Detailed Storm Rainfall Analysis for Hurricane Ivan Flooding in Georgia Using the Storm Precipitation Analysis System (SPAS) and NEXRAD Weather Radar

Ed Tomlinson, PhD and Bill Kappel
Applied Weather Associates LLC
Ron Corso
Mead and Hunt Inc
Tye W. Parzybok and Doug M. Hultstrand
Metstat Inc.

Improved Inflow Forecasts for Hydropower
Knoxville, TN
November 16, 2007
Storm Precipitation Analysis System (SPAS)

– Originally Developed to Support Probable Maximum Precipitation (PMP) Studies
  • PMP Studies Require Storm Depth-Area-Duration (DAD) Analyses
  • National Weather Service has not systematically analyzed DADs since the Mid-1950s
  • Large Flood Producing Storms have Occurred since the 1950s
Storm Precipitation Analysis System (SPAS)

Large Flood Producing Storms
- Hurricane Dianne 1955
- Hurricane Camille 1969
- Hurricane Agnes 1972
- Illinois Thunderstorms 1996
- Maine Nor’easter 1996
- Hurricane Floyd 1999
- Nebraska Thunderstorm 2002
- New Jersey Thunderstorm 2004
- Hurricane Ivan 2004
- New York Nor’easter 2007

With Storm Depth-Area-Duration Analyses
  - Can Compare Storm Size
  - Can Compare Storm Intensity
Storm Precipitation Analysis System (SPAS) with NEXRAD

- Original SPAS used only Rain Gauge Rainfall Information
- NEXRAD Weather Radar Provides Detailed Rainfall Information both in Time and Space
- NEXRAD Data from the National Weather Service does not Use Rain Gauge Observation
Storm Precipitation Analysis System (SPAS) with NEXRAD

- SPAS Calibrates NEXRAD Data Each Hour to Rain Gauge Measurements

- Result: Detailed Rainfall Analyses

  - Spatial Resolution: Approximately 1 km x 1 km
  - Temporal Resolution: One Hour down to Six Minutes
  - Areal Domain: Clip in GIS to Basin Boundaries
Hurricane Ivan Flooding In Georgia
Hurricane Ivan Flooding
– Typical Southern Appalachian Drainage Basin
Hurricane Ivan Flooding
– Typical Southern Appalachian Drainage Basin
Hurricane Ivan Flooding
– Typical Southern Appalachian Drainage Basin
Hurricane Ivan Flooding
- Series of 3 Dams along the River
Hurricane Ivan Flooding
– Series of 3 Dams along the River
Hurricane Ivan Flooding
– Series of 3 Dams along the River
Hurricane Ivan Flooding

- Historic hurricane tracks that affected northern Georgia
Hurricane Ivan Flooding

– Hurricane Ivan Track Across the Southeastern US
## Hurricane Ivan Flooding

### Rainfall Variability Across the Drainage Basin

<table>
<thead>
<tr>
<th>Mass Curve Precipitation Location</th>
<th>Max. 24-hr Ppt (in)</th>
<th>100-yr 24-hr Ppt (in)</th>
<th>Max. 24-hr &gt; 100-yr 24-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Dam</td>
<td>8.47</td>
<td>10.80</td>
<td>No</td>
</tr>
<tr>
<td>Middle Dam</td>
<td>8.29</td>
<td>10.33</td>
<td>No</td>
</tr>
<tr>
<td>Lower Dam</td>
<td>11.35</td>
<td>10.35</td>
<td>Yes</td>
</tr>
<tr>
<td>Maximum Point Rainfall</td>
<td>14.11</td>
<td>11.00+</td>
<td>Yes</td>
</tr>
<tr>
<td>Rainfall above the Upper dam</td>
<td>8.80</td>
<td>11.00+</td>
<td>No</td>
</tr>
<tr>
<td>Rainfall below the Lower Dam</td>
<td>11.45</td>
<td>10.52</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*** 100-yr 24-hr precipitation interpolated from TP-40
Hurricane Ivan Flooding

