Flood Impact Analysis Methodology

NOTE: This document was primarily generated by Google Gemini based upon analysis of the corresponding Python code and user feedback on its early drafts.

This document explains the methodology used to analyze the impact of flooding on road networks. The approach is designed to support disaster planning by identifying critical road segments that could become isolated or disrupted during flood events. The following sections provide a high-level summary followed by an intermediate-level walkthrough of the algorithm.

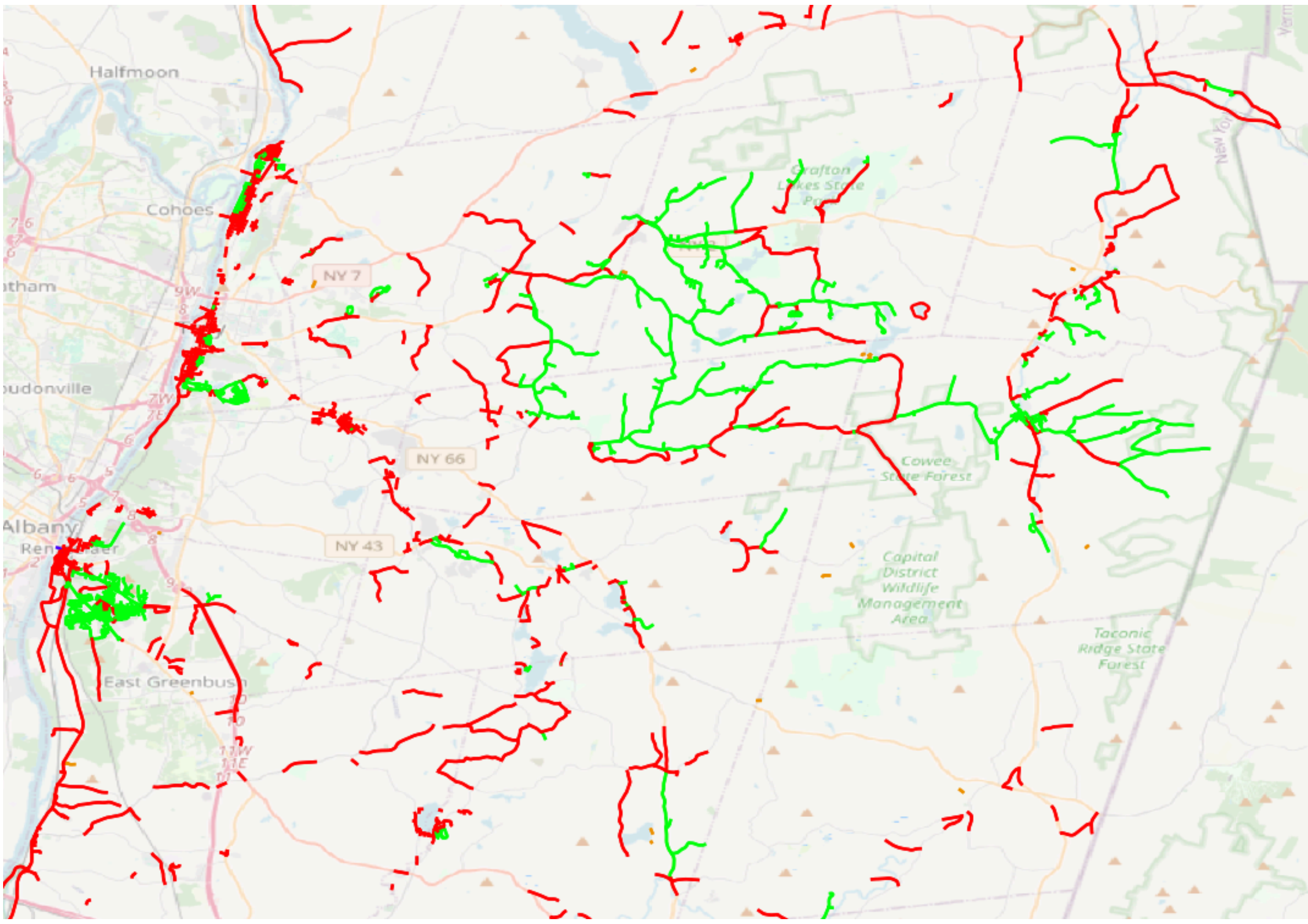
High-Level Summary

This methodology assesses the impact of flooding on road networks to inform disaster planning. By identifying roads vulnerable to flooding and evaluating network connectivity, emergency planners can anticipate isolation risks and prioritize mitigation efforts. The analysis integrates flood risk data with road network topology to determine which roads become impassable under various flood scenarios.

