Simulo Tempestas: A Simulation Tool for Hydrological Modelling

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Abstract. Man's existence has clearly interfered with nature. Ever since man appeared on the face of our planet, the landscape was adapted to make it a more habitable environment. Although early humans transformed land to accommodate their dwellings and livestock, land was changed only to a certain extent. However, modern man has altered his surroundings beyond recognition through the building of road networks, sprawling cities, industrial zones, so on and so forth. This project studies the natural flow of water over the terrain through the use of a simulation tool, with particular focus on the Maltese Islands. Such a tool would help engineers plan better the assignment of construction zones as it allows proper analysis of the effects of land development on the flow of storm water before making any commitment that would change the landscape irreversibly. Different weather scenarios, based either on past statistics or completely fictitious ones, could be fed to the tool and its effects studied in the quest of finding the best solutions to avoid man-made catastrophes.

1 Introduction

Water is a major constituent of all living matter and is the key element to life. The hydrological cycle which entails, more than anything else, the precipitation of water on the ground is thus a part of a very important cycle, as it enables this precious resource to reach every corner of the earth. At times, however, this cycle causes extreme conditions like drought and floods. *Simulo Tempestas*, derived from the Latin meaning *'simulate storms'*, is a simulation tool that performs hydrological modelling on any given area of land to help in the prediction and prevention of flooding. While this can be applied to any area, the main focus shall be on Maltese terrain.

Hydrology, is defined by The Concise Oxford Dictionary, as *'the science of the properties of the earth's water especially of its movement in relation to the land.'*

The simulator models the interaction of water with a terrain in a three dimensional virtual world to help identify possible solutions to a flooding problem. The rainy weather plays the important role of 'watering' our world and our hydrological model must be able to mimic nature in dealing with the water once it touches the ground.

Almost every year the rainy season starts with a violent storm that causes damage to our small but precious islands. The development of this project has been motivated by the serious implications of events that often have great economic repercussions and at times even loss of life. These events are brought about by two major factors that can be attributed to man's interference with nature. The first factor is the climatic change brought about by what is known as the Global Warming

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phenomenon which the entire world is experiencing. Although there is strong political and scientific debate whether or not this phenomenon is the result of atmospheric pollution, there *are* changes in the climate. Extreme weather conditions like flash flooding and drought are clearly becoming more common.

Then there is the impact of buildings on the flow of storm water. On the local scene the construction boom over the last three decades has been eating away a disproportionate amount of land while vast areas occupied by post-war buildings have been left untouched. This puts pressure on the little land left available to cater for the increasing population and the exigencies of industry, causing damage to nature's own way of dealing with run-off water. The construction of whole towns and villages snap-on in the middle of major water courses is a huge mistake of the not so distant past which could have been easily avoided had common sense prevailed and the right tools been available to plan better.

1.1 General Objectives

The objective of Simulo Tempestas is to help hydrologists, engineers and town-planners in their daily work. In order to prevent catastrophes, engineers can assess the consequences that hypothetical land transformations may have on the hydrological balance. This is a very practical methodology as it allows experimentation without putting at risk the lives of people and the destruction of our land. The simulation operates in a world characterised by two entities:

– **Terrain -** the surface on which the simulation tool will model the flow of water.
– **Climate -** the entity responsible for pummeling the terrain with water in the form of precipitation.

Having defined our virtual world the objectives of Simulo Tempestas can be better understood. The following are the basic aims of the system:

1. to allow the creation of a customisable world including both the terrain and the climate
2. to simulate storms over primarily Maltese terrain, but flexible enough for other custom terrains
3. to render the simulation graphically in three dimensions
4. to present statistics and results in such a format that it is of great use to hydrologists and engineers

To achieve these objectives the project development is subdivided into two main parts:

1. World-editor tools
2. Simulation tool

World-editor tools The idea of having world-editor tools is to create a customised simulation project for the simulation tool. Over all, the primary aims to be achieved by the world-editor tools are:

– to let a user create/modify a terrain,
– to allow the user assign different parameters to the ground like absorptivity and roughness parameters,
– to give the user the ability to divide the terrain into named regions for better identification,
– to be as customisable as possible in the creation of a climate,
– to be able to save and load project files,
– to allow the exchange of data between different projects,
– to have a mixture of 2D and 3D elements to give the user all the relevant feedback.

