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Agent-based Models in Flood Simulation - A Case Study for New Brunswick’s Flooding Events in 2018

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Agent-based Models in Flood Simulation

- A Case Study for New Brunswick's Flooding Events in 2018

by

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ABSTRACT

This thesis introduces an Agent-Based Modeling (ABM) framework for flood simulation and inversion modeling in flood-prone areas, aiming to improve our understanding of the complex dynamics of flooding and provide valuable insights for flood management. The developed model incorporates multi-source terrain datasets, and integrates water flow and meteorological conditions from remote sensing data sources. It takes into account factors such as precipitation patterns, geographical features, and Digital Elevation Model (DEM) resolution to accurately represent flood characteristics. The model's parameter settings are derived from extensive experimentation, allowing for effective control and meaningful results. By considering the impact of precipitation and the presence of rivers, the model demonstrates its ability to simulate flood inundation with a reasonable level of accuracy. Overall, this comprehensive model provides a valuable tool for flood simulation and offers insights into flood dynamics for effective flood management and mitigation strategies.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Global warming and climate change are leading to increasingly frequent and intense weather events, such as sudden and extremely heavy rainfall, which causes a heightened risk of flooding near rivers. The consequences of flooding in urban areas can be severe, resulting in high property damage, infrastructure loss, and posing a threat to personal safety. As a result, there is a growing need for efficient and accurate flooding simulation that can provide real-time updates with precipitation data to aid in disaster management efforts.

Previous research has explored various methods for flood simulation, such as hydrological models and machine learning algorithms. While these methods have their strengths, they lack a real-time flooding simulation that can capture the dynamic and complex interactions between individual agents and their environment. This gap can be addressed by utilizing Agent-based modeling (ABM), a promising approach that allows for the inclusion of a variety of agents and the ability to tune the complexity of their behaviors and interactions.

The flexibility of ABM is particularly useful in simulating the interactions between individuals and their environment during a flood event. The degree of rationality, the rules of interaction, and the behavior of the agents can be adjusted, making ABM a suitable tool for modeling the complex and dynamic nature of floods in urban areas. With ABM, it is possible to incorporate the behavior of individuals, such as their decision-making process in response to a flood event, as well as the behavior of infrastructure, such as the impact of water flow on buildings and roads.

Moreover, ABM offers the ability to simulate real-time flooding with updated precipitation data, which can help emergency responders make informed decisions about where to allocate resources and how to respond to the flood. This capability is critical in mitigating the impact of floods on urban areas.

In summary, the problem statement for this research is to explore the application of ABM in flood simulation with real-time precipitation data to enable efficient disaster management and mitigate the impact of floods on urban areas. By achieving this objective, it will be possible to develop a more comprehensive and accurate approach to flood simulation, thereby enhancing disaster management efforts and reducing the impact of flooding on urban areas.

1.2. Motivation

The motivation for using ABM in flood simulation stems from the need to understand and effectively manage the complex dynamics of flooding in flood-prone areas. Traditional flood simulation models often rely on simplified assumptions and overlook the intricate interactions between various factors that may contribute to flood inundation. ABM, on the other hand, offers several motivations for its use in flood simulation.

Firstly, ABM allows for the capture of the heterogeneity and complexity of the system, which traditional models often overlook. By modeling the behavior of individual agents and their interactions, ABM provides a more nuanced understanding of the vulnerabilities and risks associated with flooding. It takes into account not only the movement of water but also the behavior of people, buildings, and infrastructure during a flood event.

Secondly, ABM enables the exploration of different scenarios, providing insights into the potential outcomes of various flood protection measures and interventions. This allows for informed decision-making in managing flood risks and designing effective strategies. By simulating the exact process of flooding and considering the impact of different factors, such as flood protection measures or changes in land use, ABM helps in evaluating the effectiveness of these interventions and understanding their implications.

Furthermore, by considering multiple factors and their interactions, ABM will offer valuable insights for improving flood management strategies and mitigating the devastating effects of flood events. ABM can consider factors such as precipitation patterns, geographical features, and Digital Elevation Model (DEM) resolution, which are crucial in accurately simulating flood events. By incorporating these factors into the simulation, ABM will provide a more comprehensive understanding of flood dynamics. It will highlight the needs to consider the specific characteristics of the study area and tailor the model settings accordingly to achieve more accurate and realistic flood simulations.

1.3. Objectives

The research aims to investigate the effectiveness of the ABM approach in monitoring flooding hazards using real-time weather data collected from satellite images and earth sensors. The specific objectives of the research are as follows:

1. Develop a dynamic flooding simulation system: Create an ABM-based model that can simulate the dynamics of flooding events. The model will consider the interactions between individual agents, such as water flow, terrain characteristics,

and human activities, within a spatially explicit framework. This will enable a more realistic representation of flood inundation patterns.

2. Integrate multi-source terrain datasets: Incorporate various terrain datasets, including high-resolution Digital Elevation Models (DEMs), into the simulation system. By utilizing multi-source data, the model can capture the heterogeneity and complexity of the environment more accurately, leading to improved flood simulations.
3. Incorporate water flow and meteorological conditions: Integrate water flow data and meteorological conditions from multiple remote sensing data sources into the ABM-based flooding model. This will allow for the simulation of the impact of various meteorological and environmental factors on the flooding hazards. By considering factors such as precipitation patterns, the model can provide a more comprehensive understanding of flood events.
4. Adjust the model based on real-world conditions: Adjust the model parameters based on the actual conditions of the 2018 flood event in New Brunswick. By incorporating real-world data and observations, the model can be fine-tuned to accurately simulate the specific characteristics and behavior of the flood event.

By achieving these objectives, this study aims to provide a comprehensive flooding simulation model for the 2018 flood event in New Brunswick. The developed model will contribute to a better understanding of the flood dynamics and provide valuable decision-making support for protecting communities and infrastructure from the impacts of flooding.

1.4. Organization of the thesis

The thesis is organized into five chapters.

Chapter 1 introduces the research topic, including the problem statement, motivation, objectives, and organization of the thesis.

Chapter 2 provides the background and related studies, including an introduction to ABM, its applications in Earth Science, current methods of flood simulation, and spatial regression with ecological data. The study description is also presented in this chapter, followed by a summary.

Chapter 3 describes the methodology used in this research. It includes a detailed description of the study area, data collection and preparation, ABM analysis, parameter generation, and spatial data processing.

Chapter 4 presents the results and discussion of the research. It includes a comparison of models for areas with and without rivers, as well as a comparison of models with different resolutions and historical data. The chapter also discusses the final model validation using a comparable study area.

Chapter 5 concludes the thesis and provides recommendations for future studies. The conclusions drawn from the research are presented, followed by a discussion of the limitations of the study. Finally, recommendations for future research are provided to further improve the methodology and accuracy of the flood simulation models.

CHAPTER 2: RESEARCH BACKGROUND AND RELATED STUDIES

2.1 Research Background

2.1.1. GENERAL INTRODUCTION OF ABM

ABM is a computational method that simulates the interactions among adaptive agents to understand the behavior of complex systems. ABMs have been used in various disciplines, including natural resource management (Barendrecht, Viglione, & Blöschl, 2017) (Pope & Gimblett, 2015), disease spread (Barendrecht, Viglione, & Blöschl, 2017), flood risk management (Bell, Robinson, Malik, & Dewal, 2015), and sociology (Macy & Willer, 2002).

In the natural resource management domain, ABMs have been applied to investigate the feedback between climate, land use change, and hydrological cycles. For example, a prototype coupled modeling system (Bithell & Brasington, 2009) was developed to simulate land-use change in subsistence farming communities, where demographic changes influence deforestation and impact forest ecology, stream hydrology, and water availability. Similarly, in the context of cholera outbreaks in the Dadab refugee camp in Kenya (Crooks & Hailegiorgis, 2014), ABMs were used to model the spread of cholera and the interaction between humans and their environment. Results showed that the spread of cholera grew radially from contaminated water sources, and seasonal rains caused the emergence of cholera outbreaks.

Another study focuses on migration responses to climate shocks using an agent-based model (Entwisle, et al., 2016). In this study, an agent-based model is constructed to capture the dynamic linkages between demographic behaviors, agriculture and land use, which are influenced by rainfall patterns. The model is based on empirical data from Nang Rong district in northeast Thailand. They did simulations under different weather, which regimes reveal relatively small impacts on migration.

Another ABM incorporates critical indicators, including land covers, climate variability, soil quality, land-use-related policies, and population growth (Gebrehiwot, Hashemi-Beni, Kurkalova, Liang, & Jha, 2022). By studying the interrelationships among these factors, their model aims to inform the development of effective land-use policies and aid responsible agencies and policymakers in planning for improved food security. This study provides insights into how individuals or communities may transition land covers to meet their food needs (Gebrehiwot, Hashemi-Beni, Kurkalova, Liang, & Jha, 2022).

ABMs are also being used to study the coupled human-flood interactions (Bell, Robinson, Malik, & Dewal, 2015) (Yang, et al., 2023). Traditional flood risk approaches based on scenarios cannot represent these phenomena, and dynamic models are needed to explore a wider range of possible futures, including unexpected phenomena, than is possible when using scenarios (Bell, Robinson, Malik, & Dewal, 2015). A recent study focused on pluvial flood emergency evacuation at the city scale, specifically examining the 2021 pluvial flood event in Zhengzhou, China (Yang, et al., 2023). By integrating a hydraulic model to predict flood inundation with an ABM, the study analyzed the impact of flood events on human behavior and evacuation processes. The results emphasized the significance of crowd behavior in emergency evacuations and revealed a reduction in the number of evacuees due to extensive flooding. The developed ABM model proved to be effective and practical, offering valuable support for decision-making in urban flood emergency management. The findings underscored the importance of risk education and contingency plans in emergency response, highlighting the need for timely and effective evacuation measures to minimize casualties and losses.

In sociology, ABMs have been used to model social life as interactions among adaptive agents, where simple and predictable local interactions can generate global patterns, such as the diffusion of information, the emergence of norms, and the coordination of conventions. ABMs provide theoretical leverage (Macy & Willer, 2002) where the global patterns of interest are more than the aggregation of individual attributes, but at the same time, the emergent pattern cannot be understood without a bottom-up dynamical model of the microfoundations at the relational level. Recent contributions have focused on the emergence of social structure and social order out of local interaction. Dynamic social networks that are shaped by agent interaction are of theoretical interest, and ABMs are used to perform virtual experiments that test macrosociological theories by manipulating structural factors like network topology, social stratification, or spatial mobility.

Despite the advantages of ABMs, a key challenge to their utility is that the published ABM tools are rarely used beyond their original development team, and the development of models from scratch is still prevalent. However, some ABM frameworks are publicly available for use, and a different publication paradigm for the ABM community could improve the sharing of model structure and help move toward convergence on a common set of tools and assumptions.

In summary, ABMs are a powerful tool for understanding the behavior of complex systems by simulating the interactions among adaptive agents. They have been used in various disciplines, including natural resource management, disease spread, flood risk management, and sociology.

2.1.2. APPLICATION OF ABM IN EARTH SCIENCE

The application of ABM in the field of Earth Science has been relatively limited, with few available literature sources focusing on this topic. Most of the existing ABM models in Earth Science are developed and provided in NetLogo (Wilensky, 1999). These can be categorized into two main types: hydrological and fire models.

In the hydrological domain, there are several basic ABM models that have been developed. One such model is the River Meanders (Caldeira, F. and Wilensky, U., 2021), which demonstrates the meandering behavior of a river in its middle course. The model considers factors such as the path of highest-velocity flow, erosion, and deposition to simulate the evolution of the river's shape. Another model is the Erosion model (Dunham, G., Tisue, S. and Wilensky, U., 2004), which simulates soil erosion caused by water. It allows users to observe the flow of rainwater, erosion of the terrain, and the emergence of a river system as the terrain is reshaped. Additionally, the Grand Canyon model (Wilensky, 2006) focuses on simulating rainfall on a specific patch of terrain in the Grand Canyon area, exploring the interaction between rainfall, topography, and resulting canyon formation.

In the fire modeling (Wilensky, 1997) domain, there is a project that simulates the spread of fire through a forest. This model highlights the critical role of tree density in determining whether the fire will reach the right edge of the forest. It demonstrates the presence of non-linear thresholds or critical parameters in complex systems.

In conclusion, while the application of ABM in Earth Science is still relatively limited, these existing models provide valuable insights into hydrological processes, erosion, canyon formation, and fire spread. They demonstrate the potential of ABM in simulating and understanding complex Earth Science phenomena. Further research and development in this area could expand the use of ABM to address a wider range of Earth Science-related challenges and phenomena.

2.1.3 A LITERATURE REVIEW OF USING ABM IN FLOOD SIMULATION

ABM is primarily utilized in flood risk management rather than directly simulating floods from the perspective of raindrops. Zhou and Han (2020) conducted a review specifically focusing on ABM in the context of flooding. The review examined 61 representative articles and extensively discussed the advantages and limitations of ABM in flood risk management. It emphasized the increasing global interest in this research area, particularly since 2017. The review identified three main thematic areas that emerged from the literature: real-time flood emergency management, long-term flood adaptation planning, and flood hydrological modeling.

While the review highlighted the potential contribution of ABM to future flood risk management, it also acknowledged the limitations associated with the implementation of decision-making and behavior in ABM models (Zhou and Han, 2020). These limitations could affect the realism of ABM in practical field applications. As a result, the review recommended improvements in modeling frameworks, enhancements in theoretical foundations, and the refinement of testing and documentation capabilities for future ABM developments.

It is imperative to reiterate that the literature review does not primarily address the direct simulation of floods or rainfall patterns using ABM. Instead, this study draws inspiration from the broader applications of ABM within the realm of earth science, specifically in the context of rainfall models.

2.1.4. CURRENT METHODS OF FLOOD SIMULATION

Flood simulation plays an important role in understanding and mitigating the risks associated with flooding events. Several studies have demonstrated the effectiveness of simulating water level changes during flood events from a real event perspective. For example, the FLO-2D model (O'Brien, Julien, & Fullerton, 1992) utilizes a uniform grid system to simulate flood hazards, mudflows, and debris flows on alluvial fans and urban floodplains. By incorporating a quadratic rheological model based on field and laboratory data, the model accurately simulates flooding conditions ranging from clear water to hyper-concentrated sediment flows. The model's capabilities were demonstrated through the replication of the 1983 Rudd Creek mudflow, showcasing the potential of using ABM in flood simulation (O'Brien, Julien, & Fullerton, 1992).

The Godunov-type numerical scheme model (Qiuhua, 2010) demonstrates the importance of simulating real-world flood events in a two-dimensional space. Additionally, the LISFLOOD model (Knijff, Younis, & Roo, 2008) is a classic hydrological model that utilizes real data analysis. The model's setup is based on soil, land cover, and meteorological data. However, the parameterization and analysis in this model are primarily focused on European scenarios, and the model's development does not emphasize process simulation and visualization.

ABM provides unique advantages in flood simulation by representing individual raindrops as autonomous agents. By considering raindrops as agents, ABM captures the dynamic nature of flooding and enables a more realistic representation of water level changes over time.

This approach allows for the incorporation of stochasticity and randomness, reflecting the variability of rainfall patterns and their impact on flood dynamics.

Simulating water level changes using raindrops as agents provide valuable insights into the behavior and movement of water during flood events. ABM considers various factors, such as topography, surface characteristics, and drainage systems, in the interaction between raindrops and the environment. By modeling the movement and accumulation of raindrops, ABM can simulate the spatial distribution of water levels and the extent of flooding in different areas.

ABM in flood simulation also enables scenario exploration and sensitivity analysis. Researchers can manipulate the behavior of raindrop agents, such as their size, velocity, and interaction rules, to simulate various flood scenarios. This flexibility allows the evaluation of different flood management strategies and their effectiveness under varying conditions. Considering multiple scenarios provides a comprehensive understanding of flood dynamics and supports the development of informed flood mitigation and response planning strategies.

In conclusion, ABM holds significant advantages in simulating water level changes during flood events. By considering raindrops as agents, ABM captures the dynamic nature of flooding, allows for a realistic representation of water level changes, and provides insights into the behavior and movement of water. ABM facilitates scenario exploration, sensitivity analysis, and the evaluation of different flood management strategies. While traditional models have their merits, using ABM in flood simulation enhances our understanding of flood dynamics and supports informed decision-making for flood mitigation and response planning.

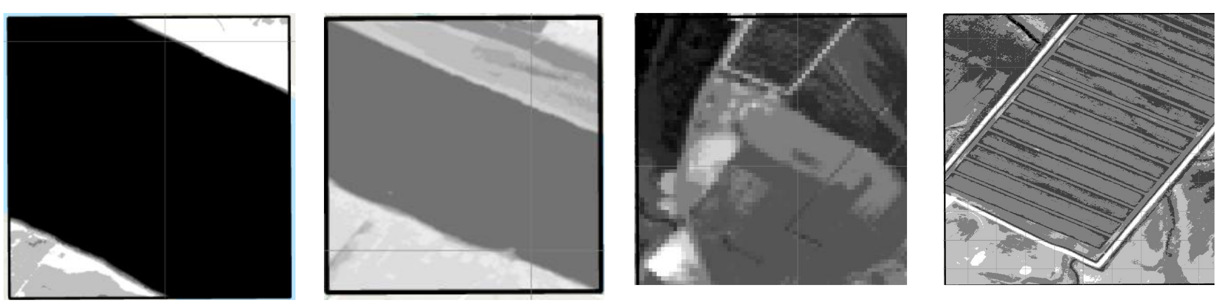
2.2. Chapter Summary

This chapter provides the background information and literature reviews on ABM and its application in Earth Science, and the existing methods of flood simulation. This sets the stage for the subsequent chapters, where the focus will be on the development and evaluation of a specific ABM-based flood simulation model.

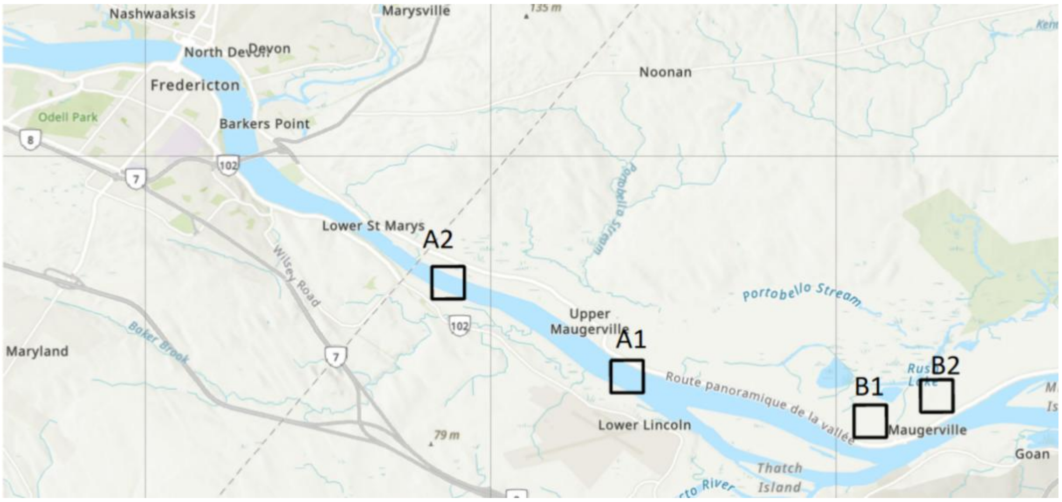
CHAPTER 3: METHODOLOGY

3.1 Study Area

This study is based on four study areas along the Saint John River in the province of New Brunswick, Canada. Each study region is clipped by the same shapefile, which is about 0.64 square kilometers. Two of the study areas include the river, while the other two only include urban areas. These four study areas are divided into two groups to form control, and the parameters of the two groups are adjusted separately. The specific study areas are shown in the following figure (Figure 1), where A1 and A2 are one group of controls, and B1 and B2 are the other groups of controls. Figure 1C illustrates the specific distribution of the four study areas. The base map used in this figure is the "World Terrain" map from ArcGIS Pro. It provides a visual representation of the study regions within the context of the surrounding geography. The detailed data pertaining to these study areas, including land use, hydrological information, and other relevant datasets, will be described in the subsequent "Data" section of the study.



A1 A2 B1 B2



C

Figure 1 Study Areas Distirbution and DEM view

3.2 Data Collection and Preparation

In order to achieve the study's objectives, several types of data were utilized. Firstly, precipitation data were collected for the corresponding research area, and this data was then used to simulate the occurrence of flooding events. Additionally, digital elevation data was obtained and analyzed to determine the most appropriate data source for the study. The study compared and analyzed two types of digital elevation data, DEM and HRDEM (HRDEM, n.d.) to determine which would provide the most accurate results for the simulation.

Moreover, historical flooding data was also used in this study. The study utilized dates with relatively large changes in flooding within the corresponding research area. These dates were selected to provide a range of conditions for the simulation and to ensure that the study could be applied to a variety of flooding events. The study then compared the use of average daily precipitation and hourly precipitation data to determine the most appropriate data for the simulation.

Finally, the study also collected data on the performance of the simulation models. This data was collected through the comparison of the simulated flooding events with actual flood events. The accuracy of the simulation models was then evaluated based on these comparisons.

In summary, the data collection process for this study involved collecting precipitation data, digital elevation data, historical flooding data, and data on the performance of the simulation models. The use of multiple data sources allowed for a comprehensive analysis of the simulation of flooding events using precipitation data.

Table 1 Summary of the data sets

<table>
<tr><th colspan="4">Summary of the data sets</th></tr>
<tr><th colspan="2">Data Name</th><th>Resource</th><th>Remarks</th></tr>
<tr><td colspan="2">Digital Terrain Model</td><td>High Resolution Digital Elevation Model Mosaic (HRDEM Mosaic) - CanElevation Series - Open Government Portal (canada.ca)</td><td></td></tr>
<tr><td colspan="2">Historical Flooding Data</td><td>Floods in Canada - Cartographic Product Collection - Open Government Portal</td><td>2018</td></tr>
<tr><td rowspan="2">Meteorological Conditions</td><td>Precipitation</td><td rowspan="2">Canadian Climate Normals - Climate - Environment and Climate Change Canada (weather.gc.ca)</td><td rowspan="2">Daily & Hourly</td></tr>
<tr><td>Average sediment concentration</td></tr>
</table>

3.3 Overall Process

The research process involves the implementation of ABM using input DEM and precipitation data, spatial data analysis using historical flooding data, result in comparison between simulated and historical data, and the final interpretation of the findings. An overall process workflow (Figure 2) is shown as follows.

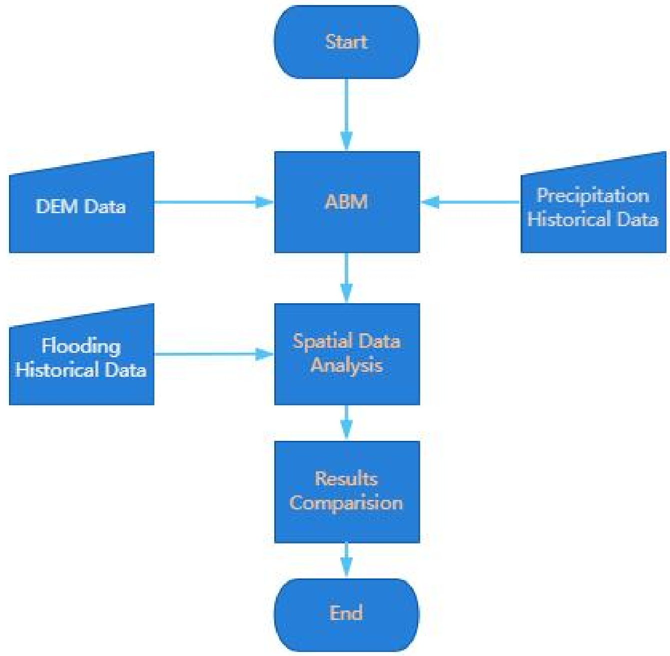


Figure 2 Workflow of Historical Flooding Data Collection

The research process begins with the initialization phase, where the study is initiated to simulate flood events using an ABM approach. The input data required for the ABM simulation includes digital elevation model (DEM) data and precipitation data. Once the ABM is implemented with the input data, it simulates the behavior and dynamics of flood events. The simulation generates output data such as water levels and flood extents.