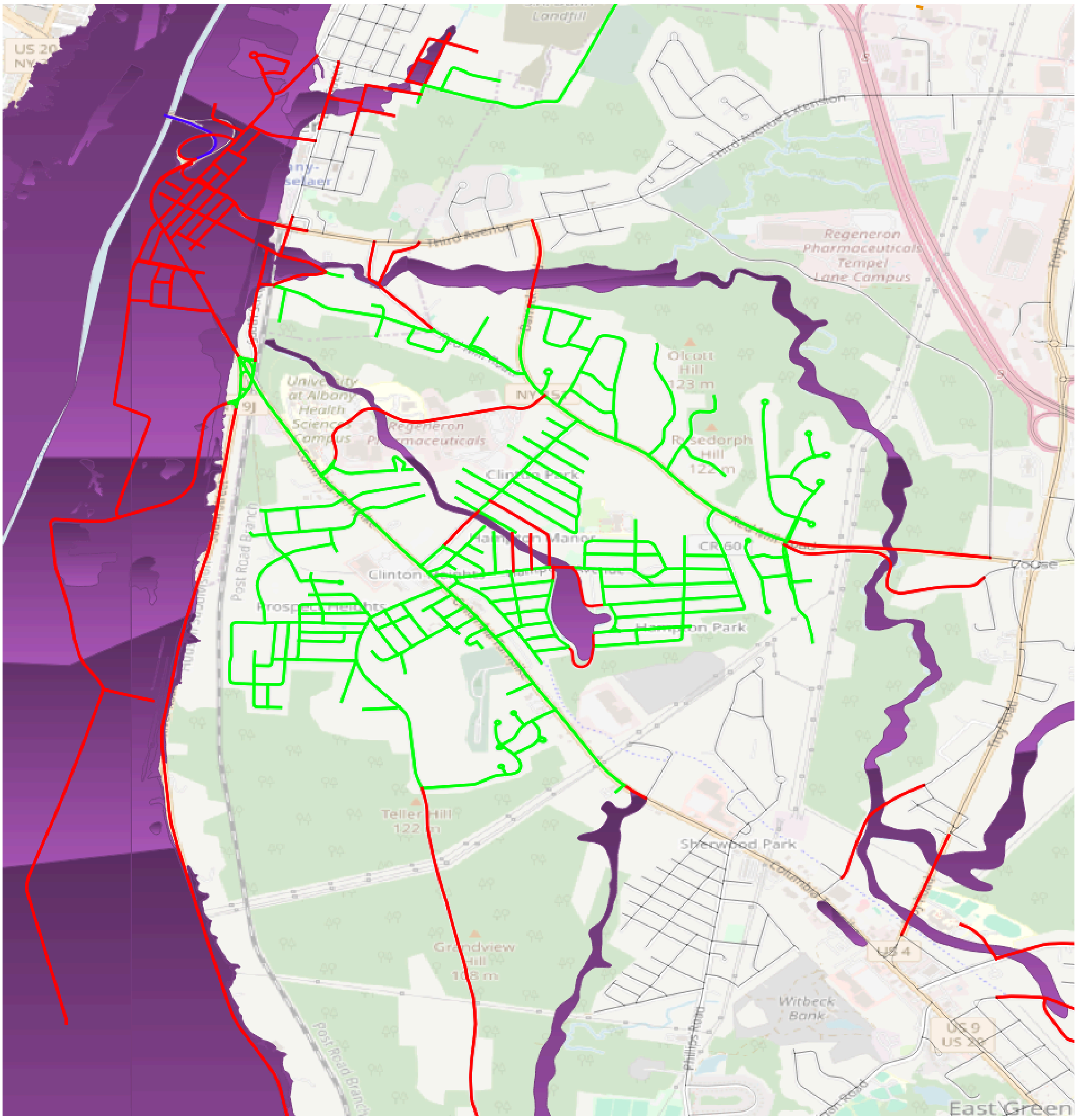
Example

Symbology

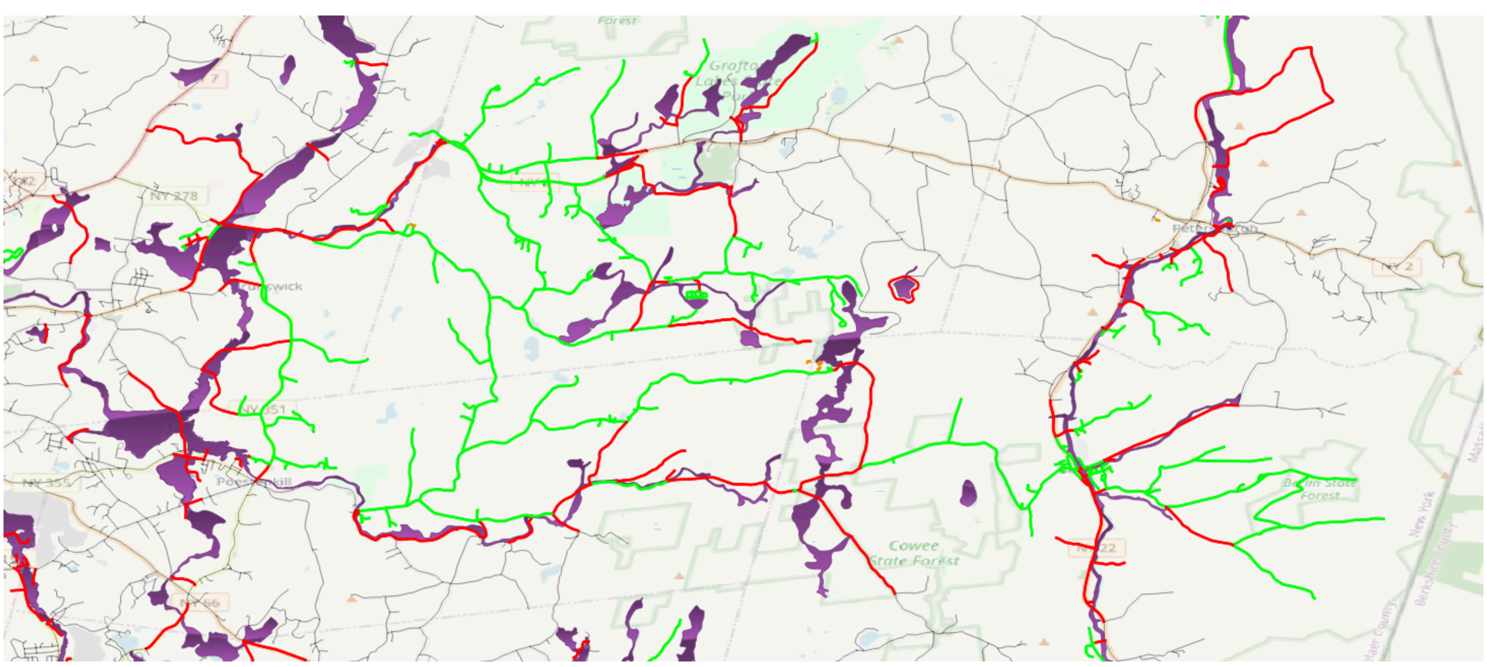
- The red are roads that are flooded.
- The green are roads that are not flooded, but are cut off from the road network due to flooding elsewhere.
- The thin black lines are roads that are unaffected by the flooding.
- The purple areas are flood zones.



