hourly analyses of rainfall over sub-basins within the drainage basin boundaries. The SPAS-lite results are used for calibration and validation of run-off models for each storm analyzed. Hydrologic modelers usually require detailed rainfall information for several historic storms that have produced extreme rainfall amounts over a basin for runoff model calibration. After identifying the largest rainfall events to be used, NEXRAD data are acquired together with available rain gauge data for locations within and in close proximity to the basin. After performing hourly calibrations of the NEXRAD data with the hourly rain gauge data, the SPAS-lite analysis produces rainfall amounts over the basin using GIS. For probable maximum precipitation studies, extreme rainfall storms that have not been previously analyzed can be analyzed with available rain gauge data using SPAS. By incorporating NEXRAD into the analysis, the spatial precision of the hourly rainfall isohyetal analyses is greatly improved resulting in more accurate DADs.

Radar-Rainfall Estimation Process

The high spatial resolution hourly rainfall allows for accurate estimates of rainfall volumes over sub-basins located within relatively flat terrain as well as within topographically complex regions. The increased accuracy of the precipitation analyses has eliminated the need for commonly made assumptions about precipitation characteristics, thereby greatly improving the precision and reliability of hydrologic analysis.

Radar has been in use by meteorologists since the 1960's to estimate rainfall depth. In general, most current radar-derived rainfall techniques rely on an assumed relationship between radar reflectivity and rainfall rate. This relationship is described by the Z-R equation below:

$$Z = A\,R^b$$

where Z is the radar reflectivity, measured in units of dBZ, R is the rainfall rate, A is the "multiplicative coefficient" and b is the "power coefficient". Both A and b are directly related to the drop size distribution (DSD) and drop number distribution (DND) within a cloud (Martner et al 2005).

The National Weather Service (NWS) utilizes these algorithms to estimate rainfall through the use of their network of NEXRAD radars located across the United States. A default Z-R algorithm of $Z = 300R^{1.4}$ is the primary algorithm used throughout the country and has proven to produce highly variable results. The variability in the results of Z vs. R is a direct result of differing DSD, DND and air mass characteristics across the United States (Dickens 2003). The DSD and DND are determined by complex interactions of microphysical processes within a cloud. They fluctuate daily, seasonally, regionally, and even within the same cloud. Some other factors include occultation or blockage of the radar beam due to terrain features and range effects that account for variations when the radar beam passes through various elevations in the cloud relative to the main precipitation portions of the cloud.

Several storms have been analyzed using NEXRAD data. One example is the analysis of the October 1996 extreme rainfall storm in southeastern Maine. The techniques described above were used to determine radar derived rainfall depth and temporal distribution estimates over an approximate 66,325mi^2 area. The project area (Figure 1.0) includes portions of Maine, New

Hampshire, Massachusetts, Vermont, Connecticut, and all of Rhode Island. The rainfall event occurred during the period October 19 through October 22, 1996.

The methodology that was used to estimate the rainfall is described as follows:

1. Surface rainfall observations measured within the project area were obtained from multiple sources for the rainfall event. A Geographic Information System (GIS) layer containing the locations of these rainfall observations was created using GIS software.

2. NEXRAD data from NWS radars sites KGYX (Gray, Maine), KBOX Taunton, Massachusetts and KOKX; (Upton, NY) were obtained from the National Climatic Data Center (NCDC). Level II Base Reflectivity data, 0.483 degree beam angle (lowest beam angle), 124 km range, data resolution of 1 degree (polar coordinates) x 1.0 km, and 0.50 dBZ data bin resolution were extracted from the Level II dataset. During the event all three radars were operating in Volume Coverage Pattern (VCP) 21 mode, which produces base reflectivity information at a temporal resolution of 6 minutes.

3. The polar coordinate base reflectivity data (Z) were converted into Cartesian coordinate ESRI ASCII II Grid GIS files and combined with the rainfall observations GIS layer. The grid cells within the GIS grid have a resolution of approximately 1.00 km^2. GIS Scripts were used to determine base reflectivity values (Z) over each grid cell, within the project area, for each radar time step.