Following the ABM simulation, the next step is spatial data analysis. Historical flooding data is inputted into the analysis, allowing for a comparison between the simulated flood data and the observed historical data. This analysis helps evaluate the accuracy and reliability of the ABM model in capturing real-world flooding events. After the spatial data analysis, the results from the ABM simulation and the historical flooding data are compared. This comparison aims to assess the performance and effectiveness of the ABM model.

3.4 ABM analysis

Our model construction primarily consists of two main parts. Firstly, we established a fundamental Agent-Based Model (ABM) and subsequently adjusted and modified the model parameters.

The foundational ABM model is derived from the Rain model, which primarily simulates the accumulation and flow of water during rainfall. In the first part, we set up the essential data, including test precipitation data and digital elevation data. In the second part, we determined all the parameters and inputted real-world data into the model.

The model is depicted in the following diagram (Figure 3).

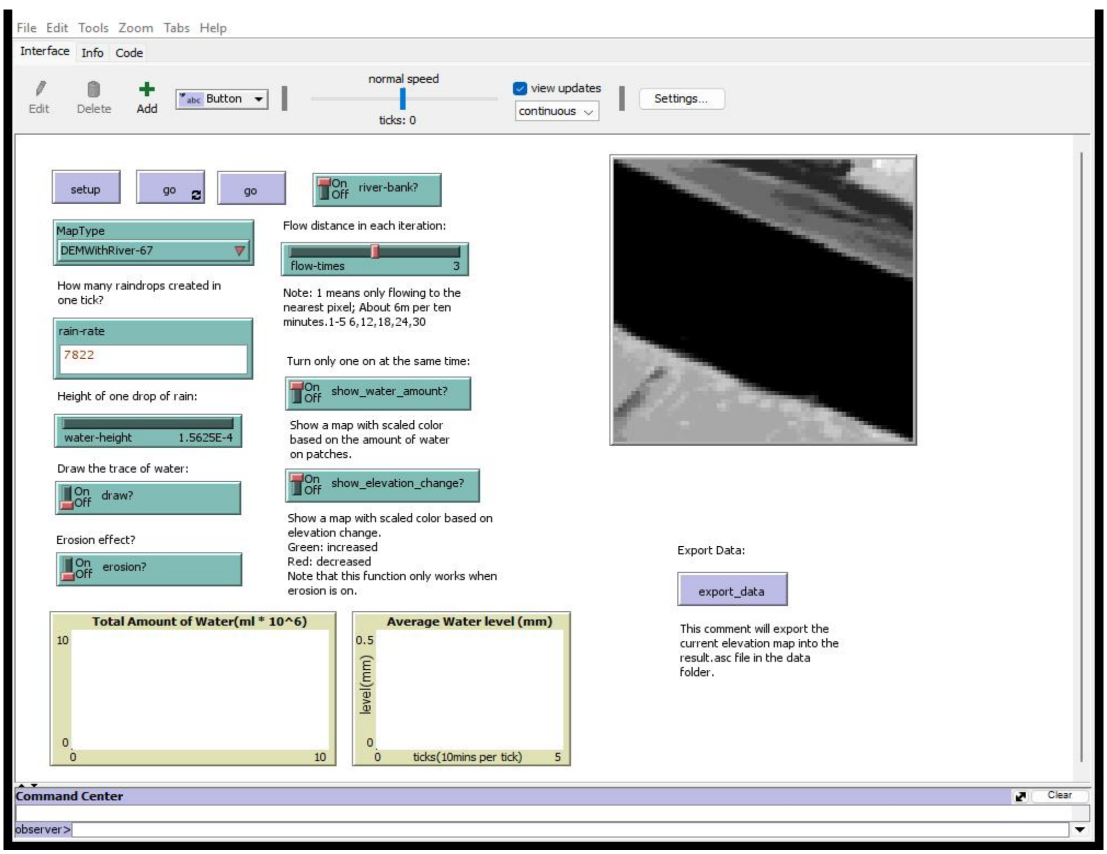


Figure 3 Netlogo Model Panel

3.4.1 BASIC ABM

3.4.1.1 ABM Platform (Software)

The software utilized for the flooding simulation and analysis was NetLogo, a widely recognized and extensively employed platform for ABM. NetLogo was deliberately chosen over other alternatives due to several compelling reasons that make it particularly suitable for this research.

One key advantage of NetLogo is its user-friendly interface, which simplifies the process of constructing and manipulating agent-based models. The software provides an intuitive graphical environment that facilitates the implementation of complex systems, enabling both experts and novices in ABM to easily design and modify simulations. This accessibility ensures a lower barrier to entry for researchers and promotes the adoption of ABM methodologies.

Another significant factor behind selecting NetLogo is its robust support for spatial modeling. In the context of the flooding simulation, the software's grid-based system, consisting of patches, allows for the representation of the spatial environment. Patches serve as cells or units representing the geographic regions in the simulation. The interaction between agents and patches enables the simulation of flooding-related phenomena, including water flow, accumulation, and the resulting inundation patterns. This spatial modeling capability makes NetLogo well-suited for studying complex spatial dynamics, such as flooding events.

Furthermore, NetLogo has an extensive model library that contains many examples of models that have been built, covering a variety of areas and issues. These model libraries provide a starting point that researchers can modify and extend to build their own flood simulation models based on their own needs and research questions. The existence of a model library can provide researchers with benefits in several ways. First, they can save time and effort, especially for those who are just starting out with NetLogo or don't have sufficient programming experience. By browsing the model library, researchers can find examples of models relevant to flood simulation, from which they can learn the basic principles and techniques of model construction.

In summary, NetLogo was selected as the software for the flooding simulation due to its user-friendly interface, robust spatial modeling capabilities, and comprehansive model library. These features make NetLogo a highly suitable tool for constructing and analyzing ABM simulations of flooding scenarios. Researchers can leverage its strengths to gain insights into the complex dynamics of flood events and explore various factors that influence their outcomes.

3.4.1.2 Structure Parameters in ABM

In an agent-based model (ABM), several key structural elements play important roles in defining the behavior and dynamics of the simulated system. Patches and Agents are shown in the Figure 4.

Patches: Patches represent the spatial environment in an ABM. They are typically arranged in a grid-like structure, forming a discrete representation of the simulated space. Each patch can store and update information such as attributes, states, or conditions relevant to the model. Patches serve as the foundation for spatial interactions and provide the context in which agents operate.

Agents(Turtles): Agents are the individual entities or actors within an ABM. They possess characteristics, behaviors, and rules that govern their actions and interactions with other agents and the environment. Agents can represent various entities, such as individuals, animals, or objects, depending on the context of the simulation. They have the ability to perceive their surroundings, make decisions, and modify the state of the system through their behaviors.

Ticks (Time Steps): Ticks or time steps represent discrete units of time in an ABM. They are used to model the progression of time within the simulation. At each tick, agents perform their actions and interact with the environment and other agents based on predefined rules and behaviors. Ticks allow for the simulation of dynamic processes and the observation of how the system evolves over time.

Behavior: Behavior in an ABM refers to the set of rules, actions, and interactions exhibited by agents in response to their environment and other agents. The behavior of an agent can include movement, decision-making, communication, resource consumption, and other actions that drive the simulation. Agents' behaviors can be defined through programming or scripting, specifying how they perceive, process information, and respond to changes in their surroundings.

These structural elements interact to create the emergent properties and dynamics observed in an ABM. Patches provide the spatial context for agent interactions, while agents' behaviors and decision-making drive the simulation's outcomes. Through the progression of time steps (ticks), the system evolves, allowing researchers to study the complex interactions and patterns that arise from the individual behaviors of agents within their spatial environment.

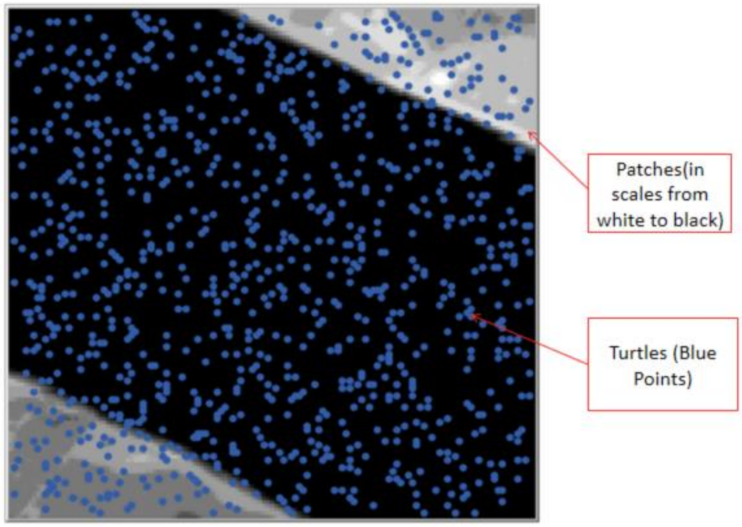


Figure 4 The Netlogo Contexts: Patches and Turtles

3.4.2 ABM MODEL

At the top of the diagram, there are three buttons for initialization and control. The "Setup" button is used to initialize the model and set the initial conditions based on the provided parameters and code. It ensures that the model is ready for simulation.

On the left side of the diagram, the "MapType" selection allows users to choose from different maps or locations for the flood simulation. Four distinct locations are provided, each with two variations of Digital Elevation Model (DEM) data, differing in resolution or accuracy. The selection of the appropriate map helps to accurately represent the topography and terrain characteristics of the chosen area.

Within the "Rain-rate" section, users can input the amount of raindrops that will be simulated to fall in the area during each iteration. This input can be adjusted interactively, allowing for dynamic changes and reflecting real-world rainfall conditions. It provides flexibility in capturing the variability of rainfall events during the flood simulation. In the model, the input for rainfall intensity (rain rate) is done through the user interface panel. Initially, we attempted to use a slider to adjust the rainfall intensity. However, considering the limitations of slider controls in terms of precision, we ultimately decided to switch to a direct input dialog box format(Figure 5). This approach allows users to directly enter the desired rainfall intensity value, providing more flexibility and accuracy in control. In the Rain Rate section, we will provide a detailed explanation of the method used to determine the rainfall intensity. We will describe how appropriate rainfall intensity values are determined based on research requirements and experimental design. Furthermore, we will explain how these values are inputted into the model for the corresponding simulation experiments. This ensures that the input of rainfall intensity aligns with the objectives and research questions of the experiment.

a b

Figure 5 Rain Rate

The "Height of one drop of rain" parameter represents the volume of an individual raindrop. Its value is determined based on calculations and can be adjusted according to the desired level of precision. By incorporating this parameter, the model can accurately simulate the effects of rainfall intensity and volume on flood formation and progression.

The "Draw of the trace of water" toggle switch allows users to visualize the flow direction of individual raindrops. When enabled, the trajectory of each raindrop is displayed, providing insights into the path and accumulation patterns of water. Disabling this option allows for a more focused analysis of the overall water accumulation without the distraction of individual raindrop trajectories.

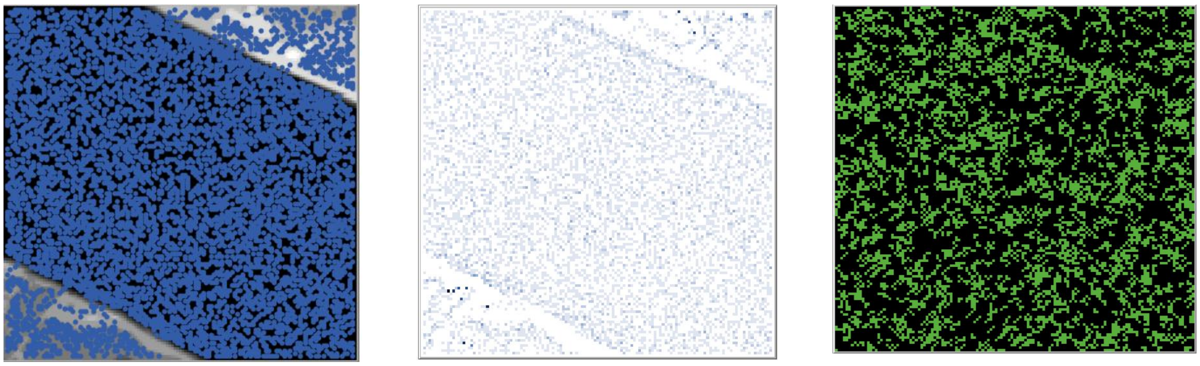
The "Erosion Effect" toggle switch controls whether erosion should be considered in the simulation. Enabling this feature allows for the modeling of erosion processes, which can significantly influence flood dynamics and landscape changes. The implementation of erosion effects is achieved through the underlying code, which will be explained in detail in the "Parameters Generation & Code Implementation"

section.

```
ask raindrops [ ifelse erosion? [flow_with_erosion][flow] ]
```

On the right side of the diagram (Figure 3), the "Flow Distance in each iteration" section enables users to adjust the maximum distance water can travel within a single iteration. By modifying this parameter, the model can simulate different flow characteristics, such as localized flooding or long-distance water propagation. The ability to customize the flow distance adds flexibility to the flood simulation model.

The "Show_water_amount" and "show_elevation_change" sections determine the information displayed on the image on the far right of the diagram. When both switches are turned off, the image presents the spatial distribution of raindrops in the simulated area (Figure 6-a). Enabling the "show_water_amount" switch highlights the temporal changes in water accumulation over the simulation period, providing insights into the progression of flood events (Figure 6-b). Enabling the "show_elevation_change" switch visualizes the cumulative changes in elevation, with different colors, green, black, and red, representing elevation increases, no change, and decreases (Figure 6-c). This visualization feature helps in understanding the topographic modifications resulting from the flood.



a b c

Figure 6 The Topographic Modification result from the Flood

At the bottom of the diagram, two line graphs illustrate the changes in water amount and water level throughout the iterations. The "water amount" graph showcases the total volume of water within the simulation area over time, providing a comprehensive view of water accumulation and movement. The "water level" graph represents the average height of the water surface, enabling the analysis of floodwater depth and its temporal variation.

To facilitate data analysis and further exploration, the model includes an "export_data" button on the far right. This functionality allows users to export the current simulation data into a tabular format, providing access to detailed information about each turtle (simulation agent) and pixel, including elevation, water accumulation, and other relevant attributes. The exported data also includes the information corresponding to the two line graphs, enabling users to perform more in-depth analyses and visualize the simulation results externally.

In addition, a flowchart presents the logical connection between each tool and functions are providing on Figure 7. The flowchart consists of two main parts: Start and Go. The Start part includes three steps: "Set border," "Resize the world into the size of the study area," and "Set the water height." These steps establish the initial conditions of the simulation by defining the boundary, adjusting the world size to match the study area, and setting the initial water height.

The Go part of the flowchart involves several decision points and actions based on user inputs. The first decision point is to determine the rain rate based on the inputted number of raindrops. The rain rate is a parameter that affects the intensity of precipitation in the simulation. The next decision point is to select the type of output image to display, which can be either "show_elevation_change" or "show_water_amount." This choice determines the visualization of the simulation results. Additionally, the flowchart includes a step to set the scale map for the specific output based on numerical values. The scale map provides a visual representation of the values in the output, allowing for easier interpretation of the results. Finally, the Go part also considers the option of erosion. It includes a decision point to determine the erosion mode or flow method based on the erosion switch. The description of the specific erosion processes will be elaborated in the subsequent Erosion section of the flowchart.

3.4.3 PARAMETERS GENERATION

3.4.3.1 Map Type

The code snippet (Figure 8b) below illustrates the options for the digital elevation model (DEM) and the corresponding panel(Figure 8a) that displays the changes. The DEM options consist of eight choices, categorized into two groups: the "with river" area and the "out of river" area. Each group contains two specific areas with identical patterns. Within each specific area, there are two different resolutions available: 67*67 and 133*133. The size of each patch, representing a pixel, varies depending on the resolution. Considering the total area of 0.64 km^2, it can be divided by the number of pixels to determine the real size of each patch. In the smaller resolution, the real size of each patch is approximately 142 m^2. In the larger resolution, the real size of each patch is approximately 36 m^2.

In the "with river" group, both specific areas include rivers, as well as similar triangular ground areas located at the top right and bottom left corners. In the "out of river" group, both specific areas are located at a similar distance away from the river.

This configuration allows for exploring the effects of different options within the DEM, providing insights into how these variations impact the simulation results and the dynamics of flooding in both river and non-river areas.

The code snippet (Figure 8b) follows a series of conditional statements (if statements) to determine the appropriate action based on the value of MapType. Each if statement checks the value of MapType against a specific condition and executes the corresponding code block if the condition is met.

In each section of the code the first two lines assign the minimum and maximum values of elevation from the GIS dataset to the variable min-e and max-e

Then, the last line iterates over all the patches in the model and sets their color based on the elevation value. The scale-color primitive maps the elevation values to a color scale, with black being the base color. The minimum and maximum elevation values (min-e and max-e) are used to determine the color scale.

The purpose of this code is to visualize the elevation map by assigning colors to the patches based on their elevation values. The specific color scale used is determined by the value of MapType. The code is repeated for different combinations of MapType and grid resolutions (67x67 and 133x133), ensuring the appropriate visualization based on the selected map type.

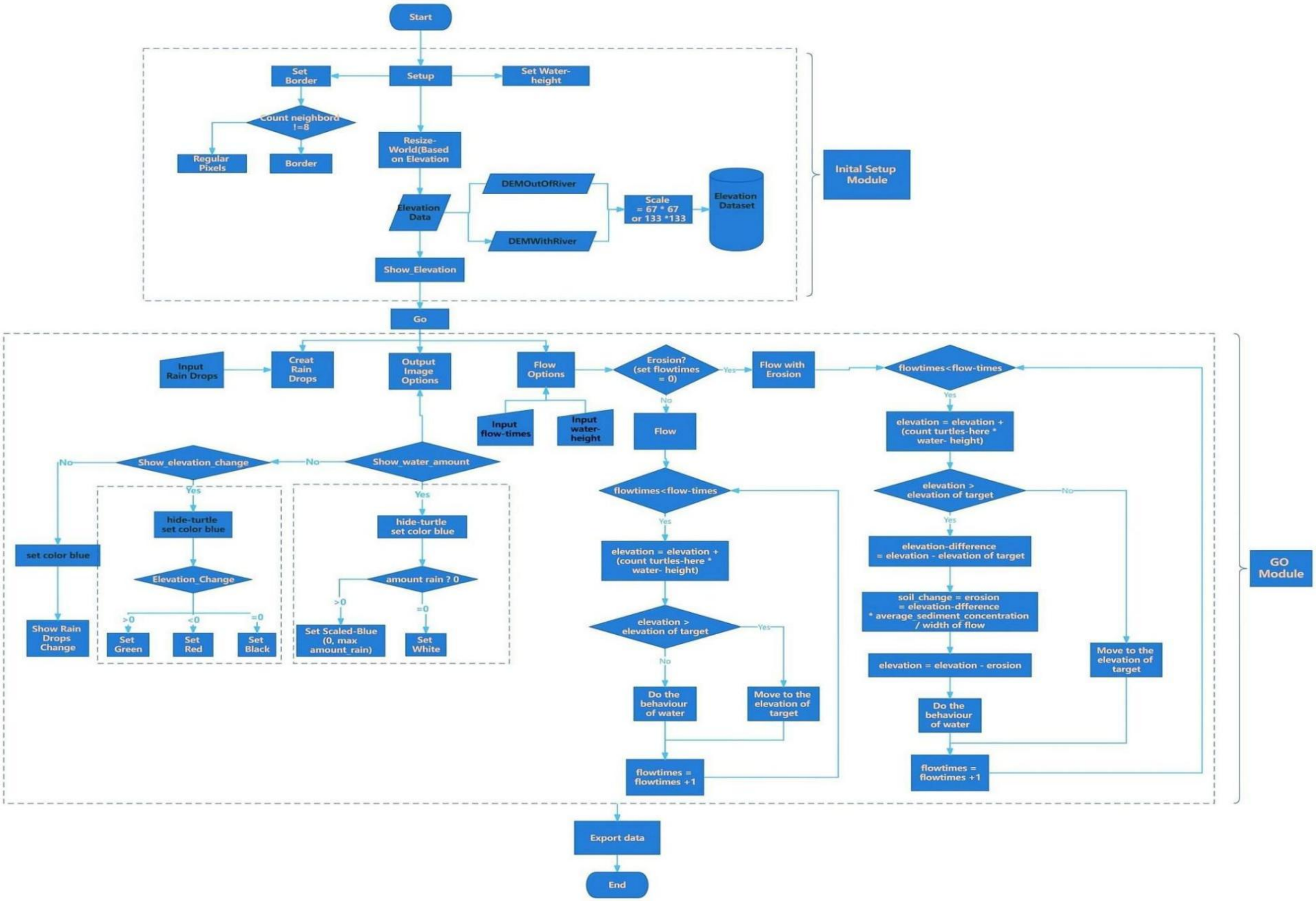
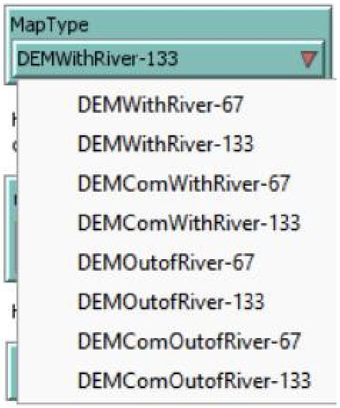


Figure 7 Flowchart of Comprehensive Flood Simulation




```
to show_elevation

   if MapType = "DEMOutOfRiver-67"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMWithRiver-67"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMOutOfRiver-133"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMWithRiver-133"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMComOutOfRiver-67"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMComWithRiver-67"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMComOutOfRiver-133"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMComWithRiver-133"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

end
```

a b

Figure 8 Netlogo Panel and Code Snippet for MapType(DEM)

3.4.3.2 Rain Rate

In order to accurately calculate the intensity of rainfall, it is essential to calculate the quantity of raindrops occurring within a given time interval (referred to as a tick) using past precipitation data. The estimation of raindrops is essential in calculating the estimated drops for the study area. We establish an equation using the total rainfall as an intermediate value:

Total Rainfall = Rainfall Amount * The Area of the Study Area

= Raindrop Volume * Number of Fallen Raindrops(X) (Equation 1)

Historical data suggests that the average volume of one raindrop ranges from 0.001 ml to 0.6 ml.(NASA, n.d.) For the purpose of our calculations, we assume a raindrop volume of 0.3 ml. By making this assumption, we can substitute the given conditions into the equation mentioned above to obtain an estimation of the daily number of fallen raindrops.

Additionally, to estimate the daily number of fallen raindrops based on the daily precipitation data, we rely on the average rainfall values recorded on the Canadian government website. For example, using the average daily rainfall of 2.2 mm on April 28, 2018, we divide it by the assumed raindrop volume (0.3 ml) to estimate the daily number of fallen raindrops for that particular day.

A sample calculation is shown below:

$$2.2 * 10^{(-1)} * 0.64 * (10^{10})\ cm^3 = 1.408 * 10^9 = 0.3 * X(drops)$$

$$X = 4.69*10^9 \text{ drops/per day}$$

$$= 1.9 * 10^8 \text{ drops/per hour}$$

$$= 3 * 10^6 \text{ drops/per minute} \qquad \text{(Equation 2)}$$

Furthermore, in order to establish a suitable time scale for the simulation, it is necessary to determine the duration of real-time that corresponds to one "tick." Balancing the limitations on iteration counts and potential slowdowns in simulation time is critical. Our objective is to simulate the changes in flood dynamics within a 24-hour period, equivalent to 1440 minutes. To replicate realistic rain and flooding over a 24-hour period, each tick represents a duration of 10 minutes in real-time. It is important to strike a balance with the tick interval, as a very small gap would require an excessive number of iterations, while a large gap would not accurately simulate the rainfall. However, during practical implementation, it was observed that performance significantly deteriorates when exceeding approximately 200 ticks. Through various tests, we determined that a 10-minute tick interval is the most suitable choice. The drops are distributed randomly among the patches. Consequently, we decided to set one tick as 10 minutes, ensuring a reasonable compromise between computational efficiency and capturing meaningful changes in flood behavior.

