<u>Blue Sticker</u>

Development Project 55-608850

Is it possible to develop a river basin simulation showing the impact upon flood plains, using F# and functional principles?

Matthew Ling
29041117

Supervisor: Dr Chris Bates

Problem Statement

"Is it possible to develop a river basin simulation showing the impact upon flood plains, using F# and functional principles?" poses an interesting two-fold problem.

Firstly, how do you go about building a simulation of a river basin and modelling the flow of the river? My strategy will be to use a first principles approach, by researching and implementing the mathematical equations that govern fluid dynamics and applying these to a river system. This contrasts with another approach I considered, using a basic model and layering the complexity on top of it to achieve the desired result, however this will be assessed later in my evaluation. For my strategy to work it will require the use of complex mathematical operations and applying complex fluid dynamic formulas to the river system problem. For the second part of the problem, I believe using a functional language like F# will allow for an implementation that is easy for scientists to understand and can take advantage of the benefits of F#. These include being able to pass functions as parameters to other functions, lazy evaluation of variables and better recursion than in object-oriented languages. For fluid simulation of rivers, the computer programs are large and complex, therefore any improvements in speed and efficiency are worth evaluating. I believe F# has numerous advantages in these areas and so it is a rich area of investigation to help reduce computation cost of these simulations, make it easier for scientists to understand and build a robust and true representation of a river system.

Literature Review

Introduction

The objective of this literature review is to ascertain if there are models for river basins that could benefit from using a functional programming approach, specifically F# for a complex scientific application is viable and if a proof of concept would prove useful in providing evidence of this.

River Basin Simulation and Floodplain Dynamics

A range of studies have examined how a river basin simulation can show floodplain behavior. Firstly, most river basin simulations are a hydrodynamic model. As shown in (Fleischmann, 2019) this report highlights the importance of flood control reservoirs and floodplains in large hydrodynamic models. (Fleischmann, 2019) focuses on the Itajai -Acu river basin in Brazil and shows how many factors, including man-made ones like flood control reservoirs, can impact the effectiveness of a river basin model. The effect of the floodplains may be more important for a wide range of maximum floods than the flood controlling reservoirs. Within this (Fleischmann, 2019) showed that it is possible to create a "basin-scale" flood management model in a complex basin, this in turn proves that it is possible to see the effect of floodplains and man-made structures on a basin wide scale. To account for all these factors to model a real-world river basin requires large amounts of data and knowledge of the different variables associated with the river. As shown in (Dysarz, 2011) variables such as sediment deposition, riparian vegetation and river embankments can heavily influence floodplain inundation. It is shown that the appearance and increase of vegetation can be the "most important cause of increase of extreme water states" and goes on to describe the balance between the need for conservation of a river's ecosystem and the removal of vegetation to decrease flooding risk. Building on this (Spink, 1998) highlights a range of factors that impact upon floodplain nutrient dynamics including, nutrient richness, plant growth, river size and position. These factors along with those from the hydrological regime play a crucial role in floodplain nutrient dynamics. Increase in the nutrients of these floodplains can lead to more plant life which in turn can act as an extra level of flood defense. To model the floodplain inundation and drainage, it is shown in (Rudorff, 2014) that hydraulic controls such as geomorphology, vegetation and water sources are important.

For my project I decided to base my simulations on the Navier Stokes equations as these equations are the basis for modern computer fluid dynamic (CFD) simulations. As shown in (Liang, 2017) using the finite volume method is one approach to solve the Navier Stokes equations in CFD simulations. This approach can provide accurate and reliable results. However, in the context of a river system it would be hard to estimate the volume of water over the whole river basin system. Therefore, a simplification or constraint may be needed if this approach is chosen. (Tian-wen, 2009) shows that when modeling the flow of an incompressible Newtonian fluid such as water, the Navier Stokes equations can be used finite element method and Newton's method to find a reasonable approximation of the complexities of the behavior of the flow. Furthermore (Helal, 2015), shows how to discretize these equations and solve them using a semi-implicit method for pressure linked equations, this in turn allows for the simulation of incompressible unsteady flows with fluid-structure interactions.