Total Rainfall Pattern

Total Storm Rainfall
SPAS Storm #1027
Sept. 16-17, 2004 -- Hurricane Ivan

Legend
- Rain gauge:
  - < 6.00
  - 6.01 - 7.00
  - 7.01 - 8.00
  - 8.01 - 9.00
  - 9.01 - 10.00
  - 10.01 - 11.00
  - 11.01 - 12.00
  - 12.01 - 13.00
  - 13.01 - 14.00
  - > 15.01
Hurricane Ivan Flooding

Rainfall at Various Locations Within the Watershed

Hourly Rainfall - September 15 - 17, 2004

- Maximum Point Rainfall
- Lower Dam
- Middle Dam
- Upper Dam
- Within basin rain gauge
Hurricane Ivan Flooding

- **Hurricane Ivan Produced Record Rainfalls**
  - Hurricane Francis created saturated conditions about 9 days prior to Hurricane Ivan.
  - Hurricane Francis set up antecedent conditions that created maximum runoff conditions.
  - At a NWS station there was 12.75 inches of rain, the highest recorded daily rainfall in 79 years of record (1927-2005).
  - The combination of the record rainfall from Hurricane Ivan and saturated conditions produced unprecedented stream flows.
Hurricane Ivan Flooding

- **Dams were not Designed nor Operated for Flood Control**
  - Unlike typical flood control dams with flood storage, the reservoirs in this case had no flood control storage.
  - Reservoirs are small as exhibited by their surface areas.
  - Full Pond reservoir areas are:
    - Upper Dam 2,775 acres
    - Middle Dam 240 acres
    - Lower Dam 834 acres
  - Any modification of flows by the dams was incidental and minimal.
  - This was recognized by FERC in the relicensing process because no flood control requirements are included in the FERC license for these dams.
Discharge Volume at Each Dam

Dam Discharge in Acre-Feet From 9/17/2004 0:00 To 9/18/04 12:00

- Upper Dam  13,525 acre-feet
- Middle Dam  17,185 acre-feet
- Lower Dam   23,760 acre-feet

The point of the above volume data is that even though the areas of the intervening DA are small, the volume of discharge increased significantly. This was due to the increasing rainfall experienced as showed by the AWA study as you go downstream.
Hurricane Ivan Flooding
– Unregulated flows vs. regulated flows

Unregulated Flows Using DA Ratios

- Peak Flows (cfs)
- Drainage area (sq. mi.)

Unregulated Flows
- Gage
- Upper Dam
- Middle Dam
- Lower Dam

Regulated Flows
Storm Precipitation Analysis System (SPAS)

- Storm analyses evaluate the spatial and temporal variations of rainfall associated with a storm
  - Isohyetal patterns
    - Hourly
    - X-hourly (i.e. 6-hour, 24-hour, etc)
    - Total Storm
  - Mass curves (time distribution)
    - At rain gauge locations
    - At any location without a rain gauge
  - Depth-Area-Duration (DAD) table
    - Maximum rainfall over standard size areas (e.g. 100 sq mi)
    - Maximum rainfall over standard time periods (e.g. 24 hours)
- Migrating to real-time
Depth-Area-Duration

Storm-centered DADs

<table>
<thead>
<tr>
<th>Area (sq. mi.)</th>
<th>Duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>6.5</td>
</tr>
<tr>
<td>10</td>
<td>8.1</td>
</tr>
<tr>
<td>100</td>
<td>5.7</td>
</tr>
<tr>
<td>200</td>
<td>5.6</td>
</tr>
<tr>
<td>500</td>
<td>5.3</td>
</tr>
<tr>
<td>1000</td>
<td>5.1</td>
</tr>
<tr>
<td>5000</td>
<td>4.4</td>
</tr>
<tr>
<td>10000</td>
<td>3.9</td>
</tr>
<tr>
<td>20000</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Depth-Area-Duration (DAD) tables do provide

Maximum rainfall
  Over standard area sizes
  For standard durations

DAD tables do not provide

Detailed temporal variations of rainfall during the storm

Detailed spatial distributions of rainfall during the storm
Use of NEXRAD Weather Radar Data in SPAS Rainfall Analyses