Based on previous calculations, an estimated $3x10^7$ raindrops would need to fall in each iteration. However, extensive testing revealed that simulating more than 20,000 raindrops per iteration can lead to abnormal program performance, such as severe lagging or system crashes. To address this limitation, we adopted an approach where a fixed number of raindrops is treated as a collective entity.

For instance, we aggregate approximately $5x10^3$ raindrops as a single entity, named as AssDrop, in the following content, resulting in around 6,000 raindrops falling in each iteration. This aggregation technique reduces computational complexity while still capturing the overall impact of precipitation in the simulation. It is important to acknowledge the potential implications and limitations of this simplification when interpreting the simulation results.

3.4.3.3 Height of one drop of rain

The height of one drop of rain is calculated based on the volume of one "AssDrop" and the area of the study area. Specifically, the water height can be determined by dividing the volume of one AssDrop by the area of the study area:

$$Waterheight(mm) = \frac{Volume\ of\ one\ AssDrop(cm^3)}{Area\ of\ the\ Study\ Area(cm^2)} * 10$$ (Equation 3)

```
set water-height 10 ^ 5 * 10 / ( 64 * 10 ^ 8 )
```

This calculation allows us to estimate the vertical extent of rainfall in terms of the height of a single AssDrop, and facilitates the verification of changes in elevation in subsequent calculations. In addition, the water height will be utilized in the flow function to calculate the overall amount of water during the rainfall.

3.4.3.4 Draw of the trace of water

The code snippet for the draw of the trace of water is shown below:

```
ifelse draw?
  [ ask turtles [ pd ] ]
  [ clear-drawing
    ask turtles [ pu ] ]
```

3.4.3.5 Erosion Effect

The objective is to estimate soil loss per unit area within the simulated environment. The calculations are performed using the following steps:

In this study, the soil loss per unit area is determined by applying the specific formula proposed by Rose in 2004 (Rose, 2004), which is derived from the original principle of erosion.

(Rose, 2004)

$$q_{av} c_{av}\, \Delta T/L = \frac{q_{av} W\,(\mathrm{m}^3)}{W\,(\mathrm{m})(\mathrm{min})} \times c_{av}\, \frac{\mathrm{kg}}{\mathrm{m}^3} \times \frac{\Delta T\,(\mathrm{min})}{L\,(\mathrm{m})} \quad \text{or kg m}^{-2}$$

(Equation 4)

This equation encapsulates the erosion process and allows for the quantification of the soil eroded per unit area. Cav represents the average sediment concentration, which indicates the average mass of sediment per unit volume of water. On the other hand, Qav refers to the volume of water per unit width of flow. By utilizing this formula, we ensure that our calculations are grounded in the fundamental understanding of erosion phenomena, as established by the original principle. The application of this equation enables us to accurately estimate the extent of soil loss and provides valuable insights into the erosive dynamics within the simulated environment.

The average sediment concentration (Cav) is a critical parameter in erosion calculations. It represents the average mass of sediment per unit volume of water within the simulated environment. For this study, the average sediment concentration is determined to be 22.64252696 kg/m^3 from Natural Resource Canada (Canada, 2023). It is important to note that different sediment concentration levels should be explored to account for potential variations in erosion rates. By testing different sediment concentrations, we can assess their impact on the erosion process and its outcomes. However, during the hazard event being simulated, there is a lack of specific data. In such cases, we rely on the historical average sediment concentration rate. However, the limitations of using historical data are obvious. In this study, the historical data only covers the period from 1966 to 1968 as there is no specific data during the hazard.

The volume of water per unit width of flow (qav) is a key parameter required for erosion calculations. It is calculated by dividing the amount of water flowing from one pixel to another (e.g., from pixel A to pixel B) by the width per pixel and the time taken for the water to traverse that distance. This calculation provides an estimation of the average water flow rate along the width of the flow.

By integrating these erosion calculations into the agent-based flood simulation model, we can estimate the soil loss per unit area. These calculations are repeated for each agent within the simulated environment, enabling a comprehensive understanding of erosion patterns and their implications for flood simulation. It is important to acknowledge that the specific formula or equation for soil loss per unit area is not provided in this study and should be referenced from appropriate sources.

```
to flow
  ;;this part uses codes from the library model Grand Cayon, with some modifications
  set flowtimes 0
  while [flowtimes < flow-times] [
  let target min-one-of neighbors [ elevation + ( count turtles-here * water-height) ]
  set elevation elevation + ( count turtles-here * water-height)

  ifelse [elevation + (count turtles-here * water-height)] of target
     < (elevation + ((count turtles-here - 0) * water-height))
    [ face target
      move-to target ]
    [ set breed waters ]
    set flowtimes flowtimes + 1
  ]
  ;;codes from Grand Cayon end here
end
```

```
to flow_with_erosion
  ;;this part uses codes from the library model Grand Cayon, with some modifications
  set flowtimes 0
  while [flowtimes < flow-times] [
  let target min-one-of neighbors [ elevation + ( count turtles-here * water-height) ]
  set elevation elevation + ( count turtles-here * water-height)

  ifelse [elevation + (count turtles-here * water-height)] of target
     < (elevation + ((count turtles-here - 0) * water-height))
    [
    ;;consider erosion effects
    ;;elevation-difference shows the difference of the amount of water between these two patch
    set elevation-difference (elevation + ((count turtles-here - 0) * water-height)) - [elevation + (count turtles-here * water-height)] of target
      ask patch-here [set elevation elevation - elevation-difference * 22.64252696 / (8 * 10 ^ 6) ];;cm^3 to m^3
      ;;area of the pixel: the amount of the soil will flow out from this pixel.
      ;; amount of water flowed into the area * amount of the soil brought by the water
      ;; the amount of the soil that will be brought from the water, depends on the water flows into the area.
      set soil soil + elevation-difference * 22.64252696 / (8 * 10 ^ 6)
      face target
      move-to target
    ]
    [ set breed waters
      ask patch-here [set elevation elevation + [soil] of myself]
      set soil 0]
   set flowtimes flowtimes + 1
  ]
  ;;codes from Grand Cayon end here
end
```

In the code provided above, several variables and conditions are utilized to govern the flow behavior. Firstly, the flowtimes variable is initialized to 0, serving as a counter for the number of flow iterations. The soil variable is also set to 0, representing the amount of soil in a specific patch. The code then enters a loop that continues executing as long as flowtimes is less than the defined flow-times value. Within the loop, the target patch with the lowest elevation, considering the elevation and the product of the count of turtles in the current patch and the water-height value, is determined. The elevation of the current patch is updated by adding the product of the turtle count and water-height. An if-else condition is employed to determine if water should flow from the current patch to the target patch. If the condition is met, erosion effects are considered. The difference in elevation between the target patch and the current patch, multiplied by a conversion factor, is subtracted from the current patch's elevation to simulate erosion. The soil present in the current patch is also updated accordingly, and the agent moves to the target patch.

3.4.3.6 Flow Distance in each iteration

The flow distance is calculated through a loop in the "flow" and "flow_with_erosion" sections mentioned earlier. Initially, the code sets the "flowtimes" parameter to 0. In the user interface, the "flow-times" parameter is set, which ranges from 1 to 5. If the "flowtimes" value is less than the "flow-times" value, the code increments "flowtimes" by 1 and completes one iteration of the loop. This process continues until the desired number of flow iterations is reached.

3.4.3.7 Show_water_amount and Show_elevation_change

To achieve simultaneous control of "Show_water_amount" and "Show_elevation_change", we implemented a dual if-else conditional statement in our code. The calculation and display sections for both aspects are mostly identical. In both cases, we classify the data and generate scale maps based on the classification.

The code structure allows for flexibility in displaying either the water amount or the elevation change based on the chosen options. By utilizing the conditional statements, the code determines which aspect to calculate and display, ensuring that the appropriate scale map is generated for the selected option.

The following code presents the steps to show the water amount and elevation change. In the show_amount_of_water procedure, the amount of water is displayed on the patches using scaled colors. Initially, the amount_rain variable of each patch is set to the count of turtles present on that patch. The maximum value of amount_rain among all patches is determined and stored in the max-e variable. Patches with a non-zero amount_rain are assigned a shade of blue using scale-color, where the color is scaled based on the amount_rain value. Patches with a amount_rain of 0 are set to white color. Lastly, the turtles are hidden from view.

In the show_elevation_change procedure, the elevation changes are visualized on the patches. The elevation_change variable of each patch is calculated as the difference between its current elevation and the initial elevation. The turtles are hidden from view, and the patches are assigned colors to represent the elevation changes. Patches with a positive elevation_change are colored green to indicate an increase in elevation, while patches with a negative elevation_change are colored red to denote a decrease in elevation. Patches with an elevation_change of 0 are set to black color.

```
ifelse show_water_amount?
  [show_amount_of_water]
  [ifelse show_elevation_change? and erosion?[show_elevation_change ]
    [  ask turtles [show-turtle]
       show_elevation]]
set flowtimes 0
```

```
to show_amount_of_water
  ;;To show by scaled color. However, because the variation is small, it may be hard to see the di
  ;; This is what is shown in our model
   ask patches [set amount_rain count turtles-here  ]
     set max-e [amount_rain] of max-one-of patches [amount_rain]
     ask patches with [amount_rain > 0 ][set pcolor scale-color blue amount_rain (max-e + 1) 0 ]
     ask patches with [amount_rain = 0 ][set pcolor white]
     ask turtles [hide-turtle]

end
```

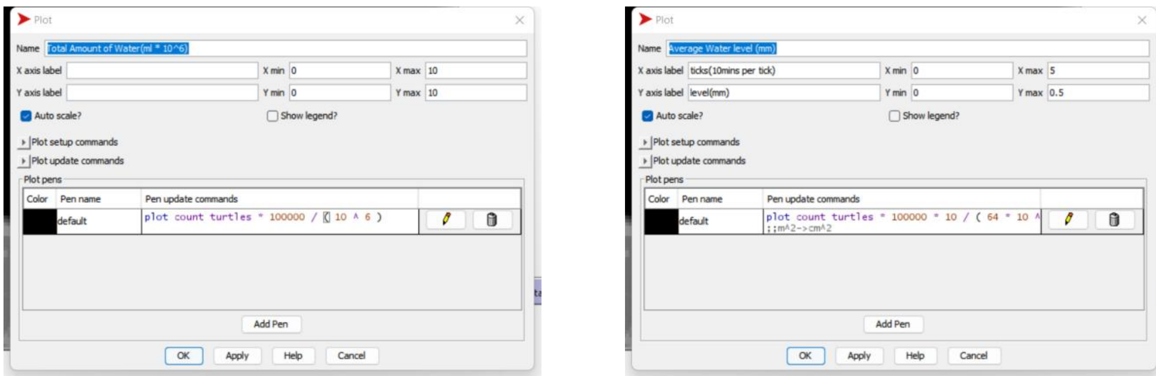
```
to show_elevation_change

  ask patches [set elevation_change elevation - initial_elevation]
  ask turtles [hide-turtle]
  ask patches with [elevation_change > 0][set pcolor green ] ;;increased
  ask patches with [elevation_change < 0][set pcolor red ]   ;;decreased
  ask patches with [elevation_change = 0][set pcolor black]

end
```

3.4.3.8 Line Graphs

The two line graphs presented below serve to visually display the changes in water level. The difference between the "total water amount"(Figure 9a) and "average water amount"(Figure 9b) lies only in whether or not an area average is taken into account. Therefore, the trends of the two graphs will be the same, with the difference lying solely in the numerical values. This section directly adds the following formulas to the Plot tool:

Total water amount = Total number of AssDrops * Volume of one AssDrop (Equation 5)

Average water amount = Total water amount / Area of the study area. (Equation 6)



a b

Figure 9 Line graph setting

3.5 Spatial Data Process

The spatial data processing in this study involves the rigorous analysis of output data obtained from the NetLogo simulation. The exported data is meticulously organized and refined to extract pertinent information related to water level dynamics during flood events. The primary focus is on identifying and selecting specific water level measurements corresponding to the occurrence of floods.

Once the data is appropriately curated, a meticulous reclassification procedure is employed to differentiate between flooded and non-flooded areas. This classification is achieved by applying well-defined criteria or thresholds, which allow for the delineation of regions experiencing inundation and those unaffected by flooding. By employing these robust classification criteria, the resulting contrasting map provides a comprehensive visual representation of the spatial extent and distribution of flooding within the study area.

This spatial data processing methodology plays a pivotal role in elucidating the complex interactions between water levels and flood occurrences. It facilitates a more nuanced understanding of flood dynamics, enabling researchers to identify vulnerable areas and assess the impact of flooding on the environment. Such rigorous spatial data analysis contributes to scientific knowledge and informs evidence-based decision-making processes pertaining to flood risk management and mitigation strategies.

The following code snippet shows the spatial analysis processes to perform data analysis and generate flooding maps. The data is read from an Excel file, specifically from the 'e1' sheet, and stored in a pandas DataFrame. Columns 'T75', 'T291', and 'T363' are extracted from the DataFrame and stored as separate variables. The code then determines flooding conditions based on the rainfall amounts in these columns and populates corresponding lists accordingly. Two additional lists are generated by comparing the flooding conditions between different days. The lists are converted to numpy arrays and reshaped to create the flooding maps. Using matplotlib, the code generates visual representations of the flooding maps with colorbars, titles, and colormaps. The resulting maps depict flooding for the first, second, and third days, as well as comparisons between the first and second days and between the second and third days.

```
#Using Amount-Rain Difference
import pandas as pd
import numpy as np
from matplotlib import image
from matplotlib import pyplot

df_e = pd.read_excel('Analysis_Final_Input.xlsx', sheet_name='e1')
```

```
Amount_Rain_75 = df_e['T75']
Amount_Rain_291 = df_e['T291']
Amount_Rain_363 = df_e['T363']

IfFlood_75 = []
IfFlood_291 = []
IfFlood_363 = []
IfFlood_Inc1 = []
IfFlood_Inc2 = []

for x in Amount_Rain_75:
  if x <= 1:
    IfFlood_75.append(0)
  else:
    IfFlood_75.append(1)

for x in Amount_Rain_291:
  if x <= 1:
    IfFlood_291.append(0)
  else:
    IfFlood_291.append(1)

for x in Amount_Rain_363:
  if x <= 1:
    IfFlood_363.append(0)
  else:
    IfFlood_363.append(1)

#If flood
for i in range(0, len(Amount_Rain_75)):
    if IfFlood_291[i] > IfFlood_75[i]:
      IfFlood_Inc1.append(1)
    else:
      IfFlood_Inc1.append(0)

for i in range(0, len(Amount_Rain_291)):
    if IfFlood_363[i] > IfFlood_291[i]:
      IfFlood_Inc2.append(1)
    else:
      IfFlood_Inc2.append(0)

IfFlood_Arr_75 = np.array(IfFlood_75).reshape(135, 135)
IfFlood_Arr_291 = np.array(IfFlood_291).reshape(135, 135)
IfFlood_Arr_363 = np.array(IfFlood_363).reshape(135, 135)
IfFlood_Inc1_Arr = np.array(IfFlood_Inc1).reshape(135, 135)
IfFlood_Inc2_Arr = np.array(IfFlood_Inc2).reshape(135, 135)

c1 = pyplot.imshow(IfFlood_Arr_75, cmap ='Blues')
pyplot.colorbar(c1)
pyplot.title("Flooding Map for the first day", fontsize=14)
pyplot.show()

c2 = pyplot.imshow(IfFlood_Arr_291, cmap ='Blues')
pyplot.colorbar(c2)
pyplot.title("Flooding Map for the second day", fontsize=14)
pyplot.show()

c3 = pyplot.imshow(IfFlood_Arr_363, cmap ='Blues')
pyplot.colorbar(c3)
pyplot.title("Flooding Map for the third day", fontsize=14)
```

```
pyplot.show()

c4 = pyplot.imshow(IfFlood_Inc1_Arr, cmap ='Greens')
pyplot.colorbar(c4)
pyplot.title("Compared Flooding Map for First and Second Days", fontsize=12)
pyplot.show()

c5 = pyplot.imshow(IfFlood_Inc2_Arr, cmap ='Greens')
pyplot.colorbar(c5)
pyplot.title("Compared Flooding Map for Second and the Third Days", fontsize=12)
pyplot.show()
```

3.6 Chapter Summary

This chapter encompasses a comprehensive research process that guides the investigation in ABM for flood simulation. It comprises several key components, starting with defining the study area and collecting relevant data. Subsequently, an ABM analysis is conducted, involving the development of a basic ABM structure and the generation of parameters. Finally, spatial data processing techniques are applied to analyze and visualize the simulation results.

The research process begins by establishing the study area, providing a geographical context for the subsequent analysis. Data collection and preparation follow, ensuring the availability of accurate and reliable data for the simulation. The ABM analysis is then undertaken, involving the construction of a basic ABM framework that defines the agents, their behaviors, and interactions within the simulated environment. Parameters are generated to capture the heterogeneity and dynamics of the system under investigation.

The final step involves the spatial data processing methodology, where the output data from the simulation are organized, filtered, and classified. This process facilitates the identification of specific water level measurements corresponding to flood events, enabling the creation of comparative maps that distinguish flooded areas from non-flooded ones.

By following this well-structured research process, the methodology chapter ensures a systematic approach to investigating flood simulation using ABM. It provides a solid foundation for subsequent chapters and contributes to the overall scientific rigor and reliability of the research findings.

CHAPTER 4: EXPERIMENT, RESULTS AND DISCUSSION

4.1 Experiment

4.1.1 MODEL SETTING PRINCIPLE

The model consists of three main variables: Maptype, Erosion, and flow-times. As mentioned earlier in the Methodology section, Maptype offers eight selectable options representing different landscape types. The Erosion variable can be controlled to either enable Erosion or disable it (no Erosion). The flow-times variable is initially set to 1 but can be adjusted within the range of 1 to 5.

To ensure an effective comparison of experimental results, a controlled variable approach is adopted. Each experiment focuses on testing a single variable while keeping other variables constant. This methodology allows for a systematic assessment of the impact of individual variables on the outcomes of the model simulations. The specific results and comparisons obtained from these experiments will be elaborated upon in subsequent sections.

Additionally, the rain-rate variable is set based on the data provided in the table below (Table 2), and its value in the model needs to be adjusted according to the value in the "ticks" column. In the table, the black highlighted rows indicate the specific time points that are of particular interest and recorded during this experiment.

Whenever the flow time is set to 1 or 5, both durations are limited to 10 minutes. The difference lies in the distance the water can flow within that fixed duration. A flow time of 1 indicates that the water will cover a distance of approximately 6 meters in 10 minutes, while a flow time of 5 means the water will cover distances of 30 meters at subsequent 10-minute intervals. The flow time parameter affects the extent and progression of water flow, influencing the spatial distribution and reach of water within the model simulation.

In the simulation, we have set the iterations at 75, 291, and 363 ticks. During the period from the 27th to the 28th of April, the rainfall starts at 23:00 on the 27th. Therefore, this particular moment is set as time 0. According to the flood records, the flood occurs at 10:30 on the 28th, at 22:10 on the 29th, and at 10:30 in the morning on the 30th. By considering a time interval of 10 minutes per tick, it is determined that the 75th tick corresponds to the flood on the 28th, the 291st tick corresponds to the flood on the 29th, and the 363rd tick corresponds to the flood on the 30th. These specific time points allow for the observation of the respective floods on their corresponding dates within the simulation.

Table 2 Model Setting Table for Rain Rate

Model Setting Table									
Year	**Month**	**Date**	**Time**	**Precipitation(mm)**	**drops/per 10 minutes**	**10^8 drops/per 10 minutes**	**One AssDrop is 10^5 ml,Then Drops in each hour**	**set in the model**	**ticks**
2018	4	27	23:00	2.2	782222222.22	7.8222	7822.22	7822	6
		28	0:00	2.1	746666666.67	7.4667	7466.67	7466	12
			1:00	0.3	106666666.67	1.0667	1066.67	1066	18
			2:00	0.2	71111111.11	0.7111	711.11	711	24
			3:00	0	0.00	0.0000	0.00	0	30
			4:00	0.4	142222222.22	1.4222	1422.22	1422	36

			5:00	0	0.00	0.0000	0.00	0	42
			6:00	0.2	71111111.11	0.7111	711.11	711	48
			7:00	0.3	106666666.67	1.0667	1066.67	1066	54
			8:00	0.7	248888888.89	2.4889	2488.89	2488	60
			10:30	0	0.00	0.0000	0.00	0	75
			20:00	0.6	213333333.33	2.1333	2133.33	2133	132
		29	0:00	0	0.00	0.0000	0.00	0	156
			8:00	0.2	71111111.11	0.7111	711.11	711	204
			22:10	0	0.00	0.0000	0.00	0	291
			23:00	0	0.00	0.0000	0.00	0	294
		30	0:00	0	0.00	0.0000	0.00	0	300
			1:00	2.4	853333333.33	8.5333	8533.33	8533	306
			2:00	0	0.00	0.0000	0.00	0	312
			3:00	0	0.00	0.0000	0.00	0	318
			4:00	2.3	817777777.78	8.1778	8177.78	8177	324
			5:00	2.6	924444444.44	9.2444	9244.44	9244	330
			6:00	0.9	320000000.00	3.2000	3200.00	3200	336
			7:00	1.2	426666666.67	4.2667	4266.67	4266	342
			8:00	0.6	213333333.33	2.1333	2133.33	2133	348
			9:00	1.7	604444444.44	6.0444	6044.44	6044	354
			10:00	4.9	1742222222.22	17.4222	17422.22	17422	360
			10:30	1.7	604444444.44	6.0444	6044.44	6044	363
			11:00	1.7	604444444.44	6.0444	6044.44	6044	366

4.1.2 SAMPLE EXPERIMENT

This section presents a sample experiment where the model is configured with Erosion = Yes, flow-times = 1, and DEM = DEMWithRiver-133 (Figure 10). Figure 10 displays the panel setup when using these settings and the direct results displayed on the panel after running the simulation until 75 ticks. As mentioned above, during the course of this experiment, three sets of data will be exported. The exported data table will encompass comprehensive information, with a primary focus on recording the elevation change for each pixel.

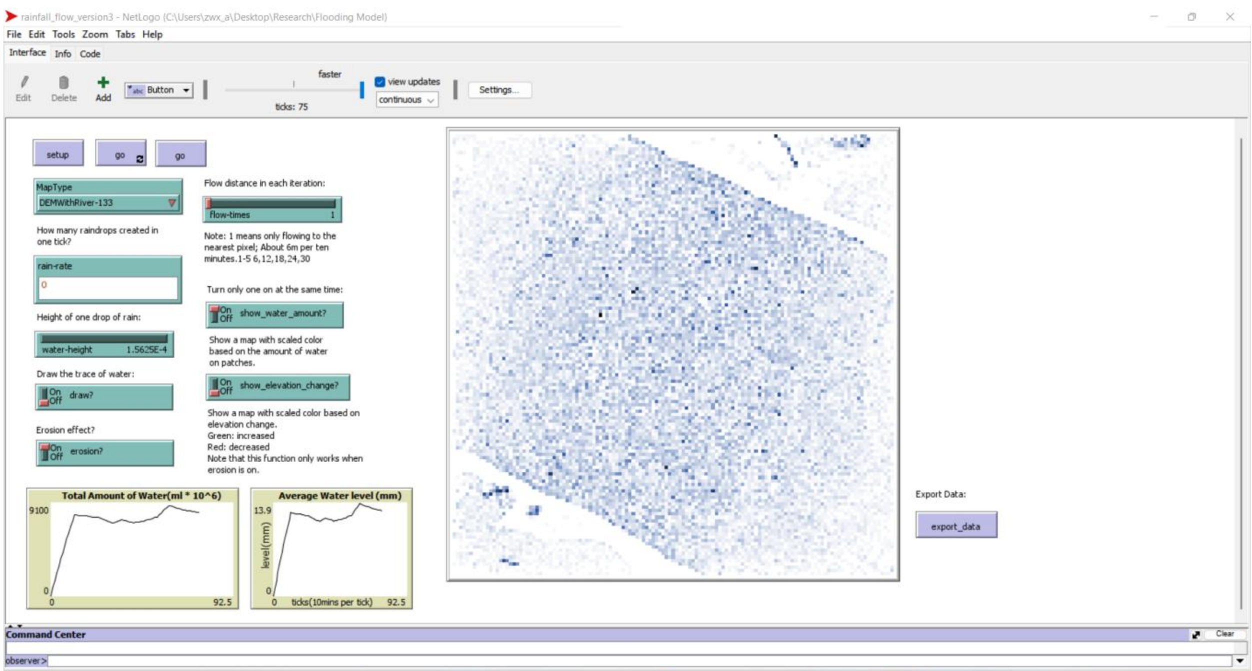


Figure 10 The Direct Changes in Elevation Values

In this particular example, we will analyze the results obtained after running the model for 75 iterations and 291 iterations, specifically at the first Flooding record. This provides an insight into the effects of erosion under the given settings. The data analysis will primarily center around the elevation change observed in each pixel, as it allows us to understand the impact of erosion on the simulated landscape.