Some of the challenges and complexities involved in modelling river basins and floodplains correctly, in (Grimaldi, 2019) it is shown how important it is to accurately predict flood peaks and to use event-based modelling to improve accuracy. In the context of this review the use of event-based modelling could be a rich area of improvement with the use of functional programming paradigms. In addition, (Grimaldi, 2019) also highlights how "low accuracy topographic data hamper accurate flood modelling at the basin scale" again showing the need for larger data sets to be used within the model. If this larger data set can be collected it would be another area where functional programming paradigms could offer better performance for the simulation. This idea of low accuracy data and data scarcity are highlighted again in (Paz, 2011) which shows the difficulty in applying 1 and 2 dimensional models for large scale simulations.

<u>Functional Programming and F#</u>

Using functional programming principles for a river basin model is the basis of this section of the literature review. To begin with functional programming offers significant advantages in modularity as discussed in (J. Hughes, 1989), which shows how complex or "messy" sections of programs can benefit from the use of higher order functions and lazy evaluations. This can be applied to river basin simulations as it can significantly improve mathematical calculations especially those that are called multiple times throughout the program. Furthermore, (Modarres, 1999) demonstrates the use of functional programming approaches in the form of goal tree success trees and master logic diagram frameworks which can be very useful when trying to model complex physical systems. The GTST-MLD (Goal Tree Success Tree and Master Logic Diagram) framework is used to create functional models for specific items in an engineering system e.g a valve, pipe, reservoir etc these components demonstrate that a functional model can be made up of small components of a system and provide accurate and detailed simulation/modelling of an engineering problem. This could be applied to the fluid dynamics used in hydrodynamic modelling of a river basin.

For this dissertation I have looked into using the F# language to provide the functional modelling component of the river basin simulation, in F# for scientists (Harrop, 2008) showing how F# can be used for complex mathematical calculations such as a discrete Fourier transform and a Danielson-Lanczos algorithm (Harrop, 2008), showing that F# is a suitable language for use in scientific computation and simulation due to it is functional first approach integrated with object oriented features. In (Donald Syme, 2013) it's shown that in F# 3.0 "internet scale information sources" can be used with the F# 3.0 Type Providers feature. This could prove crucial for river basin simulation as the scale of data needed to accurately model the river basin has been shown to be on a similar scale.

Finally, in (Tiejian Li, 2011) created a dynamic parallel algorithm for hydrological model simulations using the master slave paradigm. In the paper the software is written in C++ and could be suitable to recreate in a functional programming language such as F#. As F# has many features that can enable faster parallel execution of functions and improved efficiency. In (Reitsma, 1997) an object-oriented approach is taken to modelling a river basin model, upon further exploration it seems this software could also benefit from the use of functional programming. This can be seen in the 3 environmental DSS which before this paper were represented by separate software and data modules, (Reitsma, 1997) unites these using an object-oriented approach however this brings challenges itself. These include having to still use large data sets and complex mathematical operations to simulate the river basin, again this is hard to do in parallel with object-oriented software and could be ripe for change to use a more functional approach.

Legal, Social and Ethical Issues

As the aim of this project is to develop a river basin simulation to help manage floodplain, there are numerous issues to consider.

Ethical

Firstly, one the ethical issue to consider is ensuring that the simulation is as accurate as possible when representing real world processes. Importantly, if the simulation has issues this could lead to it producing misleading results. In turn if these results are then used by policy makers to implement a certain flood prevention strategy it may adversely affect the river system and the environment.

The environmental impact of any measure undertaken because of the simulation is another issue that must be considered. Any flood prevention measure undertaken could have unintended consequences on the environment. This could be due to the measure failing leading to excessive flooding causing damage to local ecosystems or the ecology found in and around the river. Steps must be taken to prevent any excess harm caused to the environment by any measures suggested by the simulation, including a full assessment of the local ecosystem to ensure that the needs of local communities are balanced with protecting the environment.

