Advanced Spatial and Temporal Rainfall Analyses for Use in Watershed Models

Douglas Hultstrand, Tye Parzybok, Ed Tomlinson, Bill Kappel

Abstract

Accurate estimation of the spatial and temporal distribution of rainfall is a crucial input parameter into a surface water model for hydrologic model calibration and validation. Typically, the number of rain gauges used to monitor rainfall is generally inadequate to resolve the spatial and temporal distributions of rainfall over the watershed. Techniques have been developed to calibrate NEXRAD radar data with rain gauge data to improve the accuracy of radar rainfall estimates, and produce high spatial and temporal resolution rainfall information for use in runoff model calibration and validation (Parzybok et al. 2008).

The Storm Precipitation Analysis System (SPAS) precipitation-radar algorithms were used along with National Weather Service default NEXRAD coefficients and inverse-distance weighting (IDW) for estimating the spatial and temporal rainfall distribution over Alsea watershed in northwestern Oregon. The three precipitation estimates were used as input into a hydrologic model to quantify the accuracy of precipitation inputs as compared to the hydrologic model output. Depth-area-duration (DAD) analysis was performed to determine the maximum amounts of precipitation within various durations over areas of various sizes.

Keywords: gauge adjusted radar, hydrology, depth-area-duration (DAD), spatial precipitation

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Introduction

Radar has been in use since the 1960s to estimate precipitation depth. In general, most current radar-derived precipitation methods rely on a relationship between radar reflectivity and precipitation rate:

$$Z = aR^b \tag{1}$$

where Z is the radar reflectivity (dBZ), R is the precipitation 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 the drop number distribution (DND) within a cloud (Martner et al. 2005).

The National Weather Service (NWS) uses this relationship to estimate precipitation through the use of their network of WSR-88D radars (NEXRAD) located across the United States. A default Z-R relationship of $Z=300R^{1.4}$ is the primary algorithm used throughout the country, but it often produces inaccurate results (Hunter 2008).

Study Site

The portion of the Alsea watershed above Tidewater, OR, is located within the Siuslaw National Forest, a diverse forest encompassing 630,000 acres of varying ecosystems. Alsea watershed is 331 mi^2 in size, ranges in elevation from 56 to 4,095 ft, and has a mean basin elevation of 1,050 ft (Figure 1). Average annual precipitation is approximately 81.40", with 12.68" falling in November (PRISM Group 2008). The 24-hr 2-yr precipitation event is 4.93" and the 24-hr 100-yr precipitation event is 8.78" (Miller et al. 1973).

The storm event analyzed for this paper is a 48-hr window during 6–8 November 2006. During this window, the Alsea watershed received an average of 5.55" of rainfall in a 48-hr period, an average of 4.57" in a 24-hr period and a maximum point rainfall of 6.80" in a 24-hr period. The maximum 24-hr precipitation within the Alsea watershed for this storm event is between the 2-yr and 100-yr 24-hr precipitation event (Miller et al. 1973).

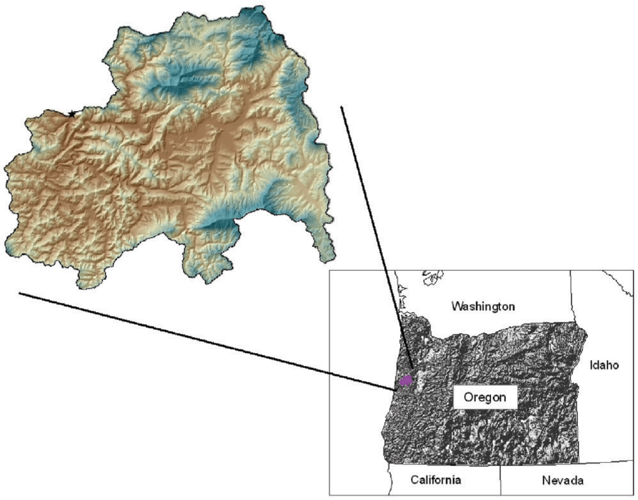

Figure 1. Study site map showing location of the Alsea watershed. Star indicates basin outlet.