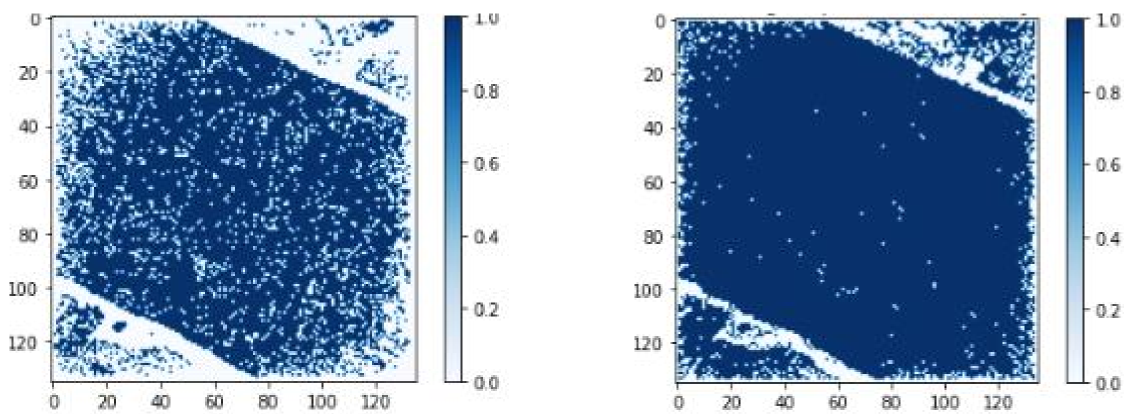
At 75 ticks, the NetLogo simulation produces the following result graph and the graph displayed shows the direct changes in elevation values:

Next, we assign a binary value to the elevation change data. If the remaining amount of rain is greater than one AssDrop, it is classified as flooding, and if it is less than one AssDrop, it is classified as no flooding. This classification allows us to generate a binary image, as shown in the following figure(Figure 11). The blue areas indicate flooding occurrences, while the white areas indicate no flooding.

The binary image (Figure 11) provides a visual representation of the spatial extent of flooding within the study area. It helps identify the specific areas that have been affected by flooding based on the threshold of one AssDrop in the remaining amount of raindrops. By distinguishing between flooded and non-flooded regions, we can better understand the patterns and distribution of flooding events.

This binary representation allows for a clearer interpretation of the flooding dynamics and facilitates further analysis of the impacts and implications of flooding in the study area. It serves as a valuable tool for identifying vulnerable areas, evaluating flood risks, and informing decision-making processes related to flood mitigation and management.

It is important to note that the binary classification of flooding is based on the specific threshold chosen (1 AssDrop in this case), and different threshold values may yield varying results. The chosen threshold is based on the specific context of the study and may vary depending on the research objectives and the characteristics of the study area. When setting the threshold, our primary consideration was the number of AssDrops that could potentially cause a significant water level within a patch. Since the AssDrop used in this experiment is relatively large, we deemed that a single AssDrop could result in a substantial water level.



a b

Figure 11 Binary flood maps

The comparison between the elevation change values and the binary flood maps provides a comprehensive visualization of the occurrence and extent of flooding. By overlaying these two images, we can easily identify the areas that experienced flooding and those that remained unaffected. The elevation change values directly represent the magnitude of changes in elevation. Positive values indicate areas where flooding occurred, while negative or near-zero values indicate non-flooded regions. This representation allows us to visually assess the spatial distribution of flooding across the study area.

To further analyze the specific regions that underwent flooding, a comparative approach was employed. By comparing the initial non-flooded state with the subsequent flooding event, we can identify areas that transitioned from non-flooded to flooded. These areas are highlighted as blue in the binary flood map (Figure 11), providing a clear indication of the regions that experienced flooding during the designated time period.

This comparative analysis enables a more focused examination of the areas that were initially unaffected by flooding but later encountered flood events. By pinpointing these areas, we can gain insights into the dynamics and patterns of flooding, which can inform flood risk assessments and support targeted mitigation efforts. The combined representation of the elevation change values and the binary flood maps (Figure 12) facilitates a comprehensive understanding of the spatial dynamics of flooding.

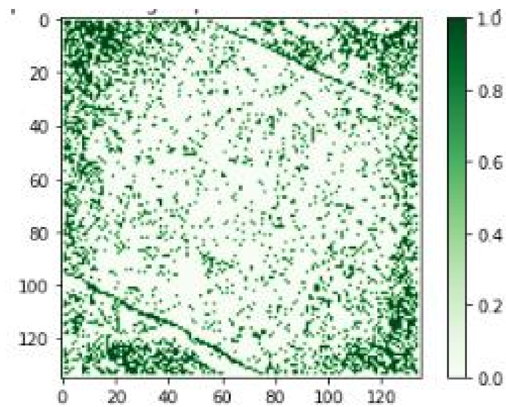


Figure 12 Comparative analysis

4.1.3 EXPERIMENT SETTING

In the following sections, we will present a comprehensive comparison and discussion of the experiments conducted, focusing on various dimensions. A summary of all the experiments used in the comparison is shown below with the specific parameters utilized for these comparative experiments:

Table 3 Summary of the experiments used in the comparison

Summary of the experiments used in the comparison				
Experiment ID	**Erosion**	**Flow-times**	**DEM**	**Comparison Chapters Remark**
Experiment.1	Yes	1	With River-133	4.2,4.3
Experiment.2	No	1	With River-133	4.2
Experiment.3	Yes	1	Out of River-133	4.2

Experiment.4	No	1	Out of River-133	4.2,4.3,4.4
Experiment.5	Yes	3	With River-133	4.3,4.4
Experiment.6	Yes	3	With River-67	4.4
Experiment.7	Yes	5	With River-133	4.3
Experiment.8	No	1	Out of River-67	4.4
Experiment.9	No	3	Out of River-133	4.3
Experiment.10	No	5	Out of River-133	4.3
Experiment.11	Yes	3	With River(Comp)-133	4.5
Experiment.12	No	1	Out of River(Comp)-133	4.5

Each experiment was designed to explore specific dimensions related to erosion and its effects. By manipulating the parameters in each dimension, we aimed to analyze the impact of different factors on erosion processes and subsequent outcomes. The selected dimensions represent key aspects relevant to the study, and their variations allowed us to observe and compare the effects of different conditions on erosion patterns and associated phenomena.

In the subsequent sections, we will delve into a detailed discussion and analysis of the results obtained from these comparative experiments, highlighting the key observations and drawing meaningful conclusions for the research study.

4.1.4 EXPERIMENT RESULTS

When conducting the aforementioned experiments using NetLogo, the following common characteristics were observed:

1. The model's runtime slows down when there is a large overall water volume and high rainfall rates. Conversely, when there is a prolonged period of zero rainfall and the water levels reach a state of equilibrium, the model's runtime speeds up.
2. The number of raindrops within individual pixels can affect the model's runtime, especially in a 67x67 model where there is a higher number of raindrops per pixel than 133x133 model. The model experiences noticeable slowdowns when handling continuous heavy rainfall.
3. As the rainfall intensity decreases, the growth of water levels may slow down or even decline. The specific outcome depends on the magnitude of the rainfall reduction. In the mentioned experiments, a sudden decrease in rainfall exceeding 2000 AssDrops led to a decline in water levels.
4. These characteristics provide insights into the behavior of the model under different rainfall conditions and shed light on the runtime performance of the simulation.

4.1.4.1 Experiment. 1

The 1st experiment is set as Erosion, one flow-times, and using WithRiver 133*133 resolution DEM.

In Experiment 1, Figure 13 clearly demonstrates the influence of precipitation rates on water levels. There are two significant increases in water levels observed during the simulation. The first increase occurs from 0 to 10 ticks, representing the first hour between 23:00 and 00:00 on April 27th. This period is characterized by heavy rainfall, leading to a notable rise in water levels. The second increase occurs from 300 to 363 ticks, representing the last half an hour between 10:00 and 10:30 on April 30th. This period experiences heavy rainfall, resulting in a significant surge in water levels. In contrast, the water levels remain relatively stable during intervals of less intense precipitation. Additionally, a gradual decrease in water levels is observed when rainfall diminishes and eventually ceases. During prolonged periods of no rainfall, the water levels reach a state of equilibrium. The highest recorded water level in the graph is 53, while the stable values in the middle range are around 14.

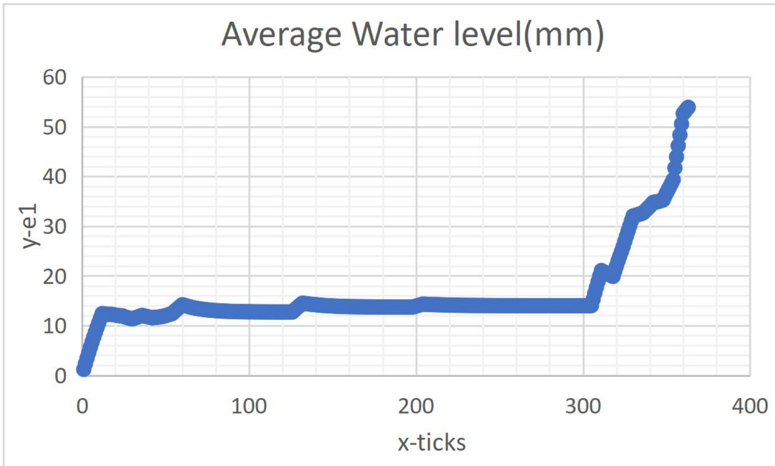


Figure 13 Average Water Level - Expe.1

The set of five binary maps accompanying the analysis depicts the spatial distribution of flooding. The initial three maps (Figure 14-a, b, c) represent the progression of flooding from the first day to the third day of continuous rainfall. Notably, after three days of uninterrupted rainfall, the floodwater engulfs a substantial portion of the study area. Subsequently, the Figure 14-d and Figure 14-e maps (shown in green) illustrate the incremental expansion of the flooded region. The flood extent experiences minimal growth between the first and second days, mostly limited to the river channel. However, a notable surge in flooding is observed from the second to the third day, resulting in an increased inundation across various areas.

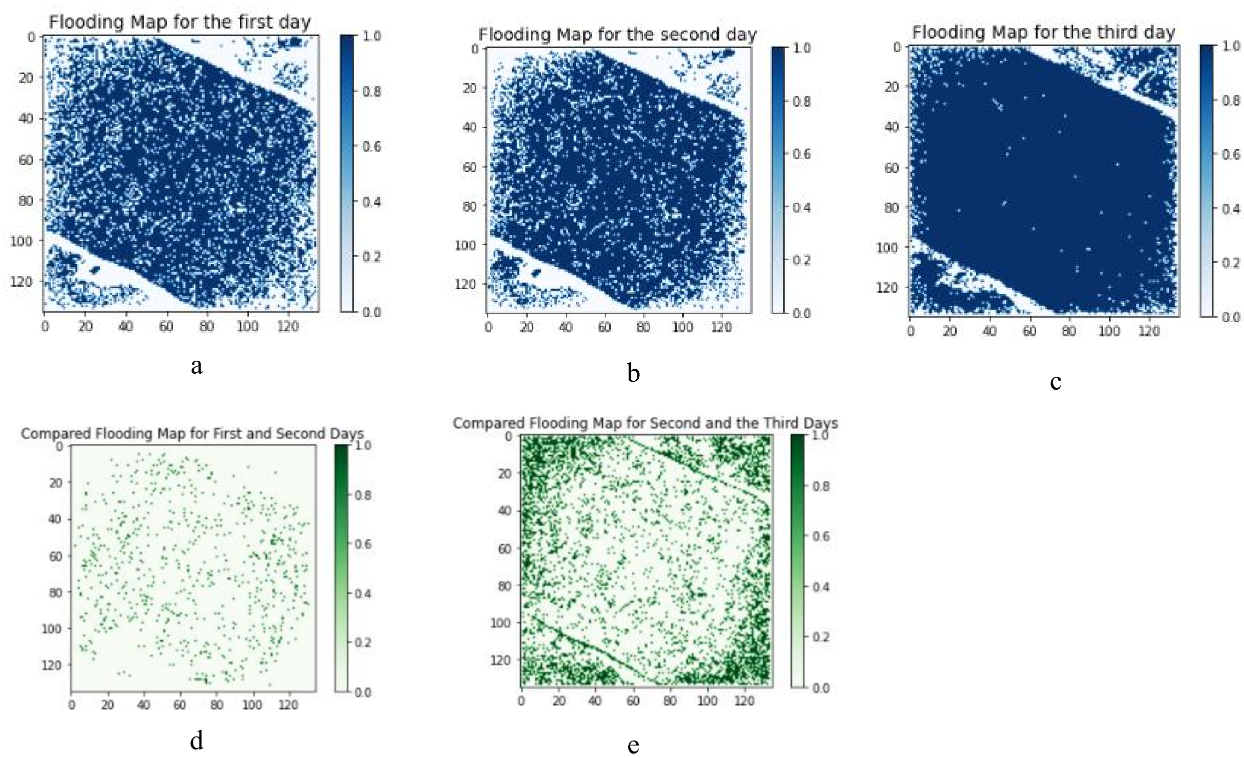


Figure 14 Flooding and Flooding Compared Maps - Expe.1

4.1.4.2 Experiment. 2

The 2nd experiment is set as No Erosion, one flow-times, and using WithRiver 133*133 resolution DEM.

In the second experiment, the point graph (Figure 15) and the two sets of binary graphs show similar results to experiment 1 (Figure 16). Therefore, a detailed description of these results is not necessary at this point. Subsequently, the forthcoming section on model comparisons will meticulously analyze these findings.

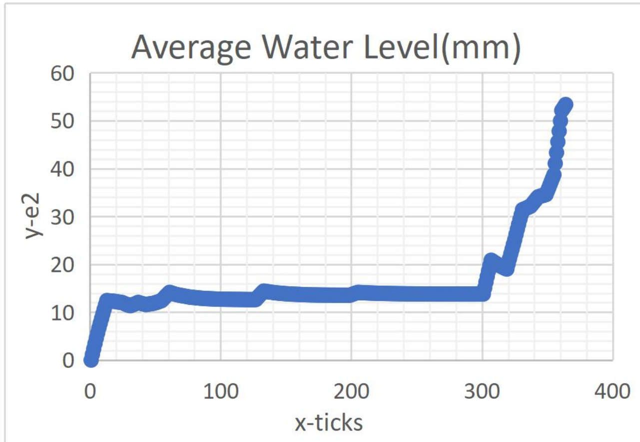


Figure 15 Average Water Level - Expe.2

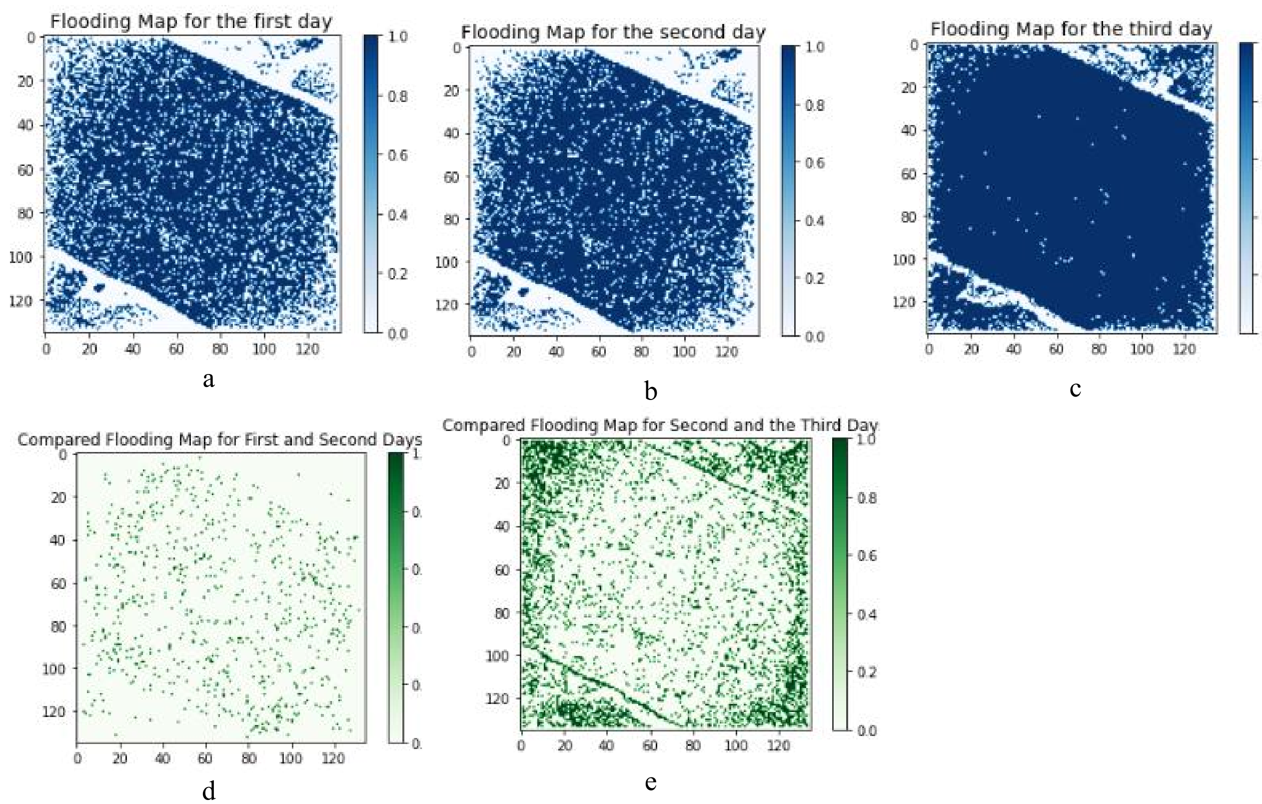


Figure 16 Flooding and Flooding Compared Maps - Expe.2

4.1.4.3 Experiment. 3

The 3rd experiment is set as Erosion, one flow-times, and using OutofRiver 133*133 resolution DEM.

In the third experiment, the changes observed in the line graph (Figure 17) are similar to those in the previous two experiments. However, there are some distinct variations in extreme regions, particularly after a prolonged period of zero rainfall, where the water level tends to stabilize. In addition, the highest recorded value in the graph is 58.04.

Regarding the binary maps, the initial three maps (Figure 18-a, b, c) depict the widespread flooding occurring after consecutive days of rainfall (on the third day). The floodwater inundates almost all geographical regions during this period. In contrast, Figure 18-d and e illustrate the progressive expansion of the flooded area. Minimal growth is observed between the first and second days, primarily confined within the river channel. However, a significant surge in inundation is evident from the second to the third day, with an increase in flood extent observed across various regions.

These observations demonstrate the consistent patterns in the line graph and the binary maps across different experiments. Further analysis and comparison of these results will be discussed in the subsequent section on model comparisons.

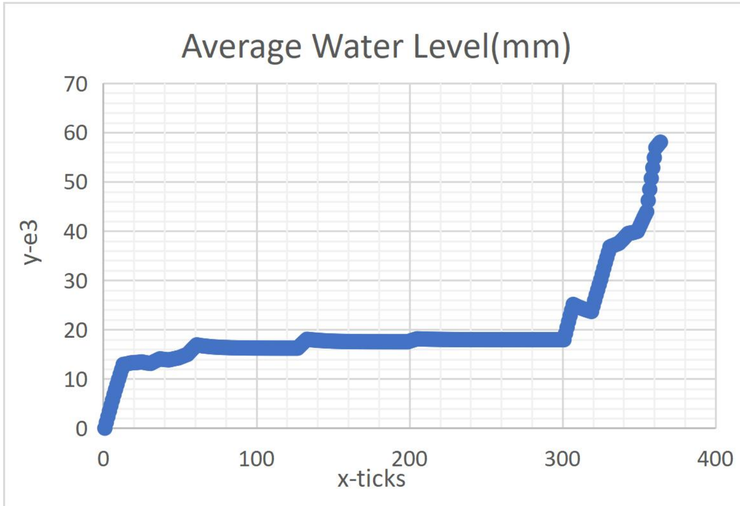


Figure 17 Average Water Level - Expe.3

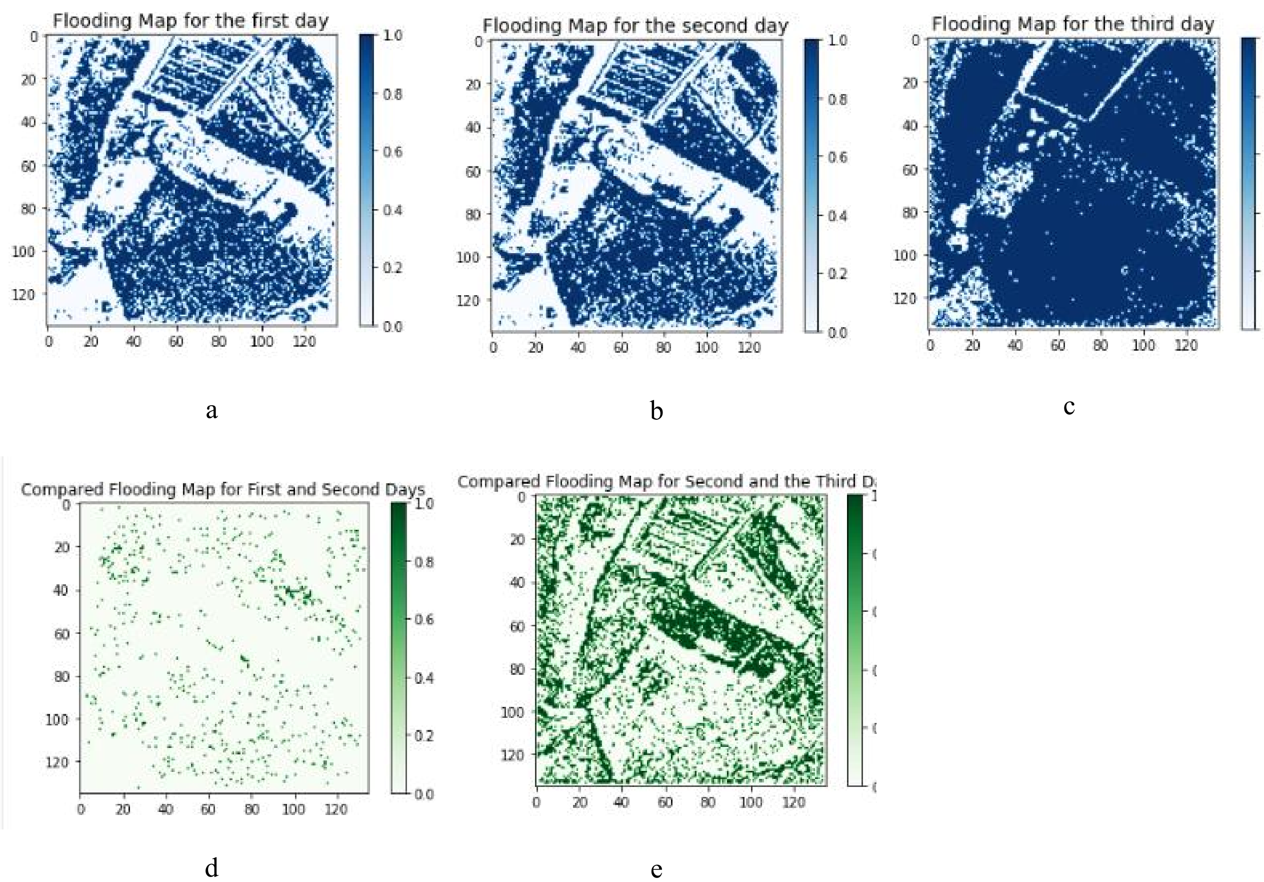


Figure 18 Flooding and Flooding Compared Maps - Expe.3

4.1.4.4 Experiment. 4

The 4th experiment is set as no Erosion, one flow-times, and using OutofRiver 133*133 resolution DEM.