Another important issue to acknowledge is that of equity and social justice, again decision based on the simulation could disproportionately affect communities from a lower socio-economic group if they are not considered and properly consulted in the decision-making process. It is important that existing inequalities are not exacerbated by flood prevention measures, such as a narrowing of the river upstream that may prevent flooding there but increases the speed of the river and disproportionate affects communities downstream.

Following on from this collaboration and participation in the decision-making process is important and ethical issue that should be acknowledged. To ensure that the flood prevention measures are ethical, stakeholders including the local communities and other relevant parties such as environmental agencies should be included in the process. This collaboration ensures that a wide range of perspectives are considered so the decision making is reflective of the interests of all those who will be affected by its implementation.

Finally for ethical issues is the to ensure that avoiding harm is at the centre of the decision-making and development process. This will come from making sure that the simulation considers all potential risks including environmental harm, social disruption and unintended consequences are explored fully. Once these risks are highlighted then steps can be taken to minimise these risks.

Legal

Moving onto the legal issues, one major issue is to ensure that the simulation itself and any interventions made because of the simulation are regulatory compliant. This not only important but is a legal requirement, this means researching any relevant laws and regulations that govern water management and environmental protection. Ensuring these are always followed and keeping up to date with any changes made.

Another important legal issue is that of liability (Ludlam, 2024), the simulation could be held liable for the accuracy and reliability of the simulation results. As mentioned above all efforts should be made to ensure this, however if this is not the case the simulation could be held liable, particularly if the results of the simulation are used to suggest certain mitigation strategies.

Finally for the legal issues is that of environmental impact assessments (GOV.UK, 2020), in the UK an environmental impact assessment is required before undertaking any work that may affect natural ecosystems. Therefore, it is pertinent that one is obtained before undertaking any construction.

Professional

A major professional consideration to consider is that of collaboration, as this simulation is trying to model a river basin accurately it will require expertise from a range of different disciplines including hydrology, ecology, geography, computer science and fluid dynamics. Therefore, it is important to ensure that collaboration between professionals from these different fields is encouraged. This will allow the simulation to accurately represent complex natural systems.

Another professional issue to acknowledge is that of transparency, as the simulation may be used to advise all assumptions and simplifications used by the simulation must be declared and made readily available. Concerns may arise if those impacted by the simulations are not fully informed about how the simulation works and its limitations.

Finally ethical guidelines and standards should be adhered to during the development and implementation of the simulations, these include the BCS (British Computer Society) code of conduct (BCS, 2022) and any other relevant authorities' guidelines such as the British ecologists code of conduct (British Ecological Society, 2024).

Evaluation

During the evaluation, the graphs produced by the application will be shown and explained. Along with this an assessment of the equation used, simplifications and assumptions made, and the engineering approaches used.