- Rain gauge measurements provide the most reliable data for rainfall amounts

- NEXRAD provides
  - High resolution temporal distributions of rainfall
  - High resolution spatial distributions of rainfall

- Approach
  - Use the measured rainfall amounts from rain gauges
  - Distribute the rainfall spatially using NEXRAD
NEXRAD

- NEXt generation weather RADar
- WSR 88D
  - Weather Service Radar
  - Technology Benchmark: 1988
  - D: Doppler
  - Replaced WSR 57
- Available Since the Early 1990’s
  - Resolution
    - Temporal: Volume Scan Every 5-6 Minutes
    - Spatial: Approximately 1 km x 1 km
Assumptions

– Rain gauge observations represent true measurements of rainfall

– The NEXRAD signals from a one square kilometer area correlate with rain gauge observations for gauges within the area
Use of NEXRAD Weather Radar Data in SPAS Rainfall Analyses

– NEXRAD data are correlated with hourly rain gauge data
  • For each hour, coefficients are selected based on the least square fit of the the Z-R equation to the available hourly rainfall observations
  • Rainfall amounts are computed for the domain covered by the NEXRAD

– Result
  • Rainfall amounts are analyzed
    – For each hour of the storm
    – At a spatial resolution of approximately 1 square kilometer
Base Reflectivity (Z)

- Base reflectivity
  - “Z”
- QC of Z grids
  - Ground clutter
  - Beam blockage
NEXRAD Weather Radar Data

- Weather radar used by meteorologists since the 1960’s to estimate rainfall depth
- Relationship between radar reflectivity and rainfall rate
  - $Z = A R^b$
    - $Z$ is the radar reflectivity (units are dBZ)
    - $R$ is the rainfall rate
    - $A$ is the “multiplicative coefficient”
    - $b$ is the “power coefficient”
  - Both $A$ and $b$ are related to the raindrop size and raindrop number distributions within a cloud
- The National Weather Service (NWS) uses this algorithm to estimate rainfall
Determine Hourly Reflectivity-Rainfall (ZR) Relationship

- **Basic Z/R equation**
  - \( Z = a R^b \)

- **NWS Z/R equation**
  - \( Z = 300R^{1.4} \) (most common)

- **SPAS-NEXRAD Z/R determination methodology**
  - Iterate to optimize \( a \) and \( b \) coefficients based on available hourly rainfall data
SPAS-NEXRAD Rainfall Grid Process

Apply hourly Z\R to QC’ed hourly Z grid ("first guess")

Compute and interpolate residuals at stations

Add “first guess” to residuals to create final grid
Basin Rainfall

- Basin average rainfall can be summarized
- Or basin average GIS files can be exported
SPAS-NEXRAD Hurricane Ivan 2004

Total Storm Rainfall
SPAS Storm #1027
Sept. 16-17, 2004 -- Hurricane Ivan

Legend
- Rain gauge
  - < 6.00
  - 6.01 - 7.00
  - 7.01 - 8.00
  - 8.01 - 9.00
  - 9.01 - 10.00
  - 10.01 - 11.00
  - 11.01 - 12.00
  - 12.01 - 13.00
  - 13.01 - 14.00
  - > 15.01

Within basin rain gauge
SPAS-NEXRAD provides:

- Proven history using accepted methodologies
- Rainfall amounts based on rain gauge observations
- Spatial resolution based on NEXRAD
  - approximately one square kilometer (1/3 nautical mile)
- Temporal resolution based on NEXRAD
  - Routinely at one hour intervals
  - As frequent as 6 minutes
Summary

SPAS-NEXRAD provides:

- **Output format**
  - Consistent with runoff/inflow modeling requirements
  - Examples
    - Average rainfall within a basin/sub-basins
    - GIS spatially distributed rainfall over a basin/sub-basins
    - Total storm rainfall over a basin/sub-basins
    - Looped storm isohyetal patterns
    - changes of rainfall patterns with time
    - changes of rainfall patterns with accumulated rainfall
Questions