High level view of the impact of 500 year flooding on Rensselaer County, New York



The impact of 500 year flooding on the Clinton Heights neighborhood in Rensselaer County, New York
Notice how a large portion of the community becomes isolated because flooding along its perimeter.



The impact of 500 year flooding on a large rural region in Rensselaer County, New York
Notice how a small number of flooded roads can isolate such a large area.

Methodology Overview

Step 1: Data Preparation

- Gather road network data and floodplain maps.
- Preprocess data to ensure accurate spatial alignment.

Step 2: Bridge Span Separation

- Before identifying spatial intersections between roads and floodplains, bridge spans are separated from non-bridge spans.
- Only non-bridge spans that spatially intersect floodplains are considered flooded.
- If a bridge completely spans a floodplain, it is considered traversable under flood conditions.

Step 3: Identifying Flooded Road Segments

- Overlay the road network with floodplain data.
- Identify non-bridge road segments that intersect flood zones.
- Classify affected roads based on flood risk severity.

Step 4: Evaluating Network Connectivity

- Construct a graph representation of the road network.
- Remove non-functional road segments (flooded or disconnected) from the graph.
- Identify disconnected regions to determine areas at risk of isolation.

Step 5: Risk Classification and Reporting

- Categorize road segments by flood recurrence intervals (e.g., 100-year, 500-year floods).
- Generate maps and reports highlighting vulnerable areas.
- Provide recommendations for improving network resilience.

This methodology provides critical insights for emergency planners, helping them anticipate and mitigate the impacts of flooding on transportation networks. By identifying potential isolation risks, decision-makers can enhance emergency response strategies and infrastructure resilience.

Intermediate-Level Walkthrough of the Algorithm

The methodology is implemented in several steps that together form a complete process to assess and label road segments based on their flood risk. Here’s how it works:

1. Data Initialization and Setup

- **Data Transfer Object (DTO):**
  - The analysis uses a `FloodImpactAnalysisDTO` to encapsulate all relevant data, including the road network graph, road segment GeoDataFrames, and floodplain data. This DTO helps organize data and ensures consistency throughout the analysis.
- **Graph Representation:**
  - The road network is modeled as a graph (`networkx.MultiDiGraph`) where road segments are "edges" connecting "nodes" (intersections or endpoints).
- **Bridge/Non-Bridge Separation:**

- Road segments are classified into bridge spans and non-bridge spans, stored in separate GeoDataFrames.

2. Spatial Analysis: Road Segments vs. Floodplains

- **Spatial Join:**
  - A spatial join operation identifies intersections between non-bridge road segments and floodplain polygons. This is optimized using spatial indexing for efficiency.
- **Flood Risk Assignment:**
  - Each road segment intersecting a floodplain is assigned a flood risk level based on the properties of the floodplain it intersects.

3. Network Impact Assessment

- **Connected Components Analysis:**
  - The road network graph is analyzed to identify connected components. This step is crucial for understanding network fragmentation.
- **Non-Functional Edge Identification:**
  - Road segments are marked as non-functional for the following reasons:
    - **FLOODED:** Directly inundated by floodwaters.
    - **BRIDGE_FUNCTIONALLY_DISCONNECTED:** Bridge segments that become disconnected because their access roads are flooded.
- **Isolation Analysis:**
  - The impact of removing non-functional segments is assessed by identifying road segments that become isolated from the main network.
- **Risk Level Propagation:**
  - Isolated road segments inherit the flood risk level of the segments that caused their isolation.

4. Output Classification

- **Flood Frequency Classification:**
  - Non-functional road segments are classified based on flood frequency:
    - **100 YEAR:** Segments in high-risk flood zones (e.g., VE, AE).
    - **500 YEAR:** Segments in lower-risk flood zones (e.g., X).
- **Data Aggregation:**
  - All impact information is compiled into a GeoDataFrame, associating each road segment with its reason for being affected, risk level, and flood frequency.