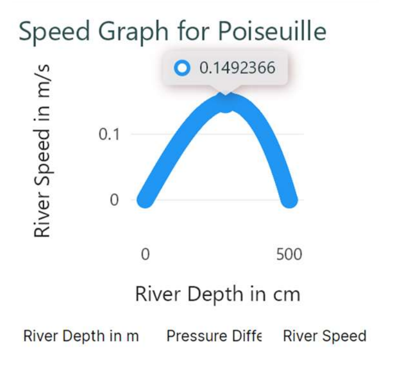

Figure 1: River Speed Graph for a River Depth of 5m

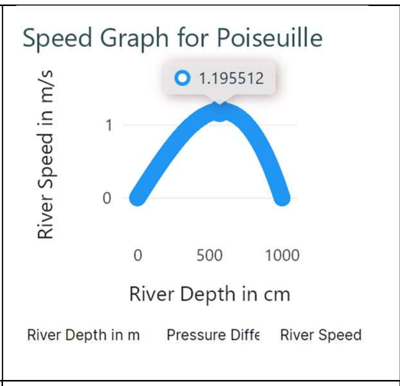

Figure 2: River Speed Graph for a River Depth of 10m

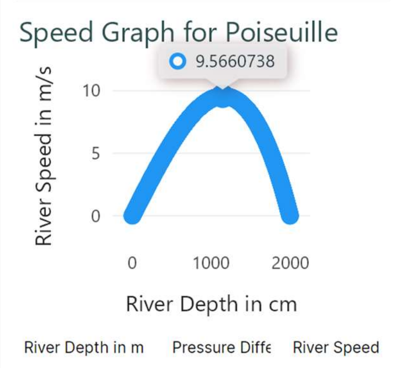

Figure 3: River Speed Graph for a River Depth of 20m

As shown above in figures 1,2 and 3 the application produces a parabola shaped curve which is expected as the formula used is $u_x(r) = \frac{1}{4\mu}\left(-\frac{dp}{dx}\right)(R^2 - r^2)$ (Brennen, 2006) . The $(R^2 - r^2)$ term predicts that the point of highest speed in the river is exactly halfway from either side of the river, as the presence of squared terms indicates the parabola shape of the curve as the R term relates to the radius of the river and the r term the radius at the point of measurement. The term μ is a constant that represents the viscosity of water at 11℃ which is the average temperature of river water in the UK (Art R. T. Jonkers, 2016). The term $\left(-\frac{dp}{dx}\right)$ represents the pressure gradient that is the driving force behind the movement of water, showing the change in pressure dp with respect to x direction dx. This formula is known as Poiseuille flow and is derived from the Navier Stokes equations, it is a formula usually used the steady flow through an infinitely long circular pipe with Radius R. The data produced by the F# model that is used to construct the graphs in Figures 1,2 and 3 follow this equation listed above, the data produced is thought to be a reasonable approximation of the river speed at these depths.

For this project the idea of find formulas from first principles was used, the Poiseuille flow equation used in F# by the application was derived from the Navier Stokes equations. However, to do these assumptions and simplifications needed to be made This includes modelling the river with Poiseuille flow, this is normally used to measure velocity in a pipe with a pressure gradient, however it has been applied to a river which is assumed to be a pipe cut in half or a channel which is like a riverbed. Another assumption made is that at the boundary of the channel the velocity of the water is zero, this is to reduce the complexity of wall normal flow. Finally, the velocity of the water is assumed to be only in one direction and that is in the same plane as the pressure gradient, again this is to simplify the solution to ensure that it is solvable.

The approach taken is this project contrasts with an empirical approach such as the Manning equation, this equation was created by looking at the data produced by measuring a river and fitting an equation to this. The Manning equation is $Q = VA = \left(\frac{1.00}{n}\right)AR^{\frac{2}{3}}\sqrt{S}$ (Corvallis Forestry Research Community, 2006) and describes uniform flow of fluid in an open channel. While this equation would be applicable to this project it was decided to not use it in favour of a first principles approach. This is due to it being a more representative model of the complex behaviours of the river water that is backed by mathematical derivations. Rather than using an objective based methodology and aiming to create a simulation to fit the data, this approach would not have the same scientific rigour and could be easily skewed by which dataset was used initially.

Some simplifications and assumptions were made with this model that will impact upon the overall accuracy of the data produced as they cannot fully model the complexity of the river system including the occurrence of turbulent flow, oscillations/ true 3-dimensional motion of the water within the river and the effect of an uneven riverbed. One simplification includes making the river an infinitely long pipe that has no velocity at either side, this is not truly representative of a river however it allows the Navier Stokes equations to be solved in a simpler manner. For programs like CFD (Computer Fluid Dynamics) they fully implement and utilize the Navier Stokes equations, therefore it can serve as proof of concept to show a simplified model in F#. This in turn can be built upon using more complex equations and solutions to the Navier Stokes. To implement these changes would increase accuracy but would require a large amount of research into more complex fluid dynamics beyond the scope of this project.

