An Investigation into the Effects of Environmental Deformation Over Time Using Node-Based River and Sediment Simulation

## Rationale

Simulation of rivers has always proven difficult when creating a virtual landscape. Several models exist to mimic the flow of water (The Lattice-Boltzman algorithm(1) is a commonly used example.) Many approaches to water simulation stray away from particle-or-node based systems, favouring vector-based approximations to calculate both path and flow(2).

Node-based flow simulations allow a virtual representation of deformation of landscape features, and the transfer of sediment(3). Such a system could, over time, allow for the creation of complex geographical features found in rivers (such as ox-bow lakes(4)) and allow for natural-looking landscapes to be created by running the simulation on any terrain.

In this portfolio project, I will create a tool that allows for the generation of a landscape, which is then deformed over time by the movement of water- simulating both natural springs and rainfall. This should provide an environment for the natural generation of real-world features that are sparsely seen in digital representations of rivers. Features like bank erosion and sediment transfer(5) are rarely present in these models due to their complexity(6) and computational intensity(7).

## Literature Review

Various studies into the potential paths of rivers exist for flooding avoidance(8). As flooding poses a significant risk in some areas, they are regularly monitored and simulated to prevent damage to infrastructure(9). While my aim is not to simulate existing rivers and instead focus on the landscape deformation over many years, pre-existing tools for flood avoidance can prove to be useful sources for my investigation, as they tackle similar concepts(10).

A study into the erosion of landscape by Nicholas McDonald(3) tackles some similar concepts to my investigation. However, this study lacks a soil map to allow for different densities of soil and sediment for its nodes. I intend to use a soil map for increased real-world accuracy, tracking different forms of sediment and their transfer(11).

Studies into fluid dynamics can provide a digital representation of a range of issues(12). Editors have been created to simulate physics in games through real-time editing(13), studies into terrain generation based on pre-existing river splines exist(14), and forms of fluid dynamics models have existed for centuries, since the time of Archimedes(15).

Studies also exist into the usage of real-time terrain creation and destruction, and the effect of it on water flow(16). However, I intend to use pre-generated landscapes as opposed to real-time generation, so this is not something to consider for this project.

## Aims

My aim is to create a tool that allows the user to generate a random landscape with height differences, a representation of foliage, and soil maps. It will then step through various periods of time, simulating the effect that fluid would have on the landscape through means of erosion and sediment deposit. Fluids should be able to both flow and form pools, as they commonly do in traditional fluid dynamics(17), and transfer sediment from banks and cliffsides. This will be done through a node-based simulation, considering differences in height and density to create the effects of erosion over time. The precision of the model should be variable, allowing for both large and small-scale simulation, from a single riverbank to acres of land.

The simulation is not planned to account for the effect of animals on the landscape, the freezing and thawing of water, or the effects of altitude on the behaviour of fluids and gasses. The inherent complexity of these features would require a full study(18) and would prove difficult to simulate in the scope of my project.

## Objectives

My program should represent:

* The formation of rivers and flow of water over a landscape.
* The effect of rain on a landscape, and the ability to flow and pool without use of a pre-defined river spline(19).
* Environmental deformation due to waterflow, and the acquisition and deposition of sediment.
* Variations in soil and rock density, and the effects of more dense ground on the flow of water.
* Simple foliage that will restrict and affect the flow of water.
* Dynamic scaling based on user specification, allowing for both small-scale and large-scale water simulation.

The program should also allow user specification of restrictions and properties of the landscape, such as average temperature, foliage density, probability of mountains, probability of natural water sources, and simulation time steps.

These should combine to allow creation of complex geographical features that are not usually seen in digital landscapes.

## Methodology

For this project, I will create a C++ OpenGL application in Visual Studio 2019. I intend to employ a node-based system of terrain generation and simulation, using defined terrain points of a user-defined precision. These will contain information regarding the soil and rock densities at different depths, the depth of any water present at that node, and the current flow direction and speed of the water. Randomization of initial terrain generation will use Perlin Noise, edited based on user specification of average landscape height and mountain formation chance.