5. Output and Integration

- **Comprehensive Output:**
  - The final output is a GeoDataFrame that includes all original road segment data, plus added columns detailing flood impact:
    - `nonfunctional_reason`
    - `nonfunctional_risk_level`
    - `nonfunctional_frequency`
    - `isolated_edge_risk_level`
    - `isolated_edge_frequency`
- **Reporting and Visualization:**

- This data can be used to generate reports, maps, and other visualizations to aid in disaster planning and decision-making.

Conclusion

This enhanced floodplain network analysis methodology provides a more structured and detailed approach to assessing flood impacts. By incorporating a DTO, modular functions, and explicit data typing, the analysis is more robust, maintainable, and easier to understand. The detailed output classification ensures that planners have the necessary information to make informed decisions and improve community resilience against flooding events.

Data Dictionary Explanation

This section provides an overview of columns in the output of the analysis of lost road edges. These columns capture and explain why certain edges have been removed from the network due to flood-related impacts.

Columns

1. `nonfunctional_reason`

- **Description:**
  - Indicates the reason why a particular road edge was removed (lost) during the analysis. The reasons include:
    - **NOT_IMPACTED:** The road edge was not impacted by flooding.
    - **FLOODED:** The road edge is inundated by floodwaters.
    - **BRIDGE_FUNCTIONALLY_DISCONNECTED:** The road edge is part of a bridge that has lost its connection to the main network.
- **Data Type:** String
- **Possible Values:** `NOT_IMPACTED`, `FLOODED`, `BRIDGE_FUNCTIONALLY_DISCONNECTED`

2. `nonfunctional_risk_level`

- **Description:**
  - A numeric value that represents the flood risk level assigned to the non-functional road edge. Lower numbers indicate a higher risk, according to the established FEMA-based flood risk hierarchy:
  - **1 (Highest Risk):** VE zones with riverine floodways in coastal zones.
  - **2-6:** Other VE and V zones.
  - **7-13:** AE, AO, AH, and A zones, ranked based on severity.
  - **14-18 (Lowest Risk):** X zones and open water areas.
- **Data Type:** Integer
- **Possible Values:** Risk level values from **1 (highest risk) to 18 (lowest risk)**.

3. `nonfunctional_frequency`

- **Description:**

- This field designates the flood frequency associated with the non-functional road edge based on the flood zone risk hierarchy:
    - **100 YEAR:** Roads in flood zones starting with `VE`, `V`, `AE`, `AO`, `AH`, or `A`. These are areas with a 1% annual chance of flooding.
    - **500 YEAR:** Roads in flood zones starting with `X` or `OPEN WATER`. These are areas with a 0.2% annual chance of flooding or minimal flood risk.
- **Data Type:** String
- **Possible Values:** `100 YEAR` or `500 YEAR`

4. `isolated_edge_risk_level`

- **Description:**
  - A numeric value that represents the flood risk level assigned to the road edge that became isolated. Lower numbers indicate a higher risk, according to the established FEMA-based flood risk hierarchy.
- **Data Type:** Integer
- **Possible Values:** Risk level values from **1 (highest risk) to 18 (lowest risk)**.

5. `isolated_edge_frequency`

- **Description:**
  - This field designates the flood frequency associated with the isolated road edge based on the flood zone risk hierarchy:
    - **100 YEAR:** Roads in flood zones starting with `VE`, `V`, `AE`, `AO`, `AH`, or `A`. These are areas with a 1% annual chance of flooding.
    - **500 YEAR:** Roads in flood zones starting with `X` or `OPEN WATER`. These are areas with a 0.2% annual chance of flooding or minimal flood risk.
- **Data Type:** String
- **Possible Values:** `100 YEAR` or `500 YEAR`

Summary

The addition of these columns (`nonfunctional_reason`, `nonfunctional_risk_level`, `nonfunctional_frequency`, `isolated_edge_risk_level`, and `isolated_edge_frequency`) helps to systematically classify and document the impact of flooding on the road network. By capturing both the nature and severity of the disconnection events, this data supports further analysis on flood resilience and infrastructure planning.