Simulation Tool The simulation tool is responsible for running the actual simulation. Its primary objectives are:

- to allow the user load project files from the world-editor tools,
- to allow the configuration of simulation run-time parameters,
- to be as explicit as possible by having a mixture of 2D and 3D elements,
- to produce results relevant to flood analysis,
- to allow the user to save the outcome of a simulation for future use.

2 Design

Simulation tools are quite useless if they are not versatile in their configuration. However, versatility might also mean the introduction of additional complexity to the system which results in an unnecessary cognitive overload on the user. It is for this reason that Simulo Tempestas has been subdivided into three different parts, each part designated as an application of its own. With three distinct applications, each of them having their own specific role in the system, the user will be able to grasp their use faster than having one big application carrying out a multitude of different functionalities. The following is how the system is divided:

1. Terrain Modifier: A tool that allows the user to modify the terrain to be able to test new situations; e.g building dams, creating deeper basins, creating new canals, etc
2. Simulation Configuration Tool: This tool allows the user to create the climatic environment and terrain settings to be used in the simulation.
3. Simulation Tool: The tool responsible for carrying out the simulation itself depending on the settings given to it using the previously mentioned tools.

During the research phase it was seen how the problem domain has been tackled by others during the past years. The different techniques related to hydrological modelling with their pros and cons were analysed. It is rather useless implementing something already done before, therefore important changes are made by using the best of the these different models to come up with a fresh solution to the problem.

2.1 Terrain

The terrain is a very crucial aspect in hydrological modelling as without it there is nothing to model. Hence, in a computer simulation, the terrain itself as well as the quality of the terrain data is quite important. Something of real importance is that the terrain model is represented in the most efficient way possible so that any operations can be performed quickly. This is a big prerequisite especially in real-time simulations. The size of the terrain and the underlying data structure with which it is represented directly affect the efficiency of the algorithms manipulating the terrain data.

Digital Elevation Model The system makes use of 50-metre Digital Elevation Model which is nothing more than a 2-dimensional grid for which elevation data exists at the intersections of the grid rows and columns. The spacing between the points on a DEM grid (i.e. the row and column, height and width respectively) directly affects the level of detail of a DEM. In the case of a hydrological modelling tool, a refined and detailed DEM is required. This elevation data can be turned into what is called a *height-map.* The points on the DEM grid which have been taken at regular intervals, when stored in a 2D grid, are represented by the row/column cells. These individual pixels/cells represent elevation values on the map and are assigned a particular shade depending on the altitude. Usually shades of grey are used to produce a gray-scale image that shows the topographic relief.

Ground Properties There are many geological parameters attributed with the terrain that enhance the accuracy of hydrological models. However, from the research performed, three detrimental parameters have been identified as being crucial to our simulation and cannot be ignored. These three properties are:

1. Absorption
2. Ground Saturation
3. Terrain Roughness

Absorption and ground saturation properties are linked to *infiltration modelling* whilst the terrain roughness is linked to *flow modelling.* Infiltration modelling is important in establishing the amount of surface run-off generated during a storm. The more absorptive the ground is, the less run-off is generated. On the other hand, flow modelling is needed to establish the flow patterns and velocities over the ground over time. To be able to perform such modelling all the relevant data must be stored in an efficient and accessible manner.

2.2 Layering

The extra information associated with the terrain can be seen as a series of layers stacked on top of each other. These layers on are not necessarily dependent on each other, they just enhance the detail of our bottom layer - the terrain. This layering approach has several advantages from both the technical and usability point of view. The user is able to store many different layers on disk and load any one of them into the application at will. Different roughness layers, for example, might be used in conjunction with a particular climate layer. This allows better objective comparisons due to the ability of comparing like with like. The discrepancies that result from the simulation are known to be due to the change in roughness parameters. Once all the layers have been loaded and all the parameters set, everything is saved to a project file. These project files can then be fed into the simulation engine, through the simulation tool, and run. The following are the layers designed for Simulo Tempestas:

Terrain Layer This layer is the most important layer of all and is at the bottom of our layer structure. The terrain layer is represented, as has been explained earlier on, as a 2D grid of height values called a DEM. Having the terrain as a layer gives us that versatility that allows us to modify the terrain's geo-morphology independently from the rest of the ground properties.