The fourth experiment shows similar trends and results with experiment 1st in both Figures 19 and 20.

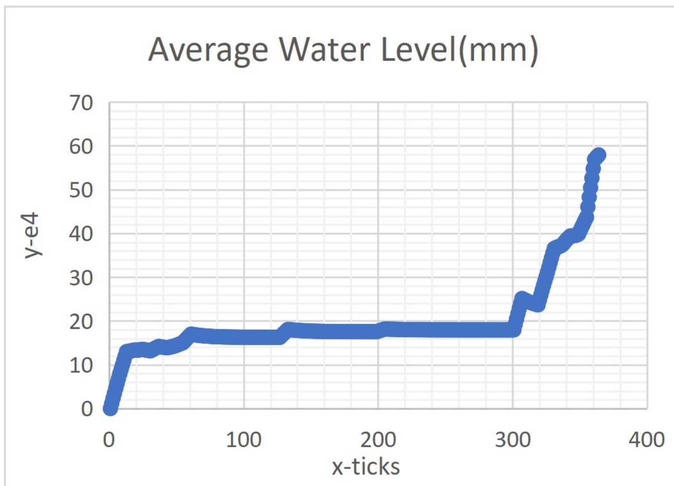
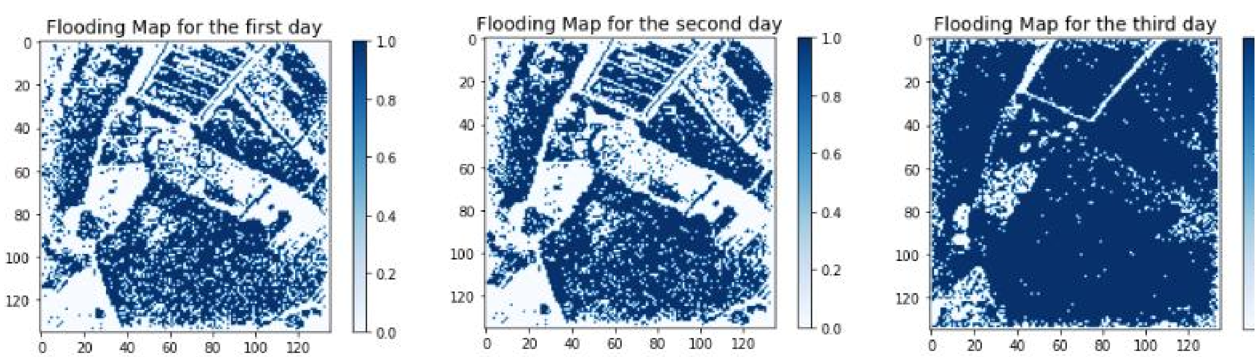
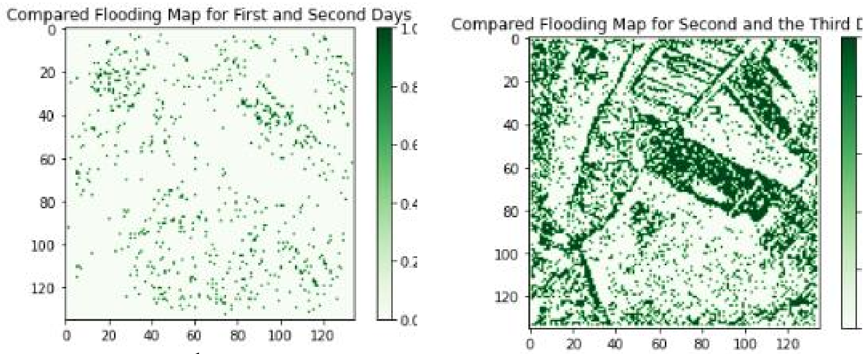


Figure 19 Average Water Level - Expe.4



a b c



d e

Figure 20 Flooding and Flooding Compared Maps - Expe.4

4.1.4.5 Experiment. 5

The 5th experiment is set as Erosion, three flow-times, and using OutofRiver 133*133 resolution DEM.

In the fifth experiment, there is a noticeable variation in the trend compared to the previous two experiments. Although two distinct phases of change are still observed (Figure 21), the intermediate phase no longer exhibits a slow and steady approach towards the changing values. Instead, the change occurs relatively quickly until it reaches a more gradual pace. Additionally, the highest recorded value in the line graph has decreased from 58.08 to 24.26. The value at the point of stabilization in the middle part of the graph is 13.

In terms of the binary graph, there are significant changes. In the first set of flooding maps, Figure 22-a and b, it can be observed that the flooding recedes on the second day, but experiences more notable expansion on the third day, as shown in Figure 22-c.

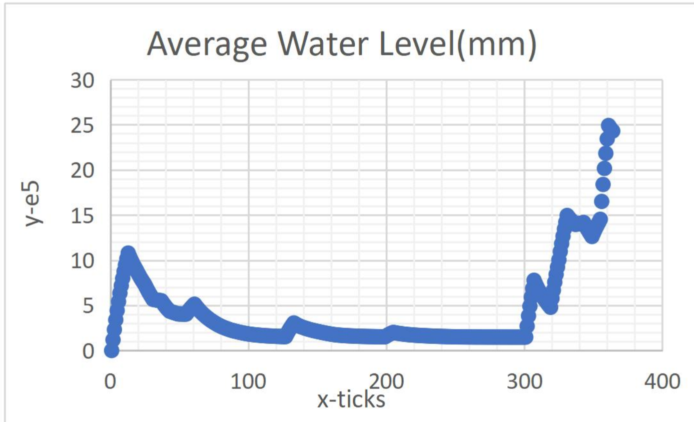


Figure 21 Average Water Level - Expe.5

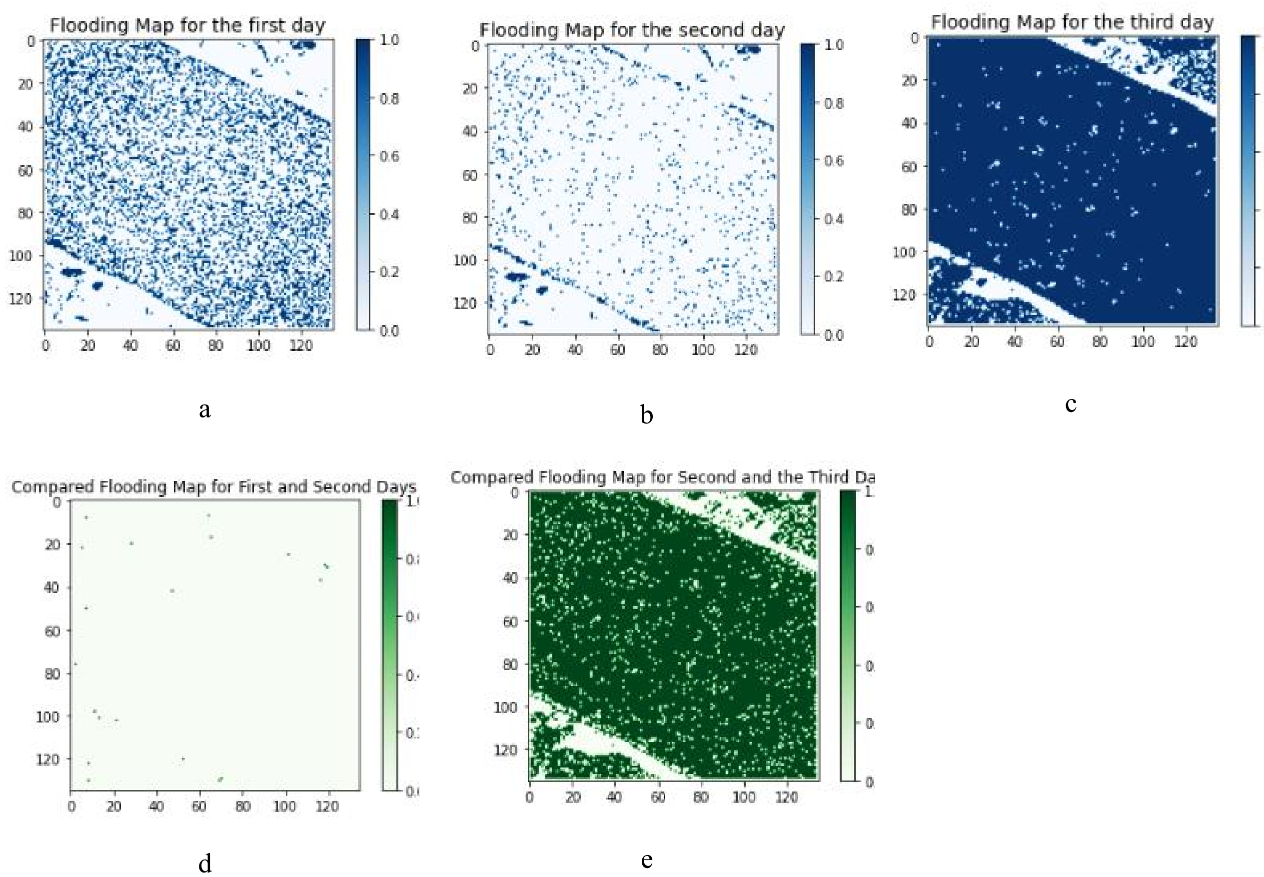


Figure 22 Flooding and Flooding Compared Maps - Expe.5

4.1.4.6 Experiment. 6

The 6th experiment is set as Erosion, three flow-times, and using WithRiver 67*67 resolution DEM.

The sixth experiment focuses on the results obtained under the same conditions as the fifth experiment when the resolution is changed to 67*67. It can be observed that the overall trend in Figure 23 remains consistent with the previous experiments. Furthermore, on the last day (Figure 24-c), flooding covered almost the entire area except for a small region in the top left corner. A more detailed comparative analysis will be presented in Section 4.4.

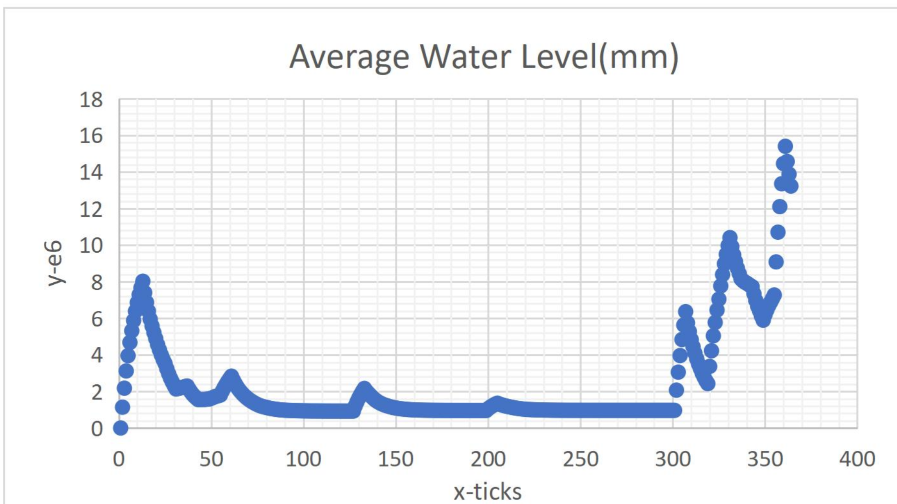
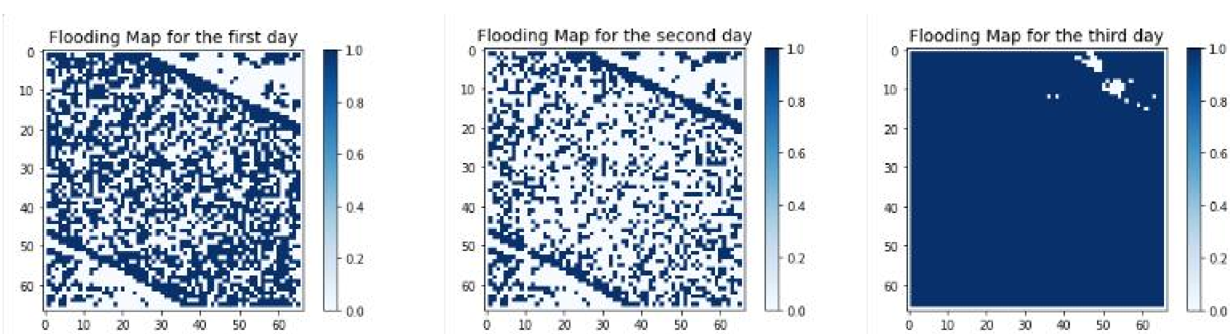
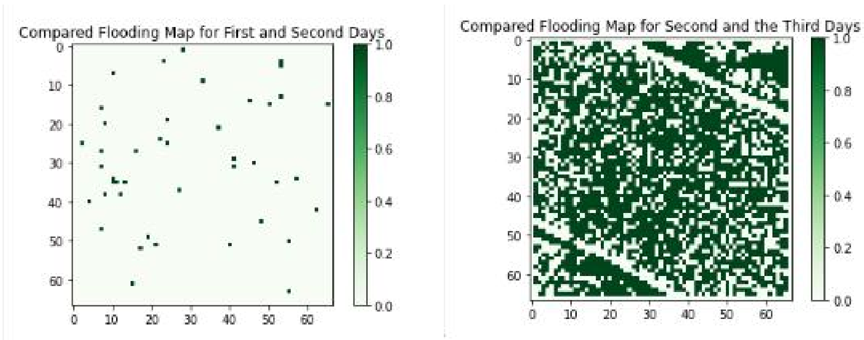


Figure 23 Average Water Level - Expe.6



a b c



d e

Figure 24 Flooding and Flooding Compared Maps - Expe.6

4.1.4.7 Experiment. 7

The 7th eexperiment is set as Erosion, five flow-times, and using WithRiver 133*133 resolution DEM.

In the seventh experiment, the overall trend in the line graph (Figure 25) and the changes in the binary graph (Figure 26) follow a similar pattern as the fifth experiment. The specific analysis of these aspects will be presented in Section 4.3 of the model comparison.

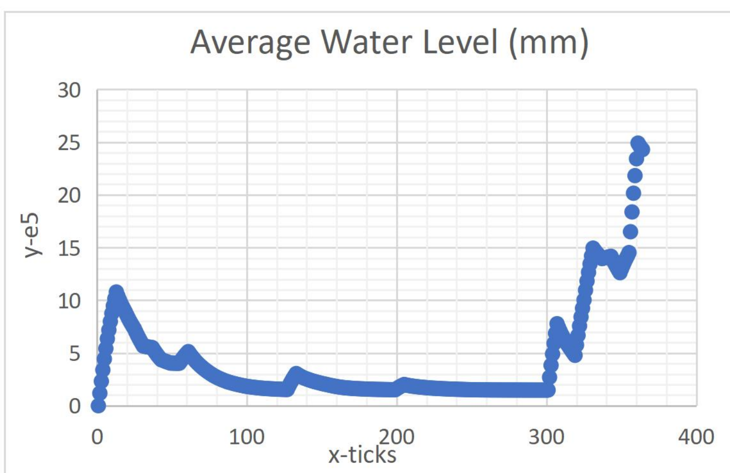


Figure 25 Average Water Level - Expe.7

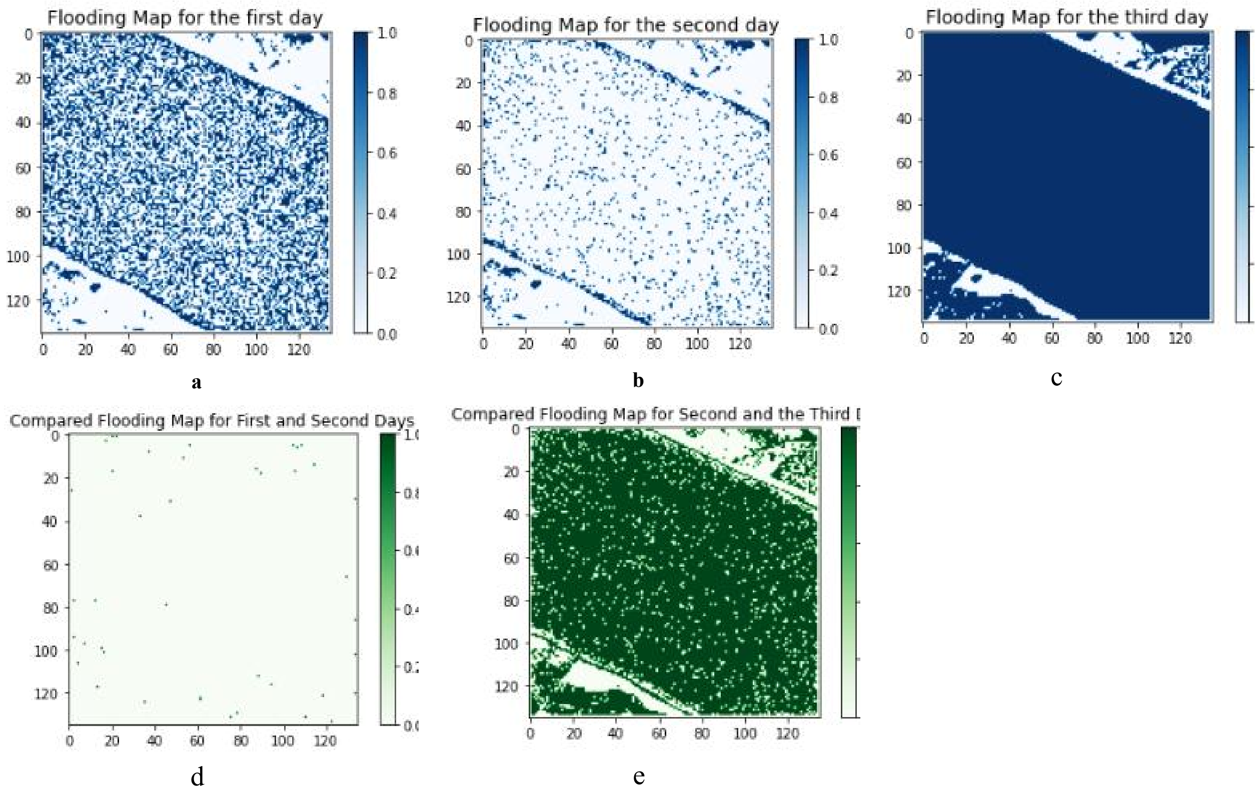


Figure 26 Flooding and Flooding Compared Maps - Expe.7

4.1.4.8 Experiment. 8

The 8th experiment is set as No Erosion, three flow-times, and using OutofRiver 67*67 resolution DEM.

In the eighth experiment, the focus is on the results obtained when the resolution is changed to 67x67 under the same conditions as the fourth experiment. The overall trend in the chart (Figure 27) is similar to that of the fourth experiment (Figure 19). Further analysis and comparison will be presented in Section 4.4.

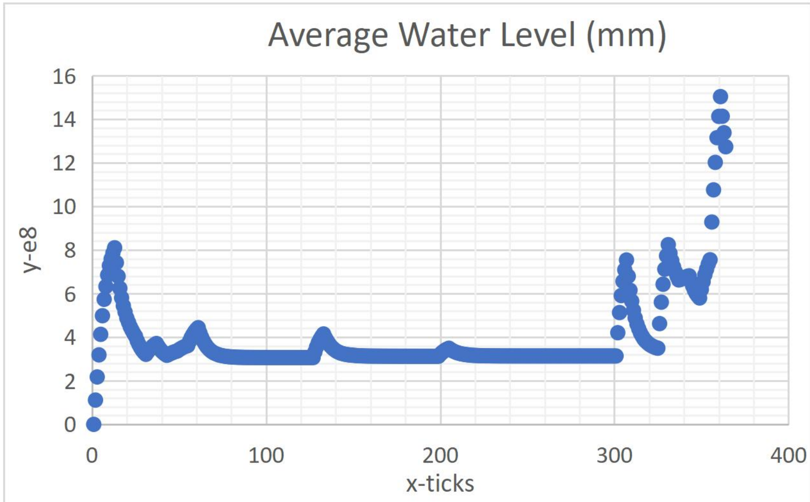


Figure 27 Average Water Level - Expe.8

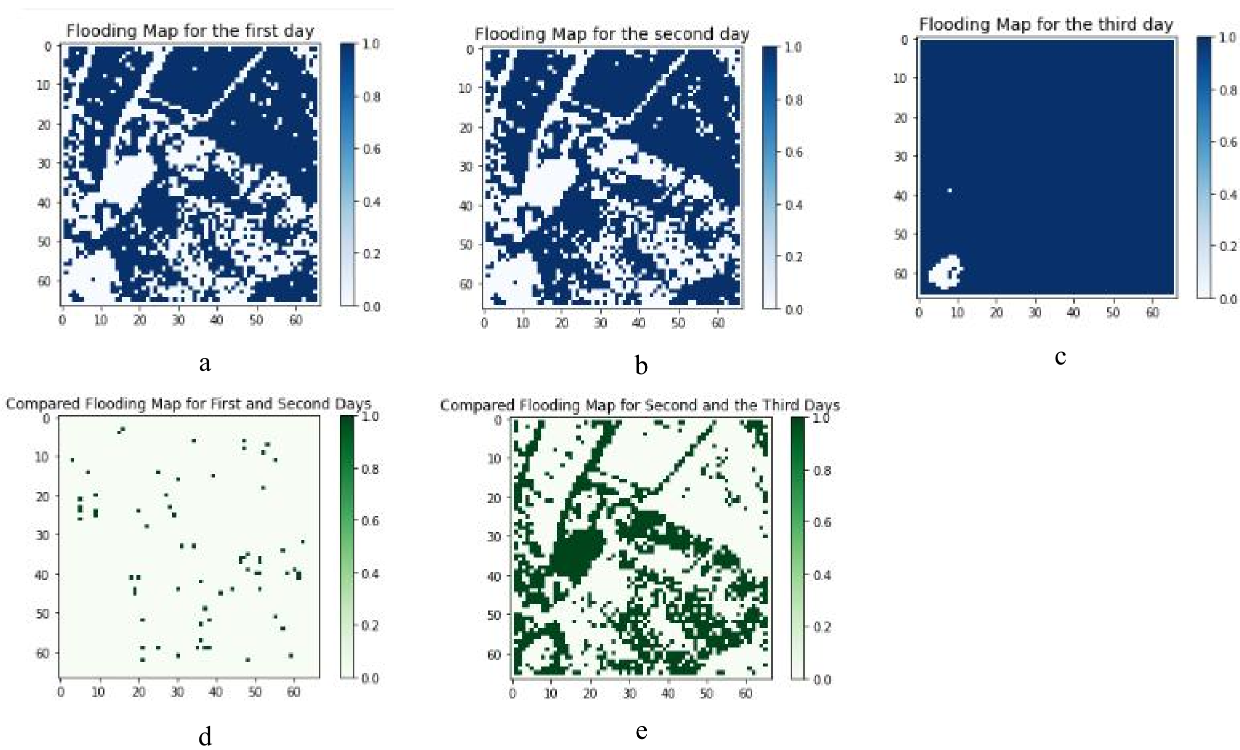


Figure 28 Flooding and Flooding Compared Maps - Expe.8

4.1.4.9 Experiment. 9

The 9th Experiment is set as No Erosion, three flow-times, and using OutofRiver 133*133 resolution DEM.