Methods

The Storm Precipitation Analysis System (SPAS) is a state-of-the-science hydrometeorological tool used to characterize the temporal and spatial details of precipitation events. SPAS was used to evaluate the accuracy of precipitation input into a hydrologic model using three precipitation inputs: Optimized, Default, and Inverse-distance weighting (IDW).

Optimized

SPAS utilizes an iterative procedure for optimizing the Z-R relationship for each hour of the analysis period. The process begins by determining if sufficient observed hourly rainfall data are available to compute a reliable Z-R. If there is insufficient observed rainfall data available, then the Z-R relationship will either adopt the previous hours' Z-R relationship (if available) or apply the default $Z=300R^{1.4}$ algorithm. If sufficient rainfall data are available, however, it is related to the hourly sum of NEXRAD reflectivity. A best-fit power function through the data points is computed. The resulting multiplicative coefficient (*a*), power coefficient (*b*), and maximum predicted rainfall are subjected to several tests to determine if the Z-R relationship is acceptable. Once a mathematically optimized hourly Z-R relationship is determined, it is applied to the scan level Z-grid to compute an initial rainfall rate (mm/hr) at each grid cell within the extent of radar data.

Spatial differences in the Z-R relationship exist across the radar domain because of differences in DSD and DND. To account for these differences, SPAS computes residuals, the difference between the initial rainfall analysis (from the Z-R equation), and the actual observed rainfall (observed–initial analysis), for each gauging station. To down-weight anomalous residuals and promote a spatially smooth pattern, the residuals are smoothed using a spatial filter. A final hourly rainfall grid is created by adding the adjusted scan grids.

Default

SPAS uses a non-iterative procedure for the Z-R relationship, $Z=300R^{1.4}$ at the scan level, and applies no bias correction.

Inverse-distance weighting

SPAS uses hourly data to temporally distribute daily data into hourly data. The hourly and daily/hourly precipitation data are spatially and temporally distributed solely on the gauge data using an IDW algorithm:

$$\hat{z}(x_0) = \frac{\sum_{i=1}^{n} \frac{z(x_i)}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \qquad (2)$$

where $\hat{z}(x_0)$ is the interpolated value, *n* is the number of sample points, $z(x_i)$ is the *i*th data value, d_i denotes the separation distance between the interpolated value and data value, and *P* denotes the weighting power.

Depth-area-duration

A depth-area-duration (DAD) analysis was calculated to provide a multi-dimensional characterization of the storm. It is a powerful tool for comparing the rainfall associated with different storm events over various spatial and temporal scales not possible with point precipitation amounts only.

Hydrologic modeling

The Hydrologic Engineering Center (HEC) U.S. Army Corps of Engineers Hydrologic Modeling System (HMS) was used to model basin streamflow. HEC-HMS used the gridded rainfall estimates for input; the model was setup and run as basin average rainfall versus distributed rainfall because of time constraints.

Results

Each of the three SPAS runs generated considerably different spatial and temporal patterns associated with the hourly and total storm grids.

Optimized rainfall

The SPAS Optimized rainfall created a pattern that is true to the spatial and temporal characteristics of the observed rain gauges. The maximum basin precipitation is 8.30" and has a basin average precipitation of 5.55" (Figure 2).

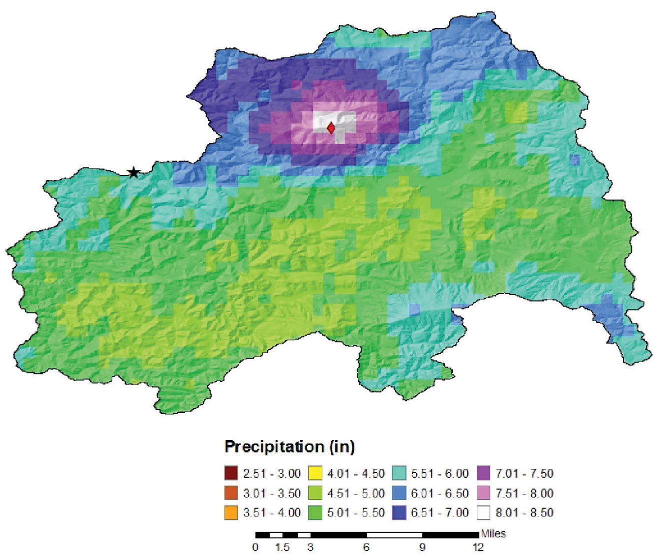

Figure 2. Optimized radar reconstruction for the 6–8 November 2006 storm event. Maximum basin precipitation is 8.30" (red diamond), average basin precipitation is 5.55", minimum basin precipitation is 4.64", and precipitation at the basin outlet is 5.81".