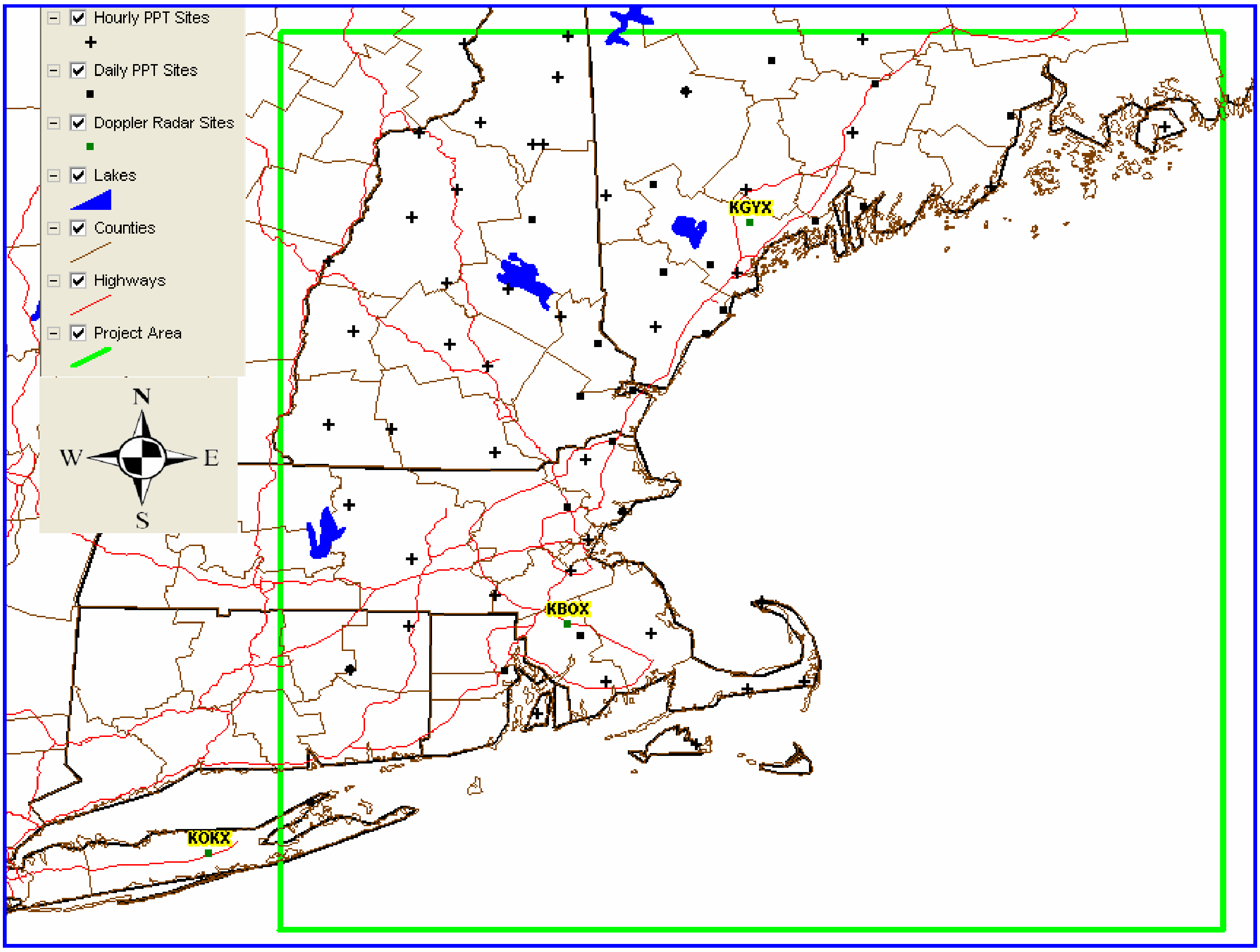

Figure 1.0: Rainfall reconstruction project area.

4. A range correction scheme developed by the United States Bureau of Reclamation was applied to each grid cell. The range correction factor (CF) used was: 1.04607 - 0.0029590 * r + 0.0000506 * r^2, where r is the range (distance in km) from the radar (Hartzell and Super, 2000). The correction was applied to grid cells that were greater than 35 km beyond the radar site. The range CF corrects for rainfall underestimation due to the radar beam passing through elevations in the cloud higher than the primary precipitation portion of the cloud.

Least Squares Z-R Procedure

A procedure was used to calculate a "best-fit" Z-R relationship for the project area. The "best-fit" Z-R relationship was calculated on an hourly basis using the least squares methodology. Least squares is a mathematical optimization technique which, when given a series of observed data values, determines a function that closely approximates the data (a "best fit"). It attempts to minimize the sum of the squares of the differences between point values generated by the function and corresponding points in the data.

The calculated hourly "best-fit" Z-R algorithm was used to estimate hourly rainfall depths for each grid square. The hourly "best-fit" Z-R algorithm was applied globally to the entire the project area that was within each of the radars range (230 km). The "best fit" Z-R algorithm was applied to all of the grid cells within the radars range and produced a total estimated precipitation depth for each hour.