In the ninth and tenth experiments, the changes observed in the line graphs (Figure 29, 31) exhibit a similar trend to the third and fourth experiments. There is no significant variation observed as in the fifth and seventh experiments. A detailed comparison of these results will be presented in Section 4.3.

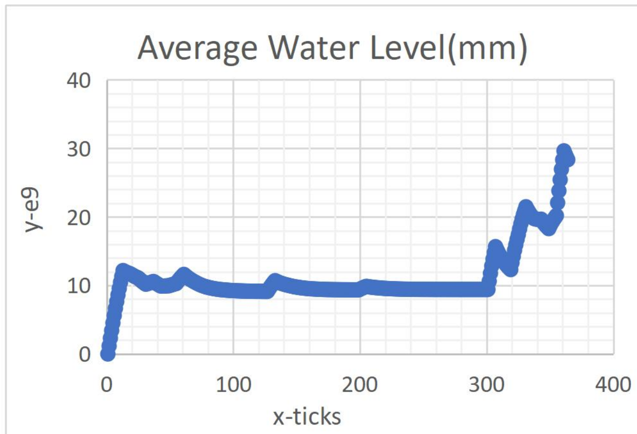


Figure 29 Average Water Level - Expe.9

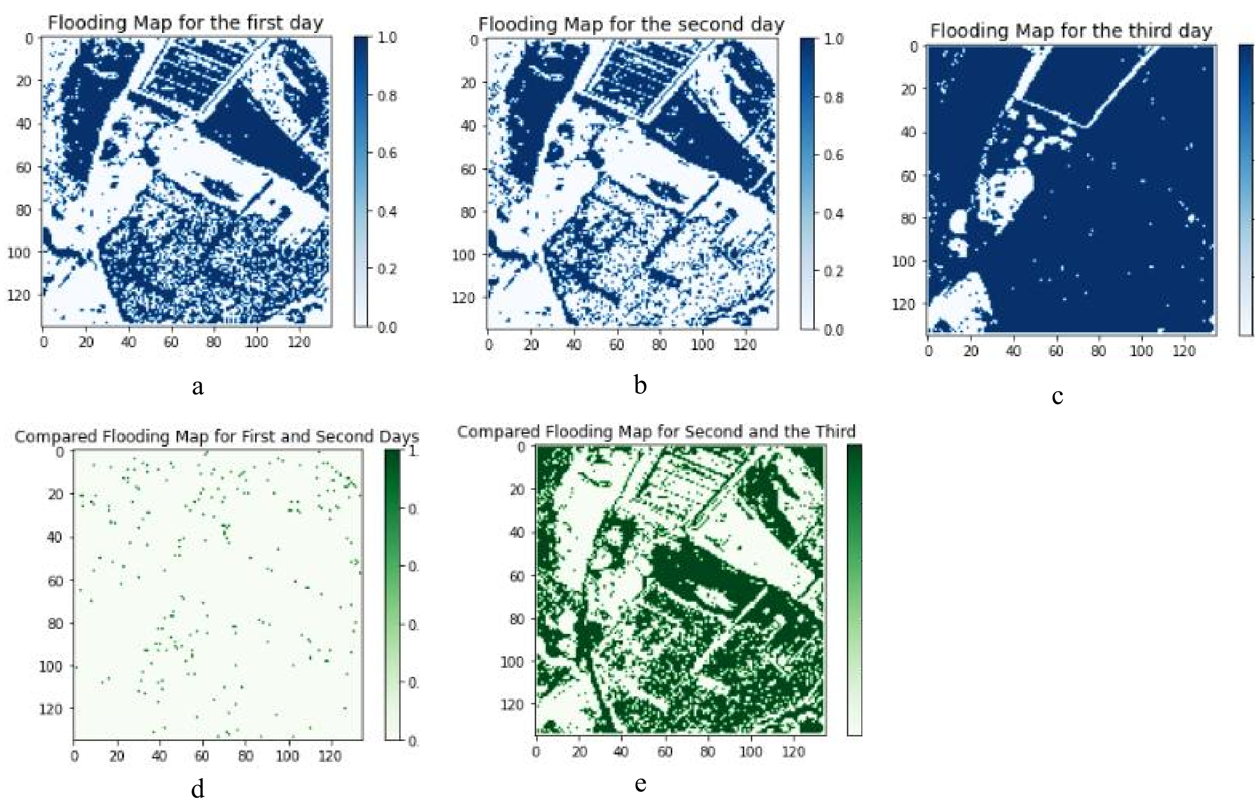


Figure 30 Flooding and Flooding Compared Maps - Expe.9

4.1.4.10 Experiment. 10

The 10th experiment is set as No Erosion, five flow-times, and using OutofRiver 133*133 resolution DEM. The results are shown in Figure 31 and 32.

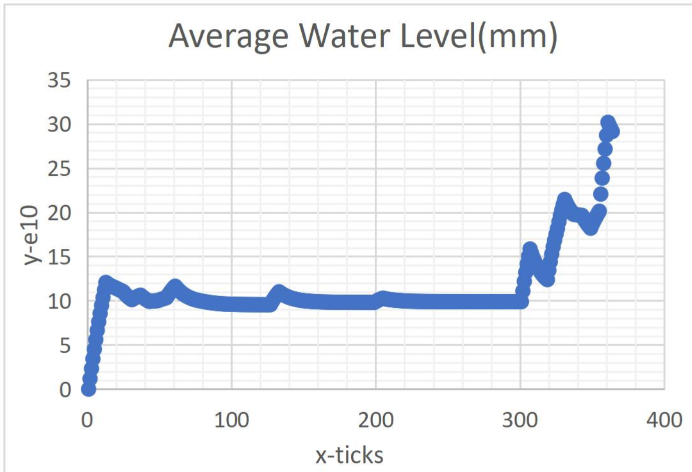


Figure 31 Average Water Level - Expe.10

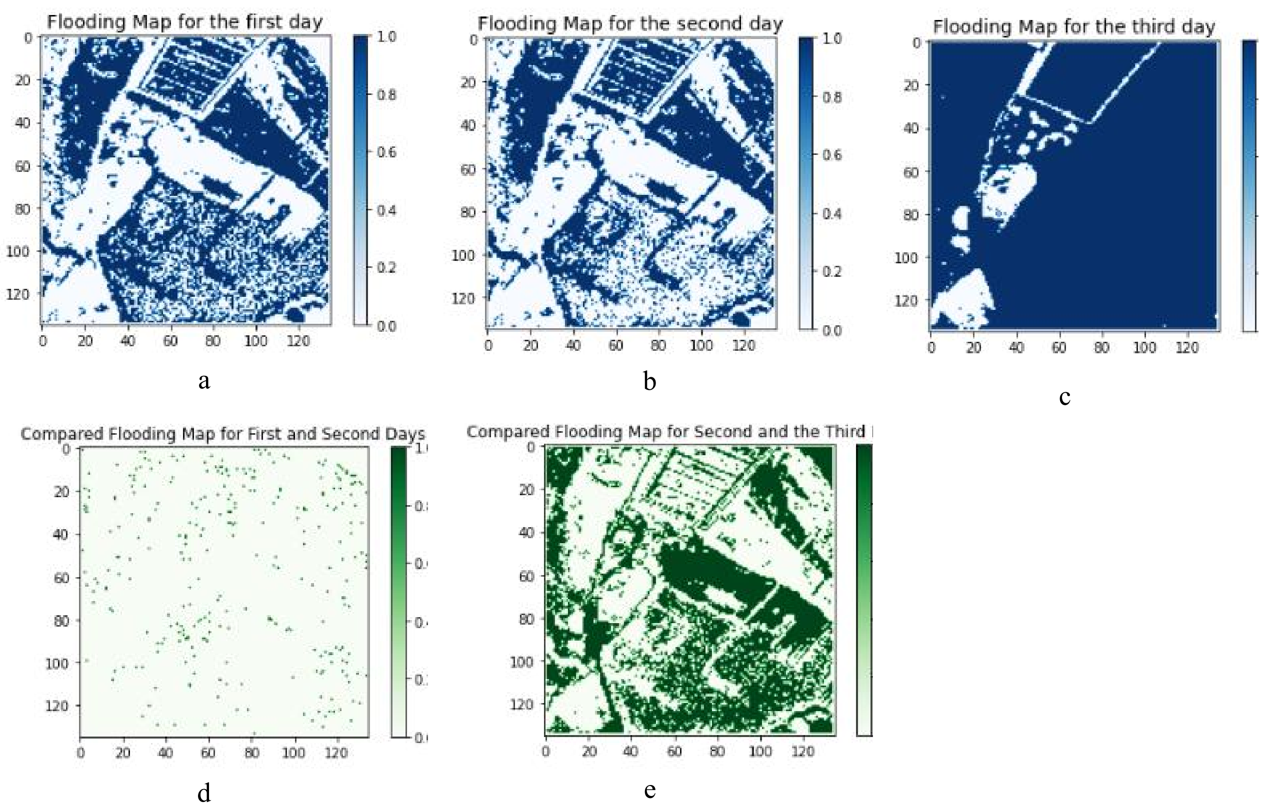


Figure 32 Flooding and Flooding Compared Maps - Expe.10

4.1.4.11 Experiment. 11

The 11th experiment is set as Erosion, three flow-times, and using With River Compared 133*133 resolution DEM. The results are shown in Figure 33 and 34. In addition, experiments 11 and 12 will not be individually described in this section as these provide the validation results for the discussed model settings in Sections 4.2, 4.3, and 4.4. Instead, the results of them will be discussed and analyzed in detail in Section 4.5 as part of model validation.

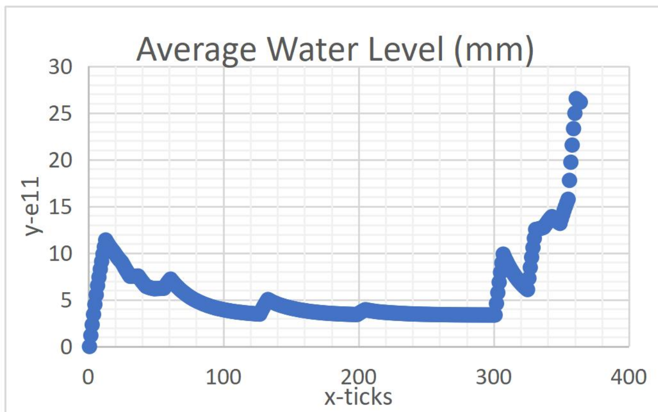


Figure 33 Average Water Level - Expe.11

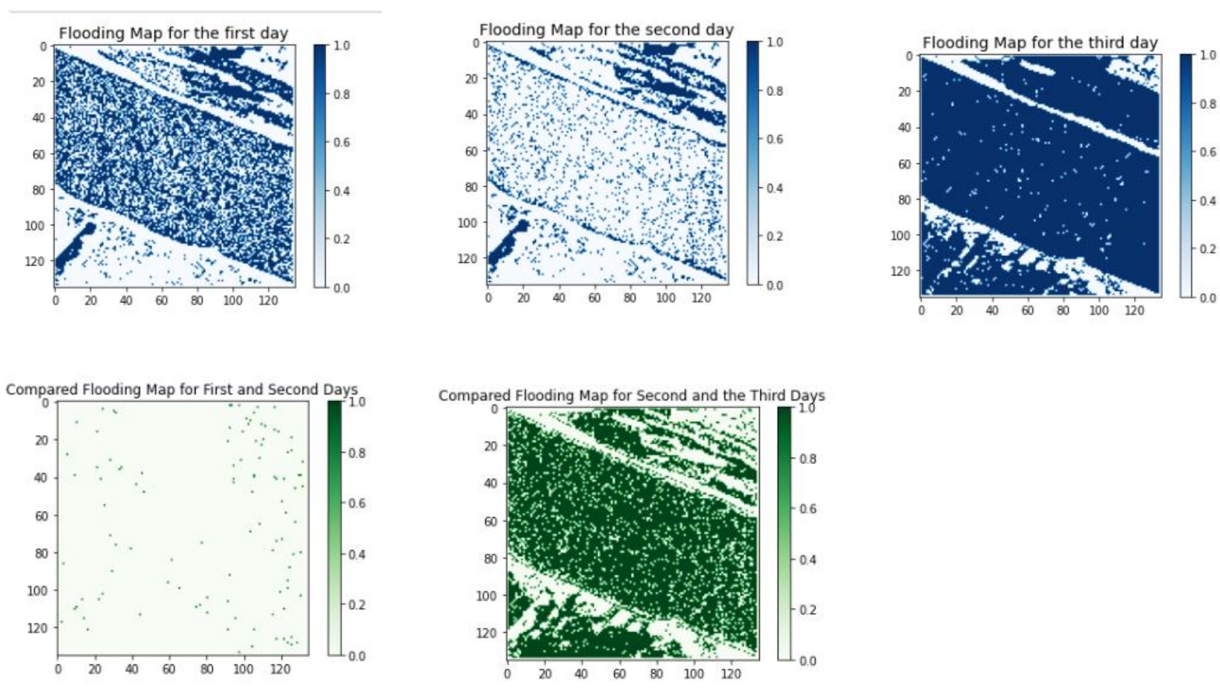


Figure 34 Flooding and Flooding Compared Maps - Expe.11

4.1.4.12 Experiment. 12

The 11th experiment is set as No Erosion, three flow-times, and using Out of River Compared 133*133 resolution DEM. The results are shown in Figure 35 and 36.

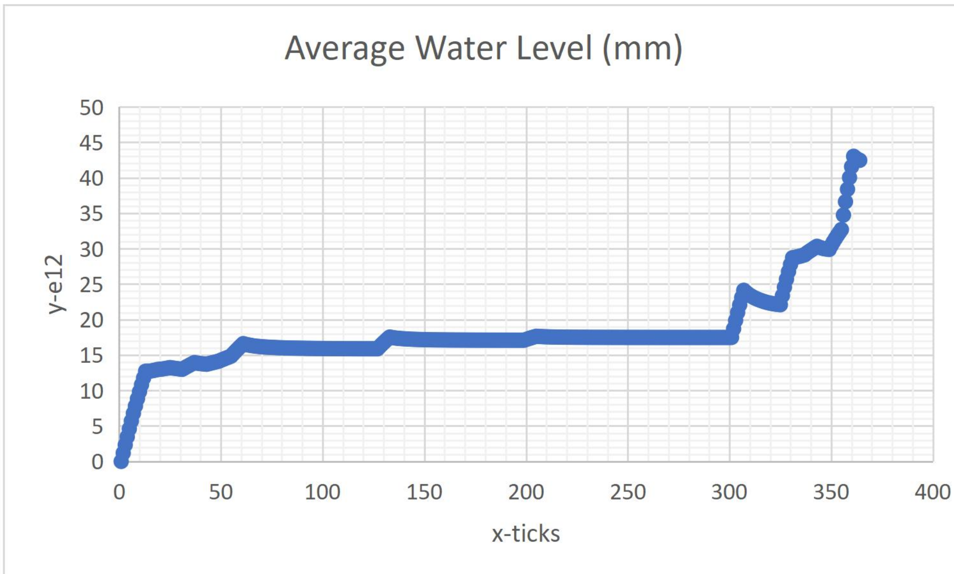


Figure 35 Average Water Level - Expe.12

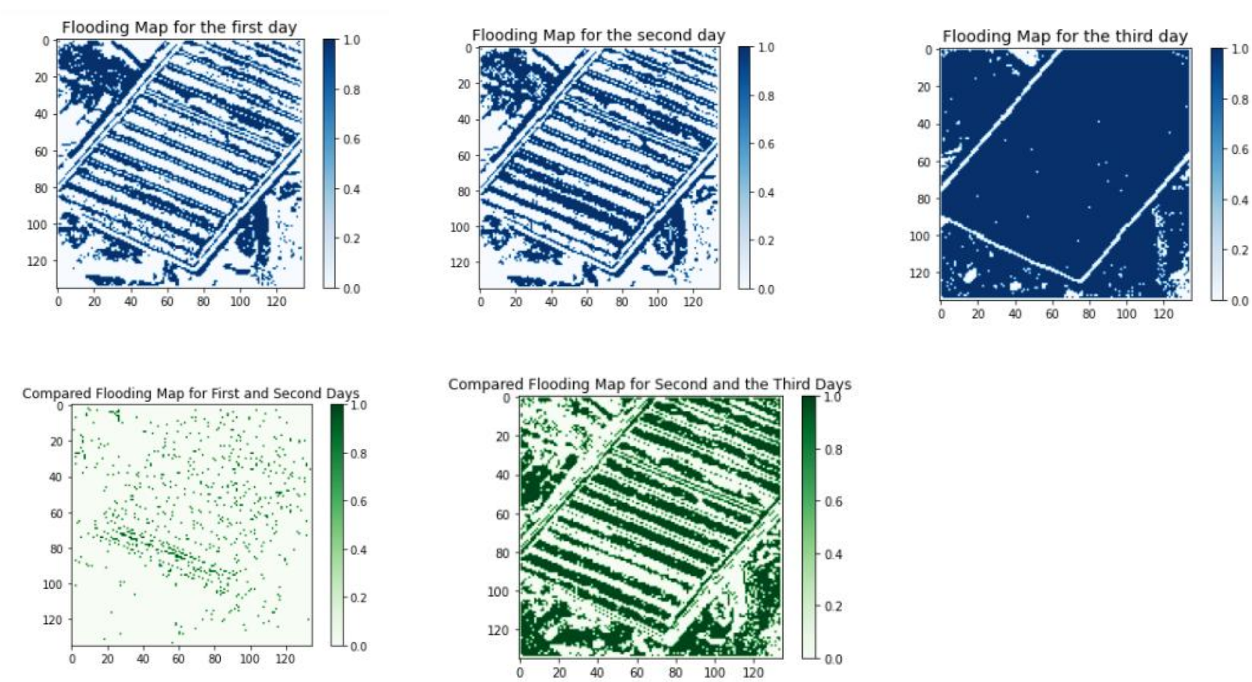


Figure 36 Flooding and Flooding Compared Maps - Expe.12

4.2 Compared Models for Erosion and Not Erosion

To assess the impact of erosion, we kept the flow-times parameter constant throughout the experiments. Additionally, since the rainfall locations are randomized in each simulation, directly comparing the number of raindrops retained in each pixel would not provide meaningful insights. For example, the following figure (Figure 37) compares the water level differences at each position between erosion and no erosion, where black indicates an increase, white indicates a decrease, and gray indicates no change. It is evident from the figure that there is no discernible pattern in the variations. However, in order to examine the influence of different environmental conditions, we introduced the comparison of average water levels.

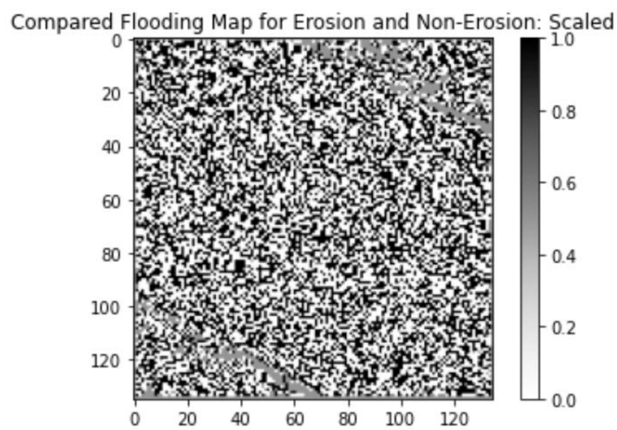


Figure 37 Sample Compared Water Differences Maps

4.2.1 WITH RIVER AREA

The comparative line graph, Figure 38, shows that, in most stages, the results with and without erosion overlap with each other. In addition, we find that the average values during rainfall periods are slightly lower when erosion is enabled compared to when erosion is disabled. However, during periods of no rainfall, the average values with erosion are slightly higher than those without erosion.

Although erosion did not significantly affect the results in this particular experiment, it is important to consider erosion in real-world scenarios, especially within river channels where sediment transport is inevitable. The lack of visible erosion effects in the experiment may be attributed to the relatively low number of flow iterations (flow-times).

To better align with real-world conditions, we recommend keeping the erosion option enabled and will enable it in the subsequent analysis of the "with river" scenario. This will allow us to explore the impact of erosion on the simulation results and provide a more comprehensive understanding of the dynamics within river areas.

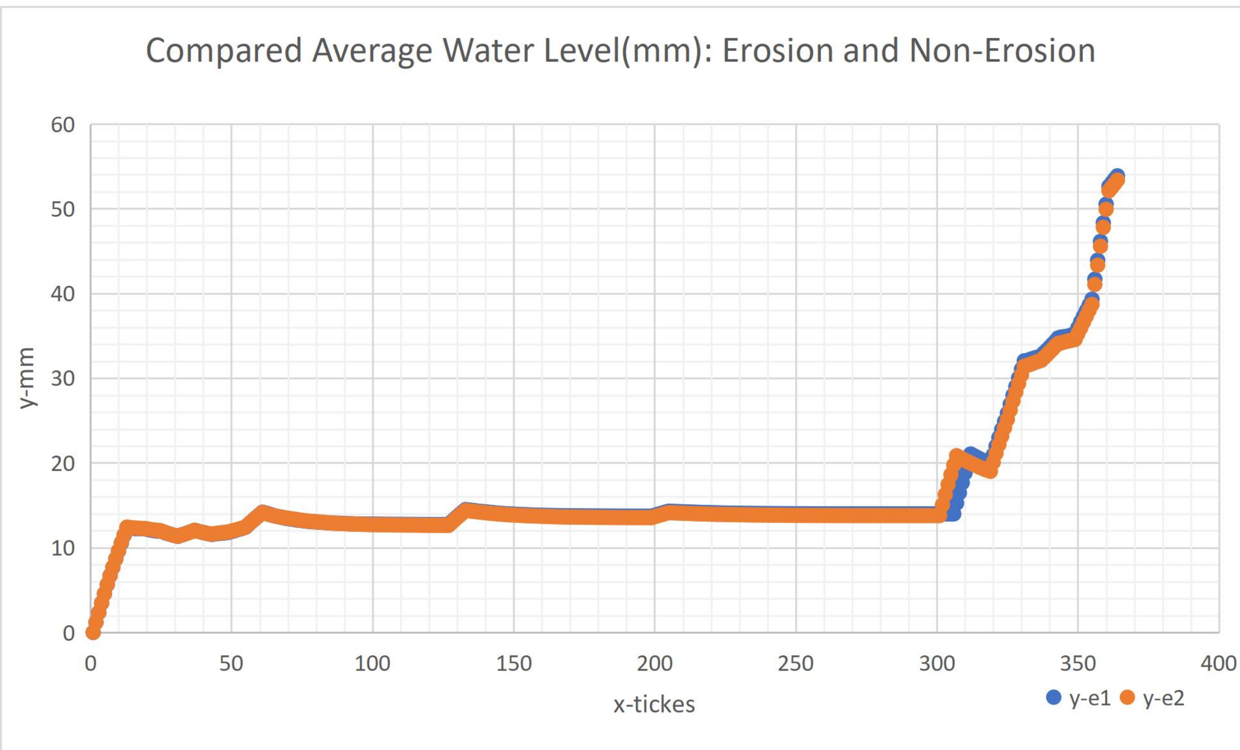


Figure 38 Compared Average Water Level for Erosion and Non-Erosion for With River Area

4.2.2 OUT OF RIVER AREA

From the comparison line chart (Figure 39), we can observe that the results with and without erosion almost completely overlap. This indicates that the erosion parameter has a minimal effect on areas without rivers. Furthermore, considering the practical context, research areas without rivers, especially highly urbanized areas with significant surface hardening, are less likely to experience erosion. Therefore, we recommend using the "No Erosion" setting for areas without rivers.

In subsequent analyses, we will apply the "No Erosion" parameter to areas without rivers to align with real-world conditions and acknowledge the limited erosion potential in such regions.