Default rainfall

The SPAS Default rainfall created a pattern that is not true to the spatial and temporal characteristics of the observed rain gauges. The maximum basin precipitation is 6.16" (location of Optimized grid) and has a basin average precipitation of 4.54" (Figure 3).

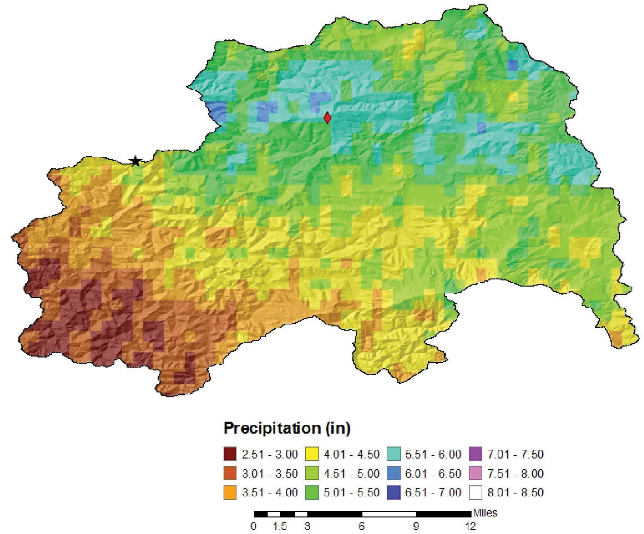

Figure 3. Default radar reconstruction for the 6–8 November 2006 storm event. Maximum basin precipitation is 6.16" (red diamond), average basin precipitation is 4.54", minimum basin precipitation is 2.51", and precipitation at the basin outlet is 4.64".

Inverse-distance weighting rainfall

The SPAS IDW rainfall created a pattern that is true to the spatial and temporal characteristics of the observed rain gauges. The spatial pattern between rain gauges is not accurate and conforms to a bulls-eye pattern The maximum basin precipitation is 7.16" (location of Optimized grid) and has a basin average precipitation of 5.42" (Figure 4).

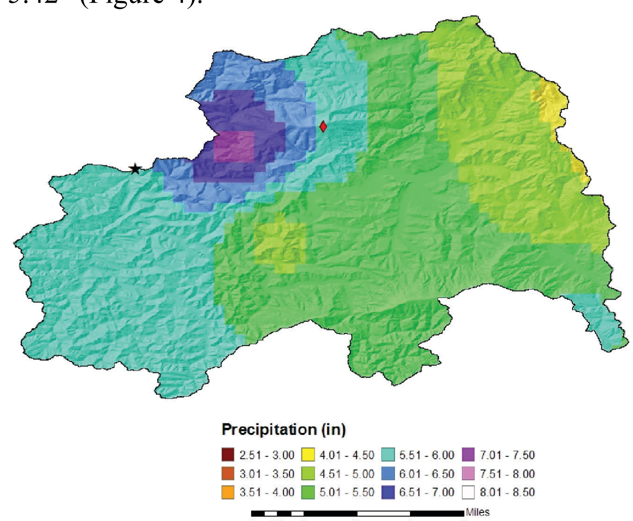

Figure 4. IDW for the 6–8 November 2006 storm event. Maximum basin precipitation is 7.16" (red diamond), average basin precipitation is 5.42", minimum basin precipitation is 4.41", and precipitation at the basin outlet is 5.83".

Mass curves

Mass curves, plots of the temporal distribution and the magnitude of precipitation, were created at three locations for each of the three SPAS runs: maximum precipitation point (from the optimized run), the basin outlet, and the basin average precipitation.

The SPAS Optimized mass curves have a large difference in the magnitude; the overall timing is in good agreement. The maximum basin precipitation was 8.30", the basin outlet was 5.80", and the average basin 5.55" (Figure 5).

