Using a hydrologic model to analyze Tropical Storm Helene streamflow scenarios under alternative antecedent conditions

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Introduction

Hurricane Helene caused record-setting flooding across western North Carolina and Southern Appalachia. While Cullowhee was not hit the hardest, it still received about 10 inches of rain in 48 hours. The area had not seen a storm like this since Hurricanes Ivan and Frances in 2004. Before Helene, Cullowhee was in a drought, with local groundwater level at a 15-year low.

Study Goal:

How would have a headwater stream response to Helene changed with different antecedent conditions.

The following metrics were used to assess how antecedent conditions change hydrologic response.

- Peak discharge
- Lag time(s)
- Peak Stage
- Runoff efficiency (ROE)

Setting

Location: Jackson County, NC, Western Carolina University Campus.

Watersheds: Gribble Gap (On WCU campus).

- Semi-dense forest.
- impervious cover; ~1.5%.

Local Climate:

- Climate: Humid subtropical.
- Temperature: Mild winters and summers.
- Avg. annual precipitation: 54 inches.

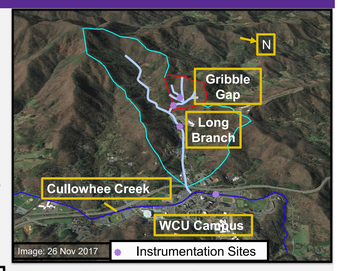


Figure 1: Map of Gribble Gap basin which is 0.06 mi²

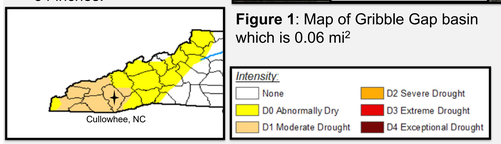


Figure 2: Western NC drought map, per U.S Drought Monitor .

Methods

Hydrologic Engineering Center - Hydrologic Modeling Software (HEC-HMS)

- Simulates watershed, channel, and water control structure processes.
- Predicts flow, stage, and timing.

Calibration

- For the observed precipitation amount a baseline scenario was calibrated to precisely predict outflow.

Precipitation Scenarios (arrows)

- Historical 100-year precipitation record for Cullowhee, NC analyzed.
- Box plot (**Figure 3**) shows the mean, median, 25th, and 75th percentiles.

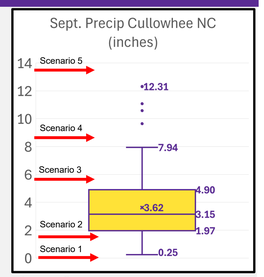


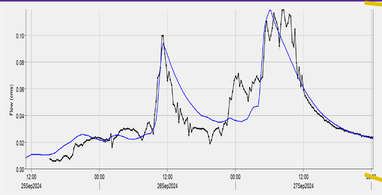
Figure 3: 12.31 inches fell in 2004 due to two consecutive hurricanes. September 2024 was the second highest on record, at 11.8 inches (9.2 inches of which from Hurricane Helene).

Calibrated Helene Baseline Scenario

Table 1: Goodness of fit statistics for Helene baseline model calibrated to observed

Goodness of Fit	
Nash-Sutclife	0.913
Percent-Bias	0.51%
RSME-St. Dev.	0.3
Modified Kling-Gupta	0.949

Goodness of fit statistics show that the calibrated model is a strong predictor of observed flow.



A model was created and calibrated to the actual flow observed during Helene.

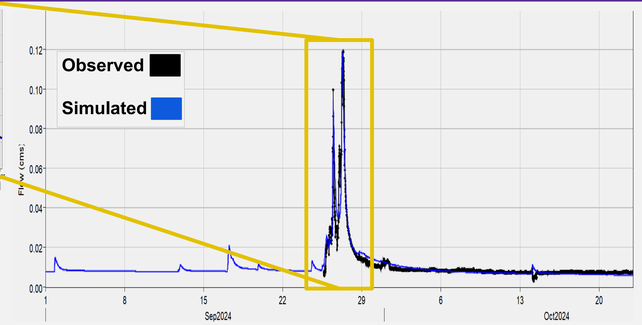


Figure 4: Simulated flow and observed flow. This is the baseline scenario model.

Results

Scenario Modeling

Five modeled antecedent scenarios were developed with varying precipitation totals, alongside the Helene baseline scenario. In each antecedent scenario, the added rainfall was distributed over a duration typical of September storm events in Cullowhee, NC.