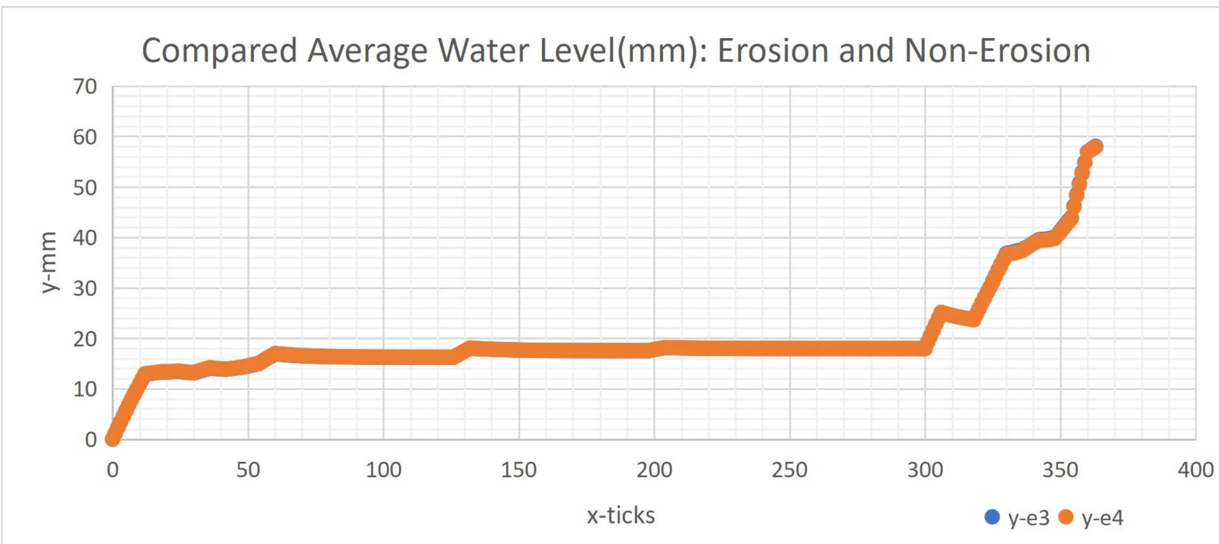


Figure 39 Compared Average Water Level for Erosion and Non-Erosion for Out of River Area

4.3 Compared Models for Different Flow-times

To further investigate the impact of erosion, it would be beneficial to observe the results with higher flow-times values. We conducted tests using flow-times values of 1, 3, and 5. From the results, it can be observed that for flow-times values of 3 and 5, the changes in water level are nearly identical in both the With River (Figure 40) and Out of River (Figure 41) areas. However, when flow-times is set to 1, there are significant differences compared to the other two values. Nevertheless, the overall trend remains the same across all three flow-times values.

To determine the appropriate flow-times value in this model, we consider a comparison with the actual flooding situation. Firstly, based on the actual daily precipitation, a flow-times value of 1 results in precipitation within a single day that is much higher than the reported 24.8mm. Therefore, we focus on flow-times values of 3 and 5.

When flow-times is set to 5, the model requires a longer runtime due to the increased number of iterations performed in each simulation. However, both the tabulated results and the graphical representations show similar performance between flow-times values of 3 and 5. Consequently, we conclude that a flow-times value of 3 is preferable.

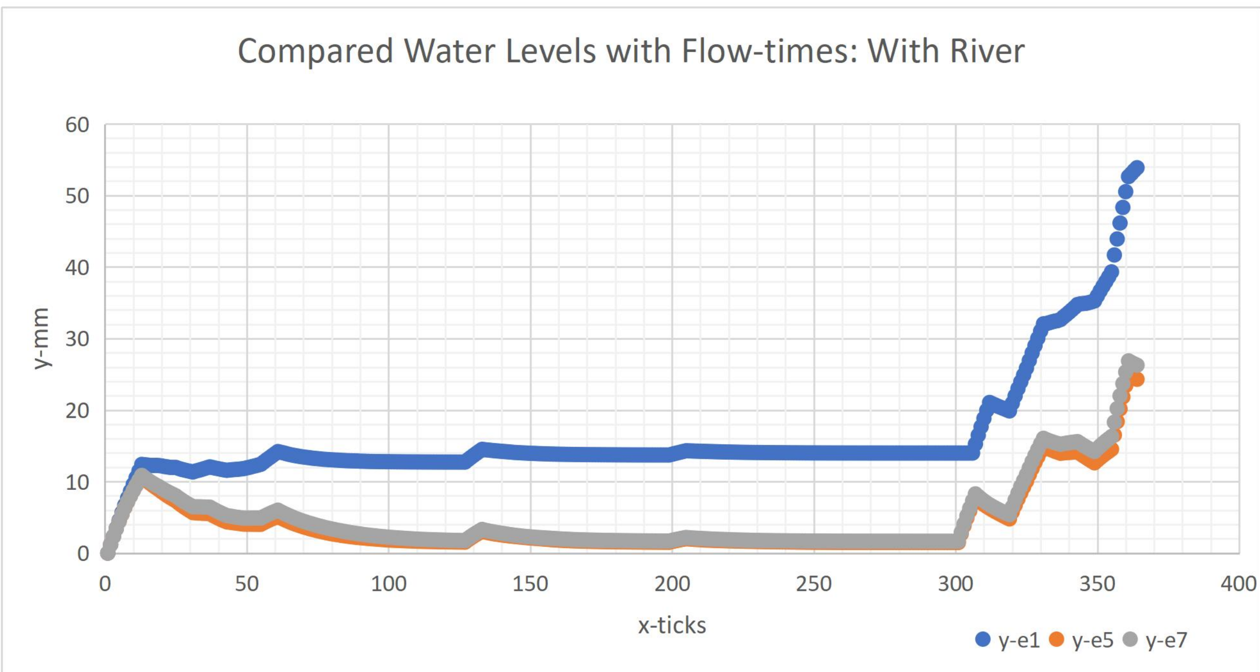


Figure 40 Compared Water Levels with Flow-times for With River Area

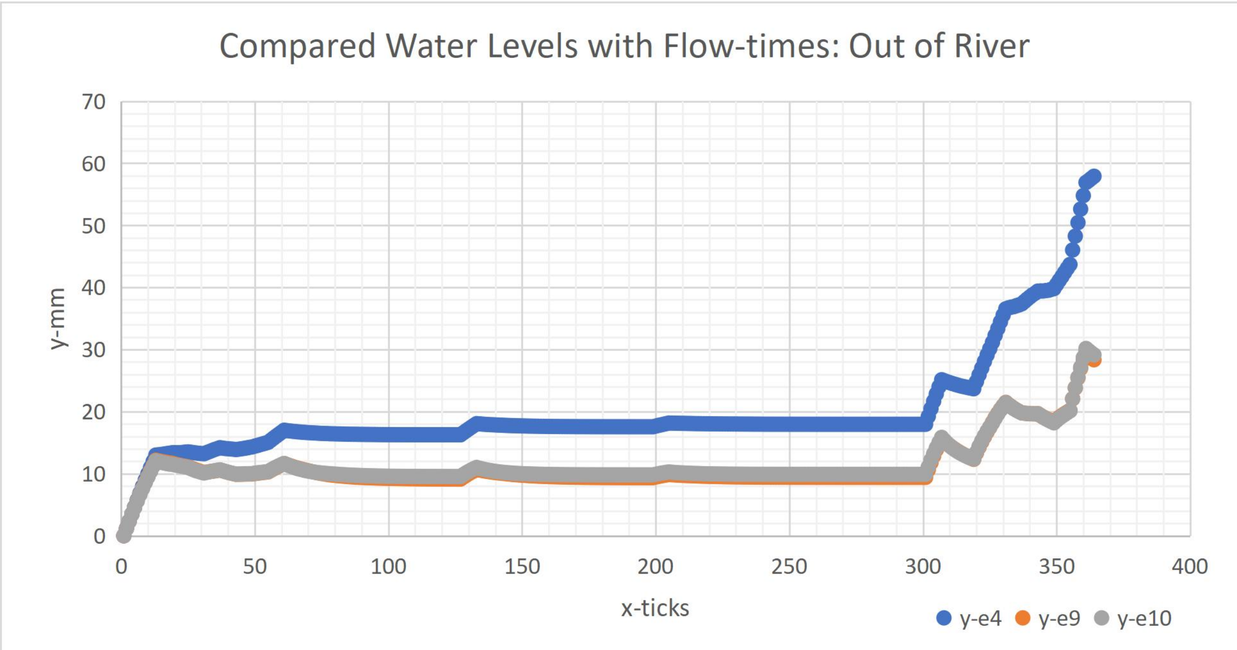


Figure 41 Compared Water Levels with Flow-times for Out of River Area

4.4 Compared Models for Different Resolutions & Historical Data

4.4.1 WITH RIVER AREA

Based on the presented comparative graph (Figure 43), it can be observed that at lower resolutions, the Average water level data is more concentrated with smaller variations. Additionally, the results indicate that at lower resolutions, the estimated water accumulation within the region is also reduced, approximately half of the value obtained at higher resolutions. This can be attributed to the fact that with a decrease in overall resolution, the number of water droplets within each pixel increases. Furthermore, the total pixel area along the edges doubles compared to the previous scenario. Consequently, the number of water droplets in the edge regions increases, leading to a doubling of water loss due to runoff.

Comparing the real precipitation data (Canada, 2023), it is observed that the cumulative precipitation on the second day is 2.8mm, while the precipitation for the entire third day is

24.8mm. Both of these values are closer to the results obtained at a resolution of 137x137, which corresponds to the higher resolution.

Furthermore, compare the flooding changes results of Experiment 5 (Figure 42b) and 6 (Figure 42c) with the actual occurrence of flooding, shown in Figure 42a. In reality, all areas were submerged by floodwaters on the second day, while the initial flooded area on the first day is shown in the pink region in Figure 42-a. The additional flooding area on the second day is represented by the green region. In reality, the entire region is flooded on the last day, which is more closely reflected by the low-resolution results rather than the high-resolution ones. This is because at lower resolutions, the fine details of flooding within each pixel are overlooked, and instead, an overall representation of the total flooding situation is displayed. When comparing the changes in the flooded areas between the two days, there is not a significant difference between the high and low-resolution results, and both show some degree of deviation from the specific areas observed in reality. As an example, in the displayed results, the top-right corner of the area gets flooded only on the second day, indicating that this region is relatively more resistant to flooding. Meanwhile, in our model simulation process, the right-top corner remains unflooded throughout the entire duration.

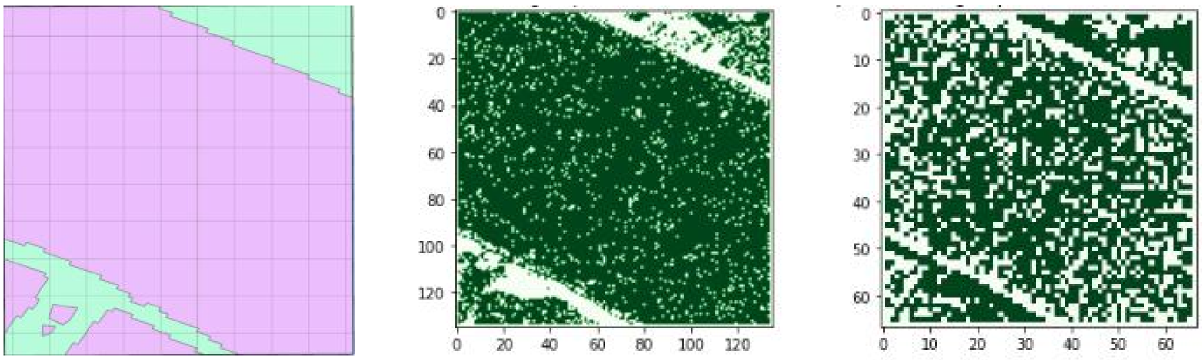
Additionally, in our analysis, we found that another potential source of error, despite accurate precipitation patterns and the accuracy of flooding results on the final day, could be the specific selection of time nodes for analyzing flooding. Although we obtained the above data based on the time nodes recorded in historical flooding data, there may be inaccuracies in the timing of those records. This analysis applies to both high-resolution and low-resolution results, as well as for the areas outside the river.

In the construction and practical application of models, the relationship between computational cost and the chosen resolution is indispensable. High resolution can offer us more detailed and precise data on water levels and precipitation distribution. However, this also signifies a higher computational burden. These high-precision data are invaluable in analyses but simultaneously demand more potent computational capabilities for processing. In certain applications requiring real-time feedback or in environments where computational resources are limited, high resolution might slow down the model's operation or even fail to meet the anticipated real-time response criteria. On the other hand, lower resolutions, though potentially lacking in data detail compared to high resolutions, are computationally much swifter.

Additionally, during the model operation, we continuously adjust the rainfall rate, making it challenging to provide a specific computational cost value. Based on experience, each model run at high resolution generally takes about two to four times longer than its low-resolution counterpart. This specific duration is further influenced by the rainfall rate, adding another layer of complexity to the calculations.

Based on the comprehensive analysis above, we can conclude that higher resolution is more accurate in capturing the spatial distribution of precipitation in areas with rivers, resulting in better alignment with the actual cumulative precipitation amounts. The finer details and localized variations captured at higher resolution may contribute to a more precise representation of the total precipitation.

It is important to note that these findings are specific to the comparison of cumulative precipitation amounts and the given scenario. Different factors and conditions may affect the relationship between resolution and accuracy in other aspects of the analysis.



A Reality Changes B 133*133 Changes C 67 * 67 Changes

Figure 42 Compared Flooding Changes for With River Area

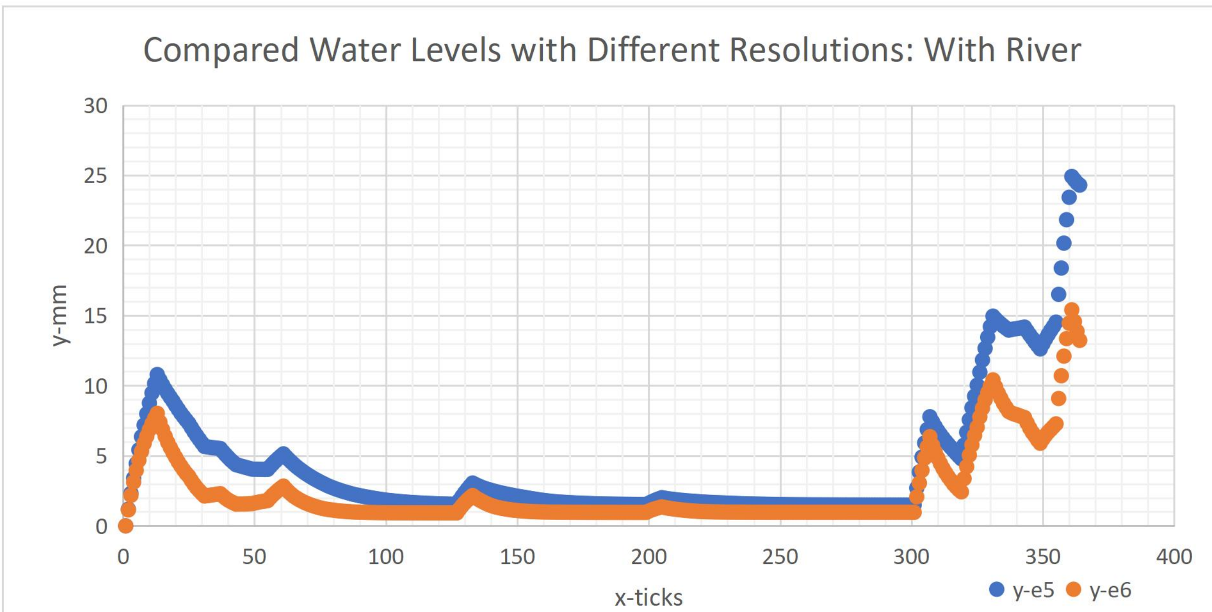


Figure 43 Compared Water Levels with Different Resolutions for With River Area

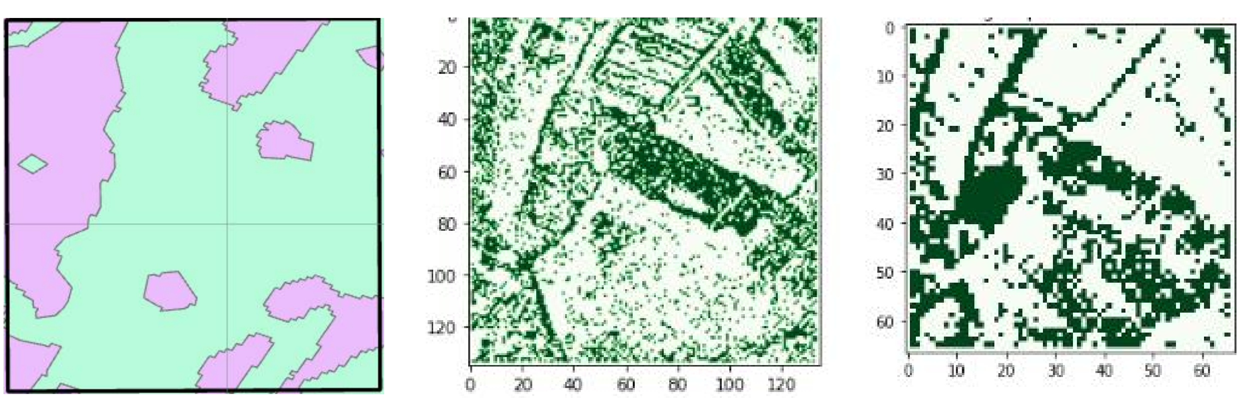
4.4.2 OUT OF RIVER AREA

In the Out of River and With River regions, both resolutions exhibit certain similarities and differences when compared to the actual flooding situation. In the case of low resolution, the simulation suggests that almost the entire area experiences flooding on the final day. Additionally, the flooding area appears more concentrated in the low-resolution simulation with the comparison of Figure 44b and 44c. However, both simulations and the actual flooding show some overlap in the expanding flood areas, although with noticeable differences.

Analyzing the changing trends of average water levels, as shown in Figures 43 and 45, in both simulations, we observe a remarkable similarity. Comparing the data, a clear multiple relationship can be observed, particularly after the initial period of concentrated rainfall, where the water level demonstrates a doubling effect.

It is worth noting that in comparison to the actual daily precipitation (24.8mm), the simulation conducted at the higher resolution (e9) yields results that are closer to the final outcome. Therefore, similar to the With River model, it is advisable to choose a higher resolution for conducting simulations.

Considering these factors, it is important to acknowledge that simulations can provide valuable insights, but they may not perfectly replicate real-world flooding events due to the inherent complexities of the physical processes involved. Further research and calibration, along with incorporating real-world data, are necessary to enhance the accuracy and reliability of flood predictions.



A Reality Changes   B 133*133 Changes   C 67 * 67 Changes

Figure 44 Compared Flooding Change for Out of River Area

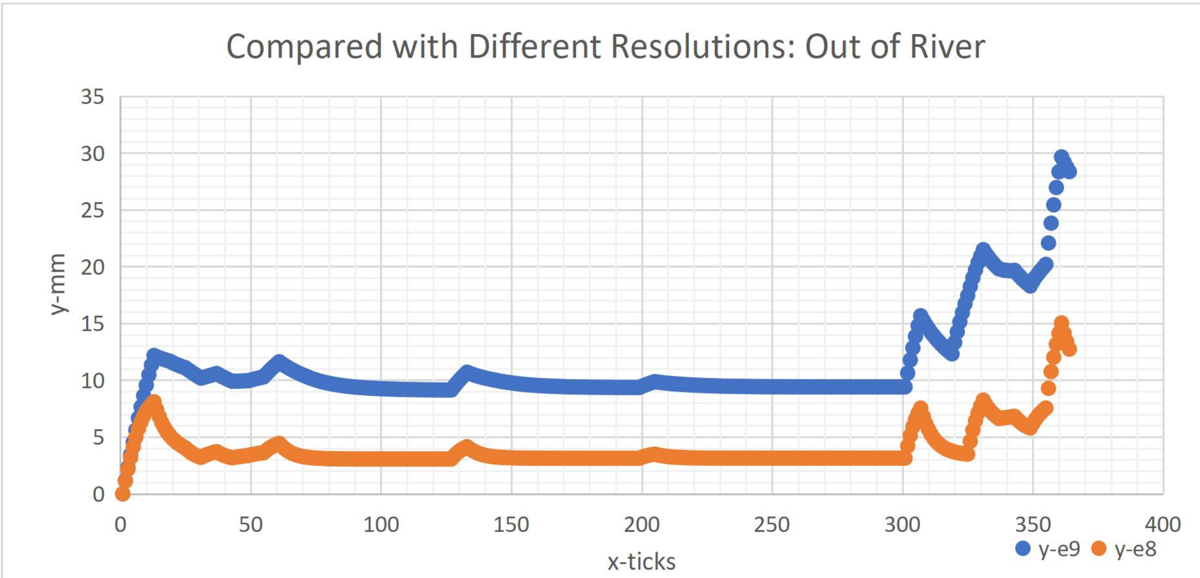


Figure 45 Compared Water Levels with Different Resolutions for Out of River Area

4.5 Final Model Validation using Comparable Study Area

Based on Figures 34e and 36e, we can observe a sharp increase in flooding, which is similar to the results obtained in previous experiments. Additionally, when comparing Figures 34e, 36e and 46, we can observe a discernible pattern in the overall growth of the flooding area. Furthermore, based on the average water level data recorded in Figure 34 for the with river area, the final water level reached 26.15mm. Comparing this with the water level from the previous day, which was 3.37mm, the difference of 22.88mm is similar to the average daily rainfall of 24.8mm in that area. In addition, the first two days of precipitation are both close to the historical records. Therefore, we consider this simulation to be reasonably accurate from the perspective of analyzing precipitation. However, it is evident that if we examine the growth of water levels for each individual pixel, the data may not be sufficiently accurate. In addition, the performance of simulation in the Out of River compared area is worse than the previously mentioned one. Although Figure 35 also presents a difference of 24.98mm, which is close to the historical data.

The average precipitation reaches 15.48mm, which is much higher than 2.2mm in the record. This discrepancy could also be attributed to the specific selection of time points, as mentioned in previous experiments.

A With River B Out of River

Figure 46 Historical Flooding Map for comparable Study Area

4.6 Chapter Summary

This chapter provides a comprehensive overview of the experiments conducted, presenting the results obtained and offering insightful discussions on various aspects of flood simulation. The findings contribute to a better understanding of flood dynamics under different conditions and inform the development of an accurate flood simulation model. The chapter covers experiment settings, results analysis, comparative models for erosion and non-erosion scenarios, different flow-times, resolutions, and historical data. Additionally, a final validation using a comparable study area is discussed. Overall, Chapter 4 consolidates the experimental findings, interprets the results, and contributes to the advancement of flood simulation models.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, this thesis successfully establishes an ABM framework for flood simulation and develops a tailored flood inversion model for the flood-prone areas in New Brunswick. Through extensive experimentation and validation, the model demonstrates its ability to simulate flood inundation with a reasonable level of accuracy, despite some inevitable inaccuracies in the finer details. The parameter settings derived from the experiments provide valuable insights for controlling the model and obtaining meaningful results.

The analysis of the results reveals interesting findings regarding the impact of precipitation and the presence of rivers on the inversion outcomes. Specifically, the inversion results for areas with rivers show better alignment with the actual flood conditions when considering the precipitation aspect. On the other hand, when examining the variability within the study area, the inversion results for areas without rivers demonstrate a closer resemblance to the reality. This highlights the importance of considering both precipitation patterns and the geographical characteristics of the study area when performing flood inversion.

Furthermore, the study investigates the influence of DEM resolution on the inversion results. Surprisingly, the use of lower-resolution DEM images leads to inversion results that more closely resemble the actual conditions within the study area. This suggests that the loss of finer details in lower-resolution data may lead to a smoother representation of the terrain, which aligns better with the observed flood patterns. However, it is crucial to note that the simulated precipitation in these cases may deviate significantly from the actual values.