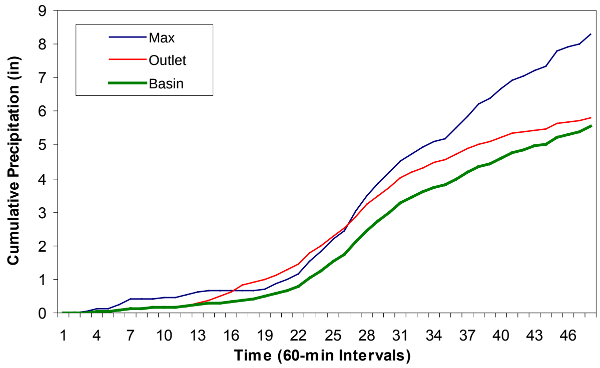

Figure 5. Optimized radar reconstruction mass curves. Maximum basin precipitation is 8.30" (blue), basin outlet precipitation is 5.80" (red), and basin average precipitation is 5.55" (green).

The SPAS Default mass curves exhibit less difference in the magnitude; the overall timing is in good agreement. The maximum basin precipitation was 5.70", the basin outlet was 4.64", and the average basin 4.54" (Figure 6).

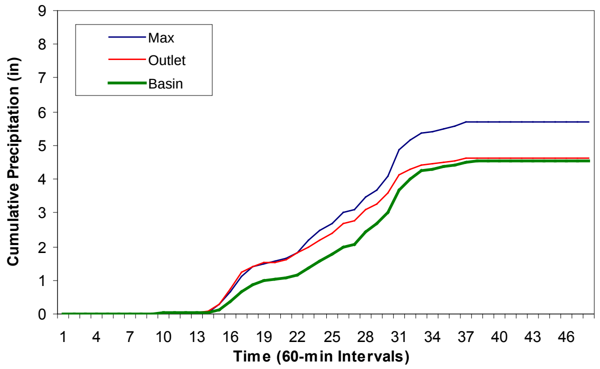

Figure 6. Default radar reconstruction mass curves. Maximum precipitation (based on optimized basin location, red diamond) is 5.70" (blue), basin outlet precipitation is 4.64" (red), and basin average precipitation is 4.54" (green).

The SPAS IDW mass curves show little difference in the magnitude and the overall timing is in good agreement. The maximum basin precipitation was 5.95", the basin outlet was 5.83", and the average basin 5.42" (Figure 7).

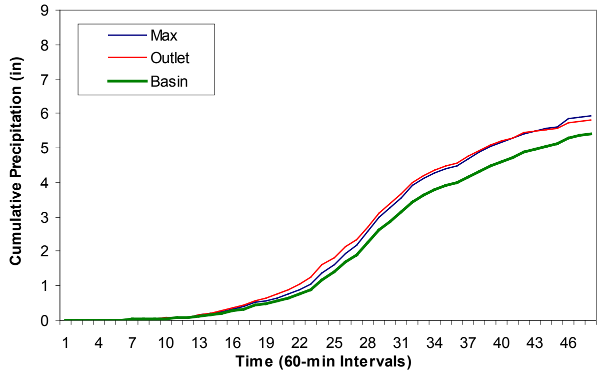

Figure 7. IDW mass curves. Maximum precipitation (based on optimized basin location, red diamond) is 5.95" (blue), basin outlet precipitation is 5.83" (red), and basin average precipitation is 5.42" (green).

Observed versus predicted precipitation

The overall fits between the total storm observed precipitation and predicted total storm precipitation at gauge locations were used to assess the overall fit of the gridded rainfall for each of the three SPAS runs.

The SPAS Optimized total storm rainfall versus the observed rainfall correlation is extremely high; the coefficient of determination is 0.923 (Figure 8; red line is the correlation and the black line is a 1-1 fit). The maximum observed precipitation (not within the watershed) is predicted almost exactly.

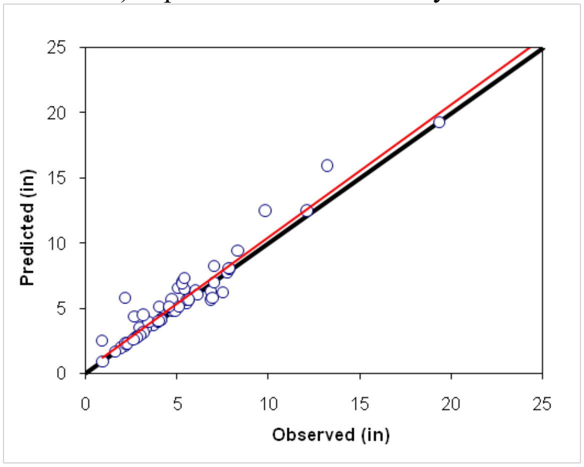

Figure 8. Optimized radar reconstruction observed precipitation versus radar reconstruction precipitation. Coefficient of determination is 0.923.