The accompanying CSV file (`data_dictionary.csv`) provides a tabular representation of this data dictionary for integration into reports or additional analyses.

Case Study: Hurricane Helene's Impact on Western North Carolina

In September 2024, Hurricane Helene brought unprecedented rainfall and severe flooding to western North Carolina, leading to catastrophic damage and widespread isolation of communities. The storm's remnants caused rivers to overflow, inundating towns, destroying infrastructure, and severing critical transportation links.

Asheville and Surrounding Areas

Asheville, the region's largest city, experienced record-breaking rainfall, resulting in extensive flooding that submerged neighborhoods like Biltmore Village and the River Arts District. Landslides and floodwaters forced the closure of major highways, including sections of I-26 and I-40, effectively isolating the city by damaging roads and disrupting power and communication services. This left residents without essential services and hindered emergency response efforts.

Broader Regional Impact

Beyond Asheville, numerous communities faced similar challenges. Flooded roads and collapsed bridges isolated towns such as Swannanoa and Fairview, complicating rescue and relief operations. The destruction of transportation infrastructure not only impeded immediate emergency responses but also prolonged recovery efforts, as access to these areas remained limited.

Sources

1. **"Helene aftermath: Buncombe officials give updates on Asheville, more"**
    - This article provides updates from Buncombe County officials on the aftermath of Hurricane Helene, including information on Asheville and surrounding areas.
    - https://www.wfmynews2.com/article/weather/severe-weather/hurricane-helene-buncombe-county-officials-give-updates-on-asheville-black-mountain/
2. **"Asheville residents see cars, home floating"**
    - This article describes the experiences of Asheville residents during Hurricane Helene, including reports of cars and homes being carried away by floodwaters.
    - https://www.citizen-times.com/story/news/local/2024/09/29/tropical-storm-helene-aftermath-whole-homes-cars-float-away/75433500007/
3. **"Asheville has been isolated after Helene wrecked roads and knocked out power and cell service"**
    - This article discusses how Hurricane Helene isolated Asheville by damaging roads and disrupting power and communication services.
    - https://www.usnews.com/news/best-states/north-carolina/articles/2024-09-28/asheville-has-been-largely-cut-off-after-helene-wrecked-roads-and-knocked-out-power-and-cell-service
4. **"Swannanoa community devastated by flood damage after Hurricane Helene"**
    - This article highlights the severe flood damage experienced by the Swannanoa community due to Hurricane Helene.
    - https://wlos.com/news/local/swannanoa-community-devastated-flood-damage-after-hurricane-helene-search-and-rescue-highway-70-deputies-buncombe-county
5. **"NCDOT says all roads in Western NC should be considered closed, even the big ones"**
    - This article discusses the widespread road closures in Western North Carolina due to Hurricane Helene.
    - https://www.yahoo.com/news/ncdot-says-roads-western-nc-205209848.html
6. **"Hurricane Helene Recap: Catastrophic Surge, Inland Flooding From Florida To The Appalachians"**
    - This article provides a comprehensive recap of Hurricane Helene's impact, including catastrophic surge and inland flooding from Florida to the Appalachians.
    - https://weather.com/storms/hurricane/news/2025-03-19-hurricane-helene-final-report-nhc-deaths-damage-flooding
7. **"Hurricane Helene: A look back on the storm and where recovery stands 6 months later"**

- This article reflects on Hurricane Helene six months after the storm, discussing the recovery efforts and ongoing challenges.
- https://www.foxweather.com/extreme-weather/hurricane-helene-anniversary-6-months-florida-north-carolina

8. **"Hurricane Helene Damage and Needs Assessment - NC OSBM"**
   - This document provides an assessment of the damage caused by Hurricane Helene and outlines the needs for recovery in North Carolina.
   - https://www.osbm.nc.gov/hurricane-helene-dna/open
9. **"Hurricane Helene Response and Recovery | NC DOI"**
   - This page details the response and recovery efforts in North Carolina following Hurricane Helene.
   - https://www.ncdoi.gov/hurricane-helene-response-and-recovery