To visualise the data, C# and .NET were chosen to create a desktop application that uses the MVVM Architecture pattern. Then the plugin Live Charts was used to create the graphs shown in figures 1,2 and 3. C# and .NET were chosen as they integrate well with F#, as they are both developed by Microsoft many features allow seamless integration between the two languages. MVVM was chosen as it was necessary to separate the logic for the desktop application (View models and Views) away from the F# equations/data production (Model). Therefore, this pattern was the most appropriate to use, and ensured that the data produced was not tampered with by the concerns of the desktop application.

Word Count (Not inclusive of Title Page or Bibliography): 3056 words

Bibliography

BCS. (2022, June 8). *BCS Code of Conduct*. Retrieved from BCS The Chartered Institute for IT: https://www.bcs.org/membership-and-registrations/become-a-member/bcs-code-of-conduct/

British Ecological Society. (2024). *Code of Conduct*. Retrieved from British Ecological Society: https://www.britishecologicalsociety.org/events/n4fg/code-of-conduct/

Donald Syme, K. B. (2013). Themes in information-rich functional programming for internet-scale data sources. *In Proceedings of the 2013 workshop on Data driven functional programming* (pp. 1-4). New York: Association for Computing Machinery.

Dysarz, T. &.-D. (2011). Application of Hydrodynamic Simulation and Frequency Analysis for Assessment of Sediment Deposition and Vegetation Impacts on Floodplain Inundation. *Polish Journal of Environmental Studies*, 20.

Fleischmann, A. C. (2019). Modeling the role of reservoirs versus floodplains on large-scale river hydrodynamics. *Natural Hazards*, 1075-1104.

GOV.UK. (2020, May 13). *Enviromental Impact Assessment*. Retrieved from GOV.UK: https://www.gov.uk/guidance/environmental-impact-assessment

Grimaldi, S. S.-P. (2019). Challenges, opportunities and pitfalls for global coupled hydrologic-hydraulic modeling of floods. *Water Resources Research*, 5277-5300.

Harrop, J. (2008). *F# for Scientists.* Hoboken, New Jersey: Wiley.

Helal, K. M. (2015). Numerical study and CFD Simulations of Incompressible Newtonian Flow by Solving steady Navier-stokes equations using Newton's method. *Journal of Mechanics of Continua and Mathematical Sciences*.

J. Hughes. (1989). Why Functional Programming Matters. *The Computer Journal*, 98-107.

Liang, S. (2017). Numerical Simulation of the Navier-Stokes Equations using Finite Volume Method.

Ludlam, J. (2024). *Corporate Liability in the United Kingdom*. Retrieved from Global Compliance News: https://www.globalcompliancenews.com/wcc/corporate-liability-in-the-united-kingdom/

Modarres, M. (1999). Functional modeling of complex systems with applications. *Annual Reliability and Maintainability Symposium* (pp. 418-425). Washington DC: IEEE.

Paz, A. C. (2011). Large-scale modelling of channel flow and floodplain inundation dynamics and its application to the Pantanal (Brazil). *Hydrol. Process*, 1498-1516.

Reitsma, R. &.-o. (1997). Object-oriented Simulation and Evaluation of River Basin Operations.

Rudorff, C. M. (2014). Flooding dynamics on the lower Amazon floodplain: 1. Hydraulic controls on water elevation, inundation extent, and river-floodplain discharge. *Water Resources Research*, 619-634.

Spink, A. S. (1998). NUTRIENT DYNAMICS OF LARGE RIVER FLOODPLAINS. *Regulated Rivers-research & Management*, 203-216.

T. Cohen Liechti, J. M.-L. (2014). Hydraulic–hydrologic model for water resources management of the Zambezi basin. *Journal of Applied Water Engineering and Research*, 105-117.

Tian-wen, Z. (2009). Navier-Stokes Equations Based Realistic Fluid Simulation. Microcomputer Information. *Microcomputer Information*.

Tiejian Li, G. W. (2011). Dynamic parallelization of hydrological model simulations. *Environmental Modelling & Software*, 1736-1746.