Baseline scenario: 11.1 inches (**9.2** inches Helene + 2.6 inches rest of month). This scenario was calibrated to observed conditions

Antecedent Scenarios (**Figure 3, red arrows**)

1. **Severe Drought**: **9.2** inches (**9.2** + 0.0 inches)
2. **Drought**: 10.2 inches (**9.2** + 1.0 inches)
3. **Moderate Rainfall**: 14.8 inches (**9.2** + 5.6 inches)
4. **High Pre Rainfall**: 17.8 inches (**9.2** + 8.6 inches)
5. **Super Storm September**: 23.0 inches (**9.2** + 13.9 inches; record pre-Helene rainfall scenario)

Scenario Output

Model	Pre-Helene Precipitation (in)**	Peak Discharge (CFS)	Peak Stage (ft)	Peak Relative to Baseline (hour : min)	ROE (9/25 to 9/28)
Observed	2.62	4.20	1.20	+2:30	10.2%
Baseline scenario	2.62	4.20	1.20	0:00	10.4%
1.) Severe Drought	0.00	4.10	1.18	0:00	9.1%
2.) Drought	1.03	4.13	1.18	0:00	9.2%
3.) Moderate Rainfall	5.63	6.43	1.73	-18:45	12.9%
4.) High Pre-Rainfall	8.63	6.43	1.73	-18:45	12.9%
5.) Super Storm September	13.94	10.60	2.71	-18:45	13.3%

Table 2: Hydrograph metrics of the different scenarios.
** - This amount of precipitation is in addition to the amount of precipitation from Helene (9.13 inches)

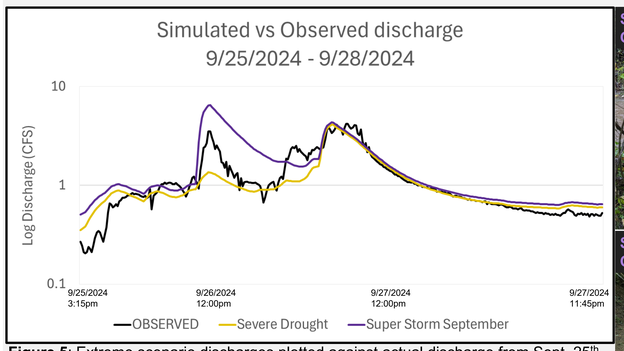


Figure 5: Extreme scenario discharges plotted against actual discharge from Sept. 25th to Sept. 28th, 2024.

Figure 6: Gribble Gap Creek in September 2024

Figure 7: Gribble Gap Creek in June 2025

Runoff Efficiency (ROE) is the ratio of basin outflow depth to total precipitation depth.

$$ROE = \frac{Outflow\ (in)}{Precipitation\ (in)} \times 100$$

ROE represents the fraction of rainfall that exits the basin as outflow; lower ROE indicates greater water storage within the basin (ex. groundwater).

Figure 8 & 9: Cullowhee Creek as seen in August 2025 (L) vs. September 2024 (R)

Conclusions

Modeling five different scenarios within Cullowhee Creek's nested watershed of Gribble Gap this study has found.

- As September gets more precipitation peak discharge increases (up to *+60%*), peak stage increases (up to *+44%*), and lag time to peak discharge decreases.
- Dry antecedent conditions lead to low ROE → more storage (91%)
- Wet antecedent conditions lead to high ROE → less storage (87%)
- Drought conditions can mitigate hydrologic response to extreme precipitation events.
- Metrics such as stage show that a wetter antecedent condition would have resulted in more inundation.
- These findings likely represent high sensitivity of other headwater basins to antecedent conditions to extreme storms.

Future Work

The Western Carolina Hydrologic Research Station hopes to continue modeling to create a continuous hydrologic model of the Cullowhee Creek watershed and its nested basins as well as other scenarios.
This includes:

- Perform similar studies for higher order streams.
- Evaluate simulated flood inundation and compare to current inundation maps.
- Continue to improve rating curves for other streams within the basin.

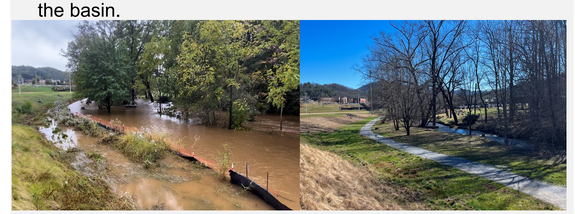


Figure 10 & 11: Cullowhee Creek on WCU's campus. September 2024 (L) vs. February 2025 (R)

Acknowledgments

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