Overall, this thesis provides valuable insights into flood simulation and inversion modeling for flood-prone areas. The findings contribute to the understanding of the complex dynamics of flooding and highlight the importance of considering various factors, such as precipitation, geographical features, and DEM resolution, in accurately simulating flood inundation.

5.2 Limitations & Recommendations

One limitation is the assumption of uniform precipitation distribution throughout the study area. In reality, precipitation patterns can vary spatially, and incorporating this variability into the model could enhance the accuracy of flood simulations. Future research can explore methods to incorporate spatially varying precipitation data, such as using weather radar or satellite observations, to improve the realism of the simulated floods.

Another limitation is the simplified representation of erosion in the model. Although erosion is a natural process that occurs in river systems, its impact on flood simulations was found to be minimal in this study. Further investigation is needed to refine the erosion modeling component and explore its influence on flood dynamics in areas with rivers. This could involve incorporating more sophisticated erosion algorithms or considering the effects of sediment transport on flood propagation.

Additionally, the use of Digital Elevation Models (DEMs) with different resolutions revealed interesting findings regarding the trade-off between detail and accuracy. High-resolution models provide detailed and accurate water level and precipitation data but come with increased computational demands. Lower-resolution DEMs provided inversion results that were more consistent with the actual conditions in the study area. However, this came at the cost of losing finer details in the terrain representation. Future research can explore techniques to combine high-resolution and low-resolution DEM data to strike a balance between capturing essential terrain features and simulating accurate flood inundation patterns.Furthermore, the validation of the model's results could be extended to a broader range of flood events and geographical locations. This would enhance the generalizability of the model and provide a more comprehensive understanding of its performance under different scenarios. Comparing the model's results with observed flood data and collaborating with hydrologists and flood management experts can further validate the model's accuracy and reliability.

In conclusion, while this thesis provides valuable insights into flood simulation and inversion modeling for flood-prone areas, there are opportunities for further improvements and advancements. By addressing the identified limitations and incorporating additional factors, such as spatially varying precipitation patterns and refined erosion modeling, future research can enhance the accuracy and applicability of flood simulations, contributing to better flood management and mitigation strategies.

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APPENDIX

Appendix I. Original Climate Data From Natural Resoure Canada

Station Name	Climate ID	Date/Time (LST)	Year	Month	Day	Time (LST)	Temp (?)	Dew Point Temp (?)	Rel Hum (%)	Precip. Amount (mm)	Wind Dir (10s deg)	Wind Spd (km/h)	Stn Press (kPa)
FREDERICTON CDA CS	8101605	27-04-2018 23:00	2018	4	27	23:00	8.8	7.7	93	2.2	15	13	100.72
FREDERICTON CDA CS	8101605	28-04-2018 0:00	2018	4	28	0:00	7.9	7.1	94	2.1	18	12	100.8
FREDERICTON CDA CS	8101605	28-04-2018 1:00	2018	4	28	1:00	7.7	7.1	96	0.3	10	6	100.66
FREDERICTON CDA CS	8101605	28-04-2018 2:00	2018	4	28	2:00	7.6	7.1	96	0.2	34	1	100.61
FREDERICTON CDA CS	8101605	28-04-2018 3:00	2018	4	28	3:00	7.7	7.3	97	0	8	3	100.5
FREDERICTON CDA CS	8101605	28-04-2018 4:00	2018	4	28	4:00	7.8	7.4	97	0.4	11	8	100.48
FREDERICTON CDA CS	8101605	28-04-2018 5:00	2018	4	28	5:00	7.6	7.3	98	0	10	5	100.43
FRED	8101	28-04-	201	4	2	6:0	7.7	7.4	98	0.2	11	4	100.3

ERICTON CDA CS	605	2018 6:00	8		8	0							9
FREDERICTON CDA CS	8101605	28-04-2018 7:00	2018	4	28	7:00	8	7.7	98	0.3		0	100.44
FREDERICTON CDA CS	8101605	28-04-2018 8:00	2018	4	28	8:00	8.4	8.1	98	0.7	6	1	100.38
FREDERICTON CDA CS	8101605	28-04-2018 9:00	2018	4	28	9:00	9	8.8	99	0	13	7	100.41
FREDERICTON CDA CS	8101605	28-04-2018 10:00	2018	4	28	10:00	9.5	9.3	99	0	12	7	100.45
FREDERICTON CDA CS	8101605	28-04-2018 11:00	2018	4	28	11:00	10.6	10.4	99	0	11	8	100.44
FREDERICTON CDA CS	8101605	28-04-2018 12:00	2018	4	28	12:00	11.3	11	98	0	7	6	100.45
FREDERICTON CDA CS	8101605	28-04-2018 13:00	2018	4	28	13:00	13.9	11.8	87	0	21	18	100.45
FREDERICTON CDA CS	8101605	28-04-2018 14:00	2018	4	28	14:00	15.2	12.4	83	0	21	17	100.48
FREDERICTON CDA CS	8101605	28-04-2018 15:00	2018	4	28	15:00	15.7	11.3	75	0	21	16	100.47
FRED	8101	28-04-	201	4	2	16:	16.	10.	69	0	21	13	100.5

ERICTON CDA CS	605	2018 16:00	8		8	00	3	7					1
FREDERICTON CDA CS	8101605	28-04-2018 17:00	2018	4	28	17:00	16.3	11.2	71	0	20	12	100.57
FREDERICTON CDA CS	8101605	28-04-2018 18:00	2018	4	28	18:00	15.7	11.1	74	0	21	11	100.57
FREDERICTON CDA CS	8101605	28-04-2018 19:00	2018	4	28	19:00	15.7	11.4	76	0	26	6	100.65
FREDERICTON CDA CS	8101605	28-04-2018 20:00	2018	4	28	20:00	13.9	10.8	82	0.6	8	3	100.71
FREDERICTON CDA CS	8101605	28-04-2018 21:00	2018	4	28	21:00	12	10.5	90	0	12	6	100.8
FREDERICTON CDA CS	8101605	28-04-2018 22:00	2018	4	28	22:00	10.1	9.2	95	0	12	6	100.82
FREDERICTON CDA CS	8101605	28-04-2018 23:00	2018	4	28	23:00	9	8.4	96	0	12	5	100.88
FREDERICTON CDA CS	8101605	29-04-2018 0:00	2018	4	29	0:00	8.4	8	97	0	15	5	100.89
FREDERICTON CDA CS	8101605	29-04-2018 1:00	2018	4	29	1:00	8.2	7.8	97	0	10	3	100.91
FRED	8101	29-04-	201	4	2	2:0	7.2	6.8	98	0	35	4	100.8

ERICTON CDA CS	605	2018 2:00	8		9	0							8
FREDERICTON CDA CS	8101605	29-04-2018 3:00	2018	4	29	3:00	6.5	6.2	98	0	35	4	100.84
FREDERICTON CDA CS	8101605	29-04-2018 4:00	2018	4	29	4:00	6.1	5.9	99	0	33	9	100.81
FREDERICTON CDA CS	8101605	29-04-2018 5:00	2018	4	29	5:00	6.3	6.1	99	0	35	5	100.79
FREDERICTON CDA CS	8101605	29-04-2018 6:00	2018	4	29	6:00	6	5.8	99	0	33	6	100.8
FREDERICTON CDA CS	8101605	29-04-2018 7:00	2018	4	29	7:00	6.6	6.4	99	0	34	8	100.82
FREDERICTON CDA CS	8101605	29-04-2018 8:00	2018	4	29	8:00	7.5	7.3	99	0.2	32	9	100.8
FREDERICTON CDA CS	8101605	29-04-2018 9:00	2018	4	29	9:00	9.6	7.7	88	0	33	8	100.76
FREDERICTON CDA CS	8101605	29-04-2018 10:00	2018	4	29	10:00	12.9	9	77	0	2	12	100.75
FREDERICTON CDA CS	8101605	29-04-2018 11:00	2018	4	29	11:00	14	8.2	68	0	1	12	100.68
FRED	8101	29-04-	201	4	2	12:	15.	8.1	62	0	5	14	100.6

ERICTON CDA CS	605	2018 12:00	8		9	00	3						3
FREDERICTON CDA CS	8101605	29-04-2018 13:00	2018	4	29	13:00	14.6	8	65	0	4	16	100.63
FREDERICTON CDA CS	8101605	29-04-2018 14:00	2018	4	29	14:00	15.3	8.7	65	0	3	12	100.63
FREDERICTON CDA CS	8101605	29-04-2018 15:00	2018	4	29	15:00	15.3	8.8	65	0	4	13	100.63
FREDERICTON CDA CS	8101605	29-04-2018 16:00	2018	4	29	16:00	15.1	8.2	63	0	3	18	100.66
FREDERICTON CDA CS	8101605	29-04-2018 17:00	2018	4	29	17:00	14.2	8	66	0	4	17	100.75
FREDERICTON CDA CS	8101605	29-04-2018 18:00	2018	4	29	18:00	12	7.3	73	0	5	17	100.79
FREDERICTON CDA CS	8101605	29-04-2018 19:00	2018	4	29	19:00	10.3	6.8	79	0	7	15	100.86
FREDERICTON CDA CS	8101605	29-04-2018 20:00	2018	4	29	20:00	9.2	6.2	81	0	6	16	100.95
FREDERICTON CDA CS	8101605	29-04-2018 21:00	2018	4	29	21:00	8.1	5.7	85	0	7	8	101.04
FRED	8101	29-04-	201	4	2	22:	7.6	5.5	87	0	7	9	101.0

ERICTON CDA CS	605	2018 22:00	8		9	00						5
FREDERICTON CDA CS	8101605	29-04-2018 23:00	2018	4	29	23:00	7	4.8	86	0	6	14	101.07
FREDERICTON CDA CS	8101605	30-04-2018 0:00	2018	4	30	0:00	5.9	4.1	88	0	5	17	101.07
FREDERICTON CDA CS	8101605	30-04-2018 1:00	2018	4	30	1:00	5.1	4.1	94	2.4	4	14	101.09
FREDERICTON CDA CS	8101605	30-04-2018 2:00	2018	4	30	2:00	5	4	93	0	6	11	101.08
FREDERICTON CDA CS	8101605	30-04-2018 3:00	2018	4	30	3:00	5.4	4.6	94	0	7	14	100.98
FREDERICTON CDA CS	8101605	30-04-2018 4:00	2018	4	30	4:00	5.6	5	96	2.3	7	15	100.98
FREDERICTON CDA CS	8101605	30-04-2018 5:00	2018	4	30	5:00	5.8	5.2	96	2.6	6	11	100.99
FREDERICTON CDA CS	8101605	30-04-2018 6:00	2018	4	30	6:00	6.1	5.4	95	0.9	6	9	101
FREDERICTON CDA CS	8101605	30-04-2018 7:00	2018	4	30	7:00	6.3	5.6	95	1.2	4	9	101.06
FRED	8101	30-04-	201	4	3	8:0	6.2	5.3	94	0.6	5	10	101.1

ERICTON CDA CS	605	2018 8:00	8		0	0							1
FREDERICTON CDA CS	8101605	30-04-2018 9:00	2018	4	30	9:00	5.9	5.1	94	1.7	2	7	101.13
FREDERICTON CDA CS	8101605	30-04-2018 10:00	2018	4	30	10:00	5.8	5.1	95	4.9	4	8	101.14
FREDERICTON CDA CS	8101605	30-04-2018 11:00	2018	4	30	11:00	6.1	5.2	94	1.7	2	10	101.08
FREDERICTON CDA CS	8101605	30-04-2018 12:00	2018	4	30	12:00	6	5.3	95	1.8	35	6	101.11
FREDERICTON CDA CS	8101605	30-04-2018 13:00	2018	4	30	13:00	6.3	5.5	95	3.3	36	6	101.13
FREDERICTON CDA CS	8101605	30-04-2018 14:00	2018	4	30	14:00	6.4	5.9	97	2.3	35	9	101.08
FREDERICTON CDA CS	8101605	30-04-2018 15:00	2018	4	30	15:00	6.3	5	92	0.8	36	12	101.05
FREDERICTON CDA CS	8101605	30-04-2018 16:00	2018	4	30	16:00	6.3	5.4	94	0	36	9	101.06
FREDERICTON CDA CS	8101605	30-04-2018 17:00	2018	4	30	17:00	5.8	5.2	96	0.5	36	9	101.08
FRED	8101	30-04-	201	4	3	18:	5.5	4.8	96	0.2	36	11	101.0

ERICTON CDA CS	605	2018 18:00	8		0	00							6
FREDERICTON CDA CS	8101605	30-04-2018 19:00	2018	4	30	19:00	4.6	3.9	95	0	36	10	101.09
FREDERICTON CDA CS	8101605	30-04-2018 20:00	2018	4	30	20:00	4.3	3.7	96	0	35	8	101.11
FREDERICTON CDA CS	8101605	30-04-2018 21:00	2018	4	30	21:00	4	3.3	95	0	34	7	101.15
FREDERICTON CDA CS	8101605	30-04-2018 22:00	2018	4	30	22:00	3.5	3.1	97	0	34	8	101.13
FREDERICTON CDA CS	8101605	30-04-2018 23:00	2018	4	30	23:00	3.4	3.1	98	0	34	8	101.12

Appendix II Codes used in Netlogo

```
;;please note part of the codes are modified from the rainfall model
extensions [gis csv]
breed [raindrops raindrop]
breed [waters water]

globals [
  elevation-dataset
  border          ;; keep the patches around the edge in a global
                  ;; so we don't ever have to ask patches in go
  min-e           ;;minimum elevation
  max-e           ;;maximum elevation
  the-row         ;;used in export-data. it is the row being written
  list_of_rain_amount
  river-boundary  ;;river boundary lines
  rivdata
  flowtimes
  riverbanks
]

patches-own [
```

```
 elevation
 initial_elevation
 elevation_change
 amount_rain   ;;how many drops of rain here
 elevation-difference

]

turtles-own[
 soil        ;;how much soil a raindrop is carrying
 ]

to setup
 ca
 if MapType = "DEMWithRiver-67" [

 resize-world -33 33 -33 33

 set elevation-dataset gis:load-dataset "data/rastert_aggrega9.asc"

 set riverbanks gis:load-dataset "data/riverbank/riverbank.shp"

 gis:set-world-envelope gis:envelope-of riverbanks

 gis:set-world-envelope gis:envelope-of elevation-dataset

 gis:apply-raster elevation-dataset elevation

 gis:apply-raster elevation-dataset initial_elevation

 show_elevation]

 if MapType = "DEMWithRiver-133" [

 resize-world -67 67 -67 67

 set elevation-dataset gis:load-dataset "data/rastert_aggrega8.asc"

 set riverbanks gis:load-dataset "data/riverbank/riverbank.shp"

 gis:set-world-envelope gis:envelope-of riverbanks

 gis:set-world-envelope gis:envelope-of elevation-dataset

 gis:apply-raster elevation-dataset elevation

 gis:apply-raster elevation-dataset initial_elevation

 show_elevation]

   if MapType = "DEMComWithRiver-67" [

 resize-world -33 33 -33 33

 set elevation-dataset gis:load-dataset "data/rastert_aggreg10.asc"

 set riverbanks gis:load-dataset "data/riverbank/riverbank_comp_line.shp"

 gis:set-world-envelope gis:envelope-of riverbanks

 gis:set-world-envelope gis:envelope-of elevation-dataset
```

```
gis:apply-raster elevation-dataset elevation
gis:apply-raster elevation-dataset initial_elevation
show_elevation]
if MapType = "DEMComWithRiver-133" [
resize-world -67 67 -67 67
set elevation-dataset gis:load-dataset "data/rastert_aggreg11.asc"
set riverbanks gis:load-dataset "data/riverbank/riverbank_comp_line.shp"
gis:set-world-envelope gis:envelope-of riverbanks
gis:set-world-envelope gis:envelope-of elevation-dataset
gis:apply-raster elevation-dataset elevation
gis:apply-raster elevation-dataset initial_elevation
show_elevation]
if MapType = "DEMOutofRiver-67" [
resize-world -33 33 -33 33
set elevation-dataset gis:load-dataset "data/rastert_aggreg14.asc"
gis:set-world-envelope gis:envelope-of elevation-dataset
gis:apply-raster elevation-dataset elevation
gis:apply-raster elevation-dataset initial_elevation
show_elevation]
if MapType = "DEMOutofRiver-133" [
resize-world -67 67 -67 67
set elevation-dataset gis:load-dataset "data/rastert_aggreg13.asc"
gis:set-world-envelope gis:envelope-of elevation-dataset
gis:apply-raster elevation-dataset elevation
gis:apply-raster elevation-dataset initial_elevation
show_elevation]
  if MapType = "DEMComOutofRiver-67" [
resize-world -33 33 -33 33
set elevation-dataset gis:load-dataset "data/rastert_aggreg16.asc"
gis:set-world-envelope gis:envelope-of elevation-dataset
```

```
 gis:apply-raster elevation-dataset elevation

 gis:apply-raster elevation-dataset initial_elevation

 show_elevation]

 if MapType = "DEMComOutofRiver-133" [

 resize-world -67 67 -67 67

 set elevation-dataset gis:load-dataset "data/rastert_aggreg15.asc"

 gis:set-world-envelope gis:envelope-of elevation-dataset

 gis:apply-raster elevation-dataset elevation

 gis:apply-raster elevation-dataset initial_elevation

 show_elevation]

 if MapType = "test" [

 resize-world -112 111 -112 111

 set elevation-dataset gis:load-dataset "data/rastert_aggreg12.asc"

 gis:set-world-envelope gis:envelope-of elevation-dataset

 gis:apply-raster elevation-dataset elevation

 gis:apply-raster elevation-dataset initial_elevation

 show_elevation]

 set-default-shape turtles "circle"

 set border patches with [ count neighbors != 8 ]

 set list_of_rain_amount []

 set water-height 10 ^ 5 * 10 / ( 64 * 10 ^ 8 )

 set flowtimes 0
 ;; how to calculate water-height for each turtle:
 ;; amount of water for each turtle is volume of each turtle / area
 ;; amount of water for each turtle is 4800 / (64 * 10^8) *10 (10 means cm to mm)
 ;; area of the study area changed from 400*10^8 into 64*10^8
 reset-ticks
end


to show_elevation

   if MapType = "DEMOutOfRiver-67"
    [set min-e gis:minimum-of elevation-dataset
     set max-e gis:maximum-of elevation-dataset
     ask patches [set pcolor scale-color black elevation min-e max-e]
    ]

   if MapType = "DEMWithRiver-67"
    [set min-e gis:minimum-of elevation-dataset
```

```
    set max-e gis:maximum-of elevation-dataset
    ask patches [set pcolor scale-color black elevation min-e max-e]
   ]

  if MapType = "DEMOutOfRiver-133"
   [set min-e gis:minimum-of elevation-dataset
    set max-e gis:maximum-of elevation-dataset
    ask patches [set pcolor scale-color black elevation min-e max-e]
   ]

  if MapType = "DEMWithRiver-133"
   [set min-e gis:minimum-of elevation-dataset
    set max-e gis:maximum-of elevation-dataset
    ask patches [set pcolor scale-color black elevation min-e max-e]
   ]

  if MapType = "DEMComOutOfRiver-67"
   [set min-e gis:minimum-of elevation-dataset
    set max-e gis:maximum-of elevation-dataset
    ask patches [set pcolor scale-color black elevation min-e max-e]
   ]

  if MapType = "DEMComWithRiver-67"
   [set min-e gis:minimum-of elevation-dataset
    set max-e gis:maximum-of elevation-dataset
    ask patches [set pcolor scale-color black elevation min-e max-e]
   ]

  if MapType = "DEMComOutOfRiver-133"
   [set min-e gis:minimum-of elevation-dataset
    set max-e gis:maximum-of elevation-dataset
    ask patches [set pcolor scale-color black elevation min-e max-e]
   ]

  if MapType = "DEMComWithRiver-133"
   [set min-e gis:minimum-of elevation-dataset
    set max-e gis:maximum-of elevation-dataset
    ask patches [set pcolor scale-color black elevation min-e max-e]
   ]

end

to go
  ;;this part uses codes from the library model Grand Cayon, with some modifications

  create-raindrops rain-rate

  [ ifelse show_water_amount? or show_elevation_change? [hide-turtle set color blue][set color blue]
    set size 2
    set soil 0
    move-to one-of patches
   ]

  ifelse draw?
    [ ask turtles [ pd ] ]
    [ clear-drawing
      ask turtles [ pu ] ]

  ask raindrops [ ifelse erosion? [flow_with_erosion][flow] ]
  ;;ask raindrops [ifelse erosion? [ifelse flow_times? [flow_erosion_two_times][flow_with_erosion]] [ ifelse flow_times?
[flow_two_times][flow] ] ]
```

```
  ;;ask raindrops [ flow ]

  ask border
  [
    ask turtles-here [ die ]
  ]

  ;;ifelse river-bank? [draw-riverbanks][]

  ;;codes from Grand Cayon end here

  ifelse show_water_amount?
    [show_amount_of_water]
    [ifelse show_elevation_change? and erosion?[show_elevation_change ]
      [  ask turtles [show-turtle]
         show_elevation]]
  set flowtimes 0

  tick
end

to draw-riverbanks
  gis:draw riverbanks red
end

to flow
  ;;this part uses codes from the library model Grand Cayon, with some modifications
  set flowtimes 0
  while [flowtimes < flow-times] [
  let target min-one-of neighbors [ elevation + ( count turtles-here * water-height) ]
  set elevation elevation + ( count turtles-here * water-height)

  ifelse [elevation + (count turtles-here * water-height)] of target
     < (elevation + ((count turtles-here - 0) * water-height))
    [ face target
      move-to target ]
    [ set breed waters ]
    set flowtimes flowtimes + 1
  ]
  ;;codes from Grand Cayon end here
end



to flow_with_erosion
  ;;this part uses codes from the library model Grand Cayon with some modifications
  set flowtimes 0
  set soil 0
  while [flowtimes < flow-times] [
  let target min-one-of neighbors [ elevation + ( count turtles-here * water-height) ]
  set elevation elevation + ( count turtles-here * water-height)

  ifelse [elevation + (count turtles-here * water-height)] of target
     < (elevation + ((count turtles-here - 0) * water-height))
    [
    ;;consider erosion effects
    ;;elevation-difference shows the difference of the amount of water between these two patch
    set elevation-difference (elevation + ((count turtles-here - 0) * water-height)) - [elevation + (count turtles-here * water-height)]
of target
      ask patch-here [set elevation elevation - elevation-difference * 22.64252696 / (8 * 10 ^ 6) ];;cm^3 to m^3
      ;;area of the pixel: the amount of the soil will flow out from this pixel.
```

```
    ;; amount of water flowed into the area * amount of the soil brought by the water
    ;; the amount of the soil that will be brought from the water, depends on the water flows into the area.
    set soil soil + elevation-difference * 22.64252696 / (8 * 10 ^ 6)
    face target
    move-to target
   ]
   [ set breed waters
    ask patch-here [set elevation elevation + [soil] of myself]
    set soil 0]
  set flowtimes flowtimes + 1
 ]
 ;;codes from Grand Cayon end here
end


to show_amount_of_water
  ;;To show by scaled color. However, because the variation is small, it may be hard to see the difference.
  ;; This is what is shown in our model
   ask patches [set amount_rain count turtles-here  ]
    set max-e [amount_rain] of max-one-of patches [amount_rain]
    ask patches with [amount_rain > 0 ][set pcolor scale-color blue amount_rain (max-e + 1) 0 ]
    ask patches with [amount_rain = 0 ][set pcolor white]
    ask turtles [hide-turtle]

end


to show_elevation_change

 ask patches [set elevation_change elevation - initial_elevation]
 ask turtles [hide-turtle]
 ask patches with [elevation_change > 0][set pcolor green ] ;;increased
 ask patches with [elevation_change < 0][set pcolor red ]   ;;decreased
 ask patches with [elevation_change = 0][set pcolor black]

end

to export_data
 file-close
 ;;file-delete "data/result.csv"
 file-open "data/result9.csv"
 export-world "data/result9.csv"
 ;;]
end
```