The SPAS Default total storm rainfall versus the observed rainfall correlation is extremely poor; the coefficient of determination is 0.347 (Figure 9; red line is the correlation and the black line is a 1-1 fit). The Default run almost always underestimated the observed precipitation.

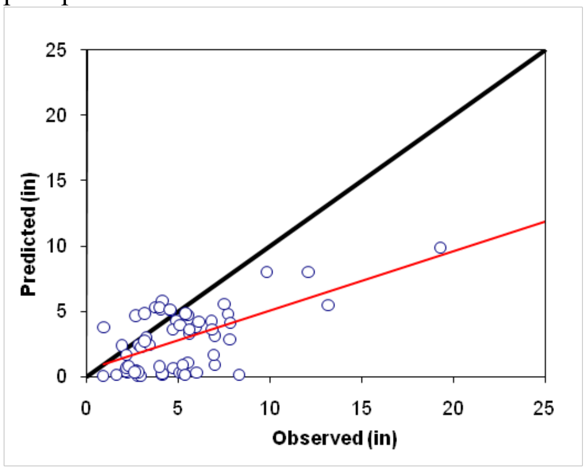

Figure 9. Default radar reconstruction observed precipitation versus radar reconstruction precipitation. Coefficient of determination is 0.347.

The SPAS IDW total storm rainfall versus the observed rainfall correlation is extremely high; the coefficient of determination is 0.971 (Figure 10; red line is the correlation and the black line is a 1-1 fit). The IDW run has a great fit due to the nature of IDW, which is an exact interpolator of the point but is not representative between gauges.

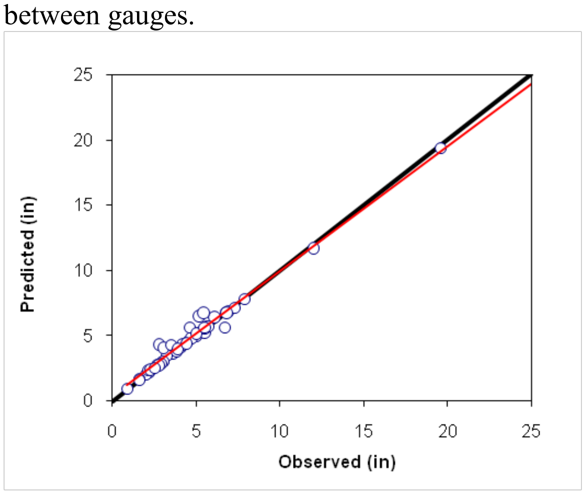

Figure 10. IDW observed precipitation versus IDW precipitation. Coefficient of determination is 0.971.

Depth-area-duration results

A DAD analysis was calculated to provide a multi-dimensional characterization of the storm within the watershed. The overall DAD suggests that the shorter duration precipitation was almost uniform across the watershed, were as the longer (>6 hrs) duration precipitation was not uniform across the watershed.

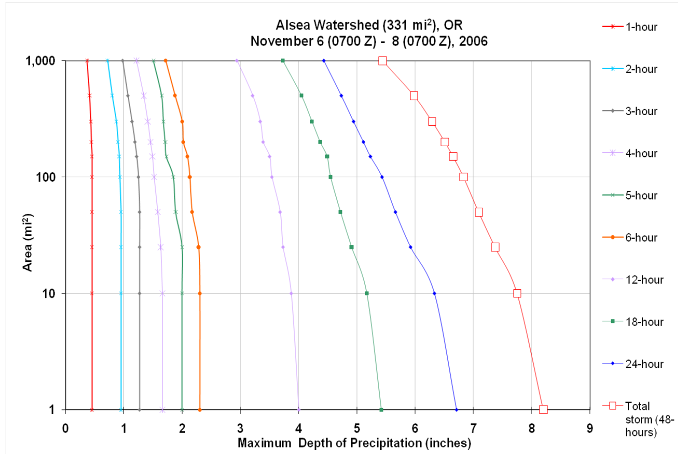

Figure 11. Optimized radar reconstruction depth-area-duration (DAD) analysis for the Alsea watershed 6–8 November 2006 storm event.