Absorption Index Layer The absorption index is a value that represents the rate of absorptivity of the ground. The absorption rates of the ground can be set and adjusted depending on the surface geology of the terrain. Such information can be usually found in soil maps. This absorption rate depends on another factor also stored in this layer - the ground saturation. These two properties are tightly coupled together as they inevitably affect each other. The decrease in the absorption rate of the ground is due to a change in its saturation. The mapping between these two parameters can be either a system-generated linear decay relationship or else a custom drawn decay graph.

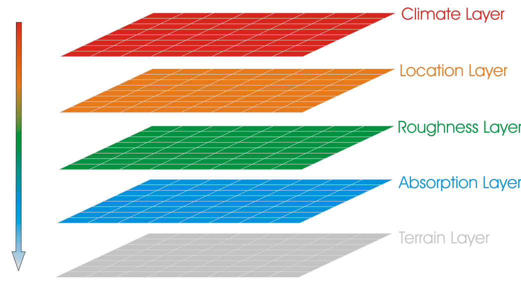


Fig. 1. *The layering in Simulo Tempestas*

Roughness Index Layer It was mentioned earlier on that our flow model will simulate the flow of water against time. A semi-empirical formula called Manning's Equation is adopted for such flow-rate prediction and is described later on in this synopsis. The so called *Manning constant,* is used in conjunction with other geo-morphological values, derived from the terrain data, to be able to calculate such water velocities. This *Manning constant* is what is being called in this system the *Roughness Index.* Allowing different areas on the ground to be assigned a roughness index enables better modelling of flow. To cite a small example, it can be said that a cemented surface allows better flow of water than a rocky and weedy surface. This index helps identify such features on the terrain.

Location Layer This layer serves the purpose of partitioning the terrain into indexed, logical partitions. Partitioning helps us understand and assimilate the results better since humans, by nature, give names to regions and places so that they are identifiable. The user might want to collect results from the tool using some particular scheme such as dividing the Maltese terrain by region e.g. North, South and Central or by locality e.g Attard, Birkirkara, Balzan.

Climate Layer The last and top most layer in our system, is as important as the rest. Ultimately, to be able to run a simulation something is needed to generate precipitation over the terrain. This layer consists of virtual clouds and wind which, as seen later on, are responsible for providing the data to our hydrological model.

3 Simulation Engine

Apart from performing the actual modelling, the simulation engine is also responsible for preparing and populating the necessary data structures that will be used during the simulation. These populated structures will be used throughout the entire simulation process many times over and have been meticulously designed and optimised to increase the efficiency of the simulation. Increasing the efficiency meant finding a balance between processor and memory usage.

The simulation process involves the triggering of appropriate events in an orderly fashion for a number of cycles. In one cycle of the simulation process, referred to as a *Tick*, the model is evolved by integrating the new input with the results of the previous cycle to produce another set of results. These in turn will be used again as input in the next cycle. Since the modelling is performed against time and our simulation engine works in a discrete manner, one cycle of events must represent some fixed amount of time. Having a cycle represent a small amount of time means that the simulation will take longer to complete. It is however left up to the user to decide how much time each cycle represents as this depends on the exigencies. The following mentions very briefly the processes required to be abstracted from nature and most importantly the way it is done.

3.1 Flow modelling

Routing the flow from one pixel to the next is one of the most important models in a hydrological simulation. Many different techniques have been presented along the years to determine how and where the water flows once it is 'dropped' on the ground by the rain-falling process. The very first flow path algorithms were the *steepest descent* methods [3], more popularly known as the D8 (Deterministic 8-node) algorithms. This method is in use by many GIS applications but has a major disadvantage as it only assigns one flow direction to one of eight possible neighbours and thus fails to model divergent flow properly. Another set of deterministic methods, called Fractional 8 (F8) assign flow to multiple directions by weighting the flow according to the slopes of descent. Such multiple-flow direction algorithm give more realistic representation of flows[2].