Algorithms for cell-based fluid dynamics will be used, such as the hydraulic erosion model(20). This method will, however, need to be modified to provide varying sediment values and erosion rates due to the soil map providing varying densities of sediment. The hydraulic erosion model should provide sufficient basis for simple water movement and erosion, however.

The algorithm consists largely of five major steps(3), calculating the individual elements of fluid simulation. The implementation of these will be discussed in the Project Plan. The algorithm is designed with GPU-based optimization in mind, but I will experiment with both CPU and GPU-based implementations of this algorithm in terms of complexity and runtime efficiency.

## Project Plan

The system will iterate through all nodes in the scene (stored in a data structure referencing their data), performing various operations to simulate the movement of water through the landscape.

Firstly, rain simulation will be performed, adding a small amount of fluid to multiple nodes in the world to allow for additional deformation of landscapes that are not naturally near water, and allowing water movement in locations that might not see a regular flow. This could potentially lead to pools and new rivers forming. Rainfall averages will be specified by the user but will vary as they do naturally.

The system will individually check each simulated node and calculate any deformation, sediment pick-up or loss, and changes to flow, using existing fluid dynamics methodology for calculation of frictional force(21) and the hydraulic erosion model.

It will then edit the landscape data accordingly. This, in turn, will affect the visual representation of the landscape drawn using OpenGL, connecting nodes with simple quads (cells). Two render passes will be made- one for the landscape, and one for the water. Visual fidelity is not the focus of the project, so simple designs will be used in this regard.

When water and sediment simulation is complete, evaporation occurs, leaving sediment deposits in positions where water containing sediment no longer exists. This will affect landscape data and increase land height values in associated areas. The rate of evaporation will depend on a global user-defined temperature.

This cycle should allow sufficient simulation to create geographical features that are often missing from digital representations of rivers. For example, sediment pick up, deposit, and erosion should combine to allow the creation of ox-bow lakes.

# References

1. <https://physics.weber.edu/schroeder/fluids/>
2. <http://servidor.demec.ufpr.br/CFD/bibliografia/Ferziger%20Peric%20-%20Computational%20Methods%20for%20Fluid%20Dynamics,%203rd%20Ed%20-%202002.pdf>
3. <https://nickmcd.me/2020/04/15/procedural-hydrology>
4. <https://www.nationalgeographic.org/encyclopedia/oxbow-lake/>
5. <https://www.therrc.co.uk/MOT/References/EA_DEFRA_Sediment_transport_and_alluvial_resistance_in_rivers.pdf>
6. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.449.5576&rep=rep1&type=pdf>
7. <https://huw-man.github.io/Interactive-Erosion-Simulator-on-GPU/>
8. <https://www.mdpi.com/2220-9964/9/3/163/pdf>
9. <https://waterco.co.uk/river-modelling/>
10. <http://nora.nerc.ac.uk/id/eprint/10422/1/Cole_et_al_Bristol_Radar_Workshop_28_July_2010.pdf>
11. <https://geo.libretexts.org/@go/page/760>
12. <https://heritagesciencejournal.springeropen.com/articles/10.1186/s40494-019-0259-9>
13. <https://80.lv/articles/river-editor-water-simulation-in-real-time/>
14. <https://hal.archives-ouvertes.fr/hal-01339224/document>
15. <https://www.cambridge.org/core/books/abs/works-of-archimedes/on-floating-bodies-book-i/256198AE9365D4B099BF23A7BBD50D41>
16. <https://80.lv/articles/river-editor-water-simulation-in-real-time/>
17. <http://www.jlakes.org/config/hpkx/news_category/2015-06-01/PhysicsofLakesVolume3MethodsofUnderstandingLakesasComponents.pdf>
18. <https://www.sciencedirect.com/science/article/pii/S2211379717302437>
19. <https://docs.unrealengine.com/4.27/en-US/BuildingWorlds/Landscape/Editing/Splines/>
20. <https://hal.inria.fr/inria-00402079/document>
21. <https://www.ldeo.columbia.edu/~martins/hydro/lectures/fluid_dynamics.html>