Hydrologic modeling

The observed cumulative streamflow for the Alsea watershed is 2.23”, the SPAS Optimized cumulative streamflow is 2.18”, the SPAS Default cumulative streamflow is 2.12”, and the SPAS IDW cumulative streamflow is 2.14”. The incremental precipitation (SPAS Optimized data) and the cumulative streamflow for each three SPAS runs vary in magnitude, but the overall timing has good agreement (Figure 12).

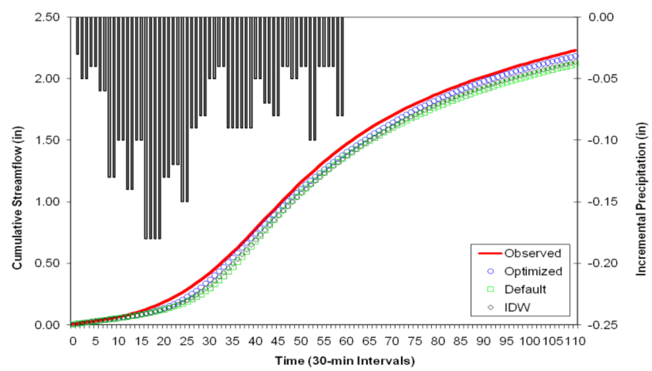

Figure 12. Cumulative streamflow modeled with the optimized (blue), default (green), and IDW (black) average basin hourly precipitation grids. Optimized precipitation is shown (grey).

The overall fits between the observed cumulative streamflow and the predicted cumulative streamflow were used to assess the relative error of the gridded rainfall for each of the three SPAS runs. All three basin average precipitation inputs generate extremely high relationships. The SPAS Optimized cumulative streamflow correlation is 0.976, the SPAS Default cumulative streamflow correlation is 0.954, and the SPAS IDW cumulative streamflow correlation is 0.973 (Figure 13).

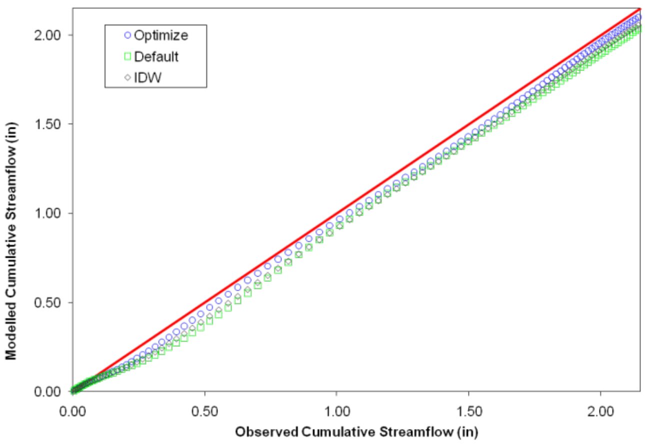

Figure 13. Observed cumulative streamflow (red) versus modeled cumulative streamflow for optimized (blue, $r^2 = 0.976$), default (green, $r^2 = 0.954$), and IDW (black, $r^2 = 0.973$) precipitation.

Conclusions

The Optimized SPAS run was able to maintain the spatial and temporal distribution of rainfall, whereas the SPAS Default and IDW were not able to maintain either the spatial or the temporal rainfall distribution.

These results suggest that the SPAS Optimized gridded precipitation, basin average, input into HEC-HMS produced better cumulative streamflow results when compared to the SPAS Default and IDW basin average precipitation inputs.

The integration of radar rainfall data into hydrologic models allows engineers and hydrologists to more accurately characterize rainfall events. The Optimized SPAS run generated the best hydrologic model results, as a result of a more accurate placement of rain at the right time.

Future work will entail the use of a spatial distributed hydrologic model, where each pixel within the basin will be used to characterize the relationship and processes between rainfall and streamflow. This model will characterize intrabasin variations in rainfall more accurately than one using basin-average rainfall estimates.

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