Known Issues/Data Errors

Several issues were identified in the radar-rainfall estimation process that may contribute to a less than perfect correlation between radar rainfall depth estimates and rainfall depth observations. These issues include the following:

1. **Area average radar-rainfall depth estimates versus observed point rainfall depths:** A rainfall observation measured by a rain gauge represents a much smaller area then the area that the radar is sampling. The area that the radar is sampling in which the rain gauge is located is approximately $1km^2$ and contains the average reflectivity (Z) within the area being sampled. Therefore by converting Z to $R_{estimated}$ within the sample area that contains the rain gauge, an area averaged rainfall depth is being compared to a point rainfall depth. This can contribute to correlations greater than or less than 1.0 within the project area.

2. **Rain gage catch:** Errors exist with regard to catchment of rainfall by rain gages. These errors include wind/turbulence losses and tipping bucket losses with high rainfall rates. The wind/turbulence errors are usually around 5% but can be as large as 40% in high winds. Tipping buckets miss a small amount of rainfall during each tip of the bucket due to the bucket travel and tip time. As rainfall intensities increase, the volumetric loss of rainfall due to tipping tends to increase. At rainfall intensities greater than 152 mm per hour, 1 mm tipping buckets will under report rainfall in the range of 0-5% depending on how the gauge was calibrated. Smaller tipping buckets can have higher volumetric losses due to higher tip frequencies.

3. **Radar Calibration:** NEXRAD radars calibrate reflectivity every volume scan, using an internally generated test. The test determines changes in internal variables such as beam power and path loss of the receiver signal processor since the last off-line calibration. If this value becomes large, it is likely that there is a problem with the calibration and precipitation estimates could be significantly in error. The calibration test is supposed to maintain a reflectivity precision of 1 dBZ[1].

4. **Attenuation:** Attenuation is the reduction in power of the radar beams energy as it travels from the antenna to the target and back, and is caused by the absorption and the scattering of power from the beam by precipitation. Attenuation can result in errors in Z as large as 1 dBZ especially when the radar beam is sampling a large area of heavy precipitation, as was the case for the October 1996 rainfall event.

[1] A 1dBZ error translates to an accuracy of + or - 17% when the default Z/R relationship $Z = 300R^{1.4}$ is used

5. **Range effects:** The curvature of the Earth and standard refraction result in the radar beam becoming more elevated above the surface with increasing range. With the increased elevation of the radar beam comes a decrease in Z values due to the radar beam not sampling the main precipitation portion of the cloud. A correction scheme was applied for this issue and is described in the methodology section.

6. **Radar Beam Occultation:** There was radar occultation (beam blockage) of greater than 60% due to terrain features across an area in north central New Hampshire. The KGYX 0.483 radar beam encountered greater than 60% occultation due to the radar beam's energy intersecting Mount Washington and other high terrain along the 296 to 299 degree radial at approximately 60 miles from the radar site. A correction to this error is being developed and may be implemented.

7. **Radar data gaps:** During the rainfall event the KBOX radar stopped operating for approximately 8 hours. Because of this radar reflectivity values derived from KOKX were used to supplement the southern portion the KBOX domain area and KGYX was used to supplement the northern portion of the KBOX domain area. Due to the long distance of some of the grid cells from the KOKX radar range effect errors were likely great causing low $R_{estimation}$ values.

Improvements in Storm Analyses Using NEXRAD

Incorporating NEXRAD data into storm rainfall analyses improves both the spatial and temporal resolution of the rainfall analyses. The approach taken by AWA relies on hourly rain gauge observations to provide quantification of the rainfall amounts while relying on the NEXRAD data to provide the spatial distribution of rainfall between rain gauge sites. By determining the most appropriate coefficients for the Z-R equation on an hourly basis, the approach anchors the rainfall amounts to historically accepted rain gauge data while using the NEXRAD data to distribute rainfall between rain gauge sites for each hour of the storm. By re-computing the coefficients during each hour of the storm, hourly changes in the storm cloud microphysics are addressed.

The result of incorporating NEXRAD data into the Storm Precipitation Analysis System, SPAS, provides a significant improvement in the spatial aspects of the rainfall analyses. Next, it provides spatial rainfall information over open water regions (reservoirs and oceans) where historically rainfall information has been lacking. Additionally, although only hourly rainfall analyses have been produced to date, rainfall amounts for temporal periods as short as five minutes can be provided, depending on the NEXRAD scan mode used during the storm.

These dramatic improvements in both the temporal and spatial resolution of historic storm analyses provide rainfall information with increased precision and accuracy for use in run-off model calibrations. Spatially, rainfall amounts can be provided over area sizes as small as approximately a square kilometer and temporally, as often as every five minutes. For model calibrations that require basin average rainfall amounts, the rainfall patterns can be clipped to the basin boundaries using GIS software and the average rainfall within the basin can be provided for whatever time periods are needed, e.g. 15 minute, 1 hour, 3 hour, etc. These refinements in rainfall analyses will reduce errors in the rainfall input parameters that have historically be issues in run-off model calibration.

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