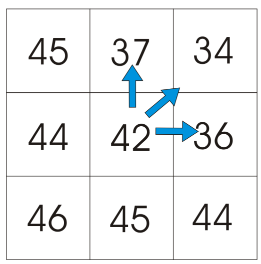


Fig. 2. *F8 multiple-flow method*

The method designed for Simulo Tempestas operates in a multiple-flow fashion and is integrated with a 'diffuse wave equation', called the Manning equation, to be able to calculate flow speeds depending on the surrounding lower-lying cells. If one or more neighbouring cells are lower in height, water will flow to each of them at a rate which is directly proportional to the gradient of descent - the steeper the descent the more the water will find it 'attractive' to use as an escape. The Manning equation is reproduced below:

$$V = \frac{U_m}{n} \,.\, R_h^{\frac{2}{3}} \,.\, S^{\frac{1}{2}} \quad (1)$$

$$F = V.CA \quad (2)$$

Due to the discrete nature of the DEM each of these cell-blocks, with a base area of 50 x 50 metres (i.e. 2500 m^2), behaves like a container. Therefore the volume introduced into the cell, ignoring for a moment the amount of water infiltrated into the ground, is contained within it and will contribute toward raising the water level of the entire cell.

Having the the **slope percentage** (pre-calculated), the **Manning constant** (provided), the **water level** in the cell (calculated at run-time) the flow **velocity** can be calculated using equation (1). The **volume** discharged can then be calculated by making an assumption about the geo-morphology of the channels that the cell shares an equal boundary of 25m with its eight neighbours. Having the width of the stream and water level the volume of water discharged can be derived through equation (2).

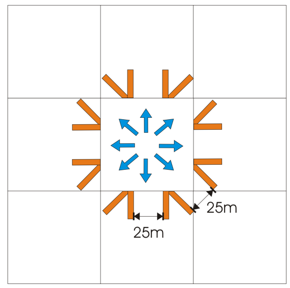


Fig. 3. *The channels assumed to exist between the cells*

The flow system developed can be considered to be particle-oriented system as each cell acts individually by pumping out the water to its neighbouring cells. This abstraction, termed as *FlowCell* in the context of Simulo Tempestas, is used to signify that to model water flow these pumps shall be pumping water into each other.

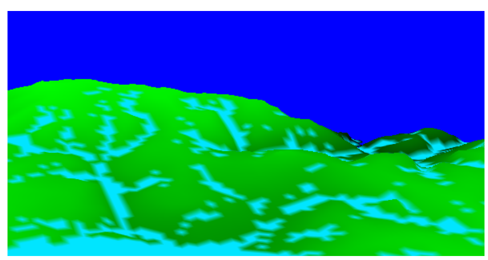


Fig. 4. *Screenshot - Run-off generation minutes after a storm begins*

Flat lands and Catchment areas All pixels on the terrain must be able to route flow downward if we are to produce a flood model. However, certain regions on the terrain like flat and pit areas cannot pass water as no steeper neighbours exist. Most hydrological modelling applications implement a pixel filling algorithm in the pre-processing stages to alter those cells on the ground that cannot pass water to other cells. The terrain is modified in these areas to force flow. This action seems to be to drastic so in our case, instead of making modifications to the terrain like the pixel filling algorithm, these regions are treated differently by creating to different concepts - *Flatlands* and *Catchments*.

Flatlands Flatlands are areas on the terrain composed of two or more neighbouring cells that have the same elevation value. In real-life, when water is poured onto a flat surface like a table, the water spreads all over the surface uniformly. The water keeps spreading, given that there is a sufficient volume of water to do so, until it encounters a drop in elevation (like the edge of a table) after which it all drains out from the boundary leaving only a thin film due to water tension properties. This is how Simulo Tempestas models the flow over a flat terrain. Whenever water is introduced to a small part in a flat piece of land, the water spreads throughout uniformly contributing to a rise in the water level throughout the entire area. Then, at the boundary of the flat land two different scenarios are possible:

1. The flat land might be part of a pit and thus all boundary pixels have a higher lying neighbour (discussed under the *Catchments* right after),
2. or else at least one boundary cell has a lower lying neighbour.

Since these group of cells are now treated as one object there is no need to make any alterations to the individual cells. During the simulation, when modelling precipitation, the entire flat land is treated as one piece therefore any water introduced is contributing to a global rise and any water flowing out is contributing to a global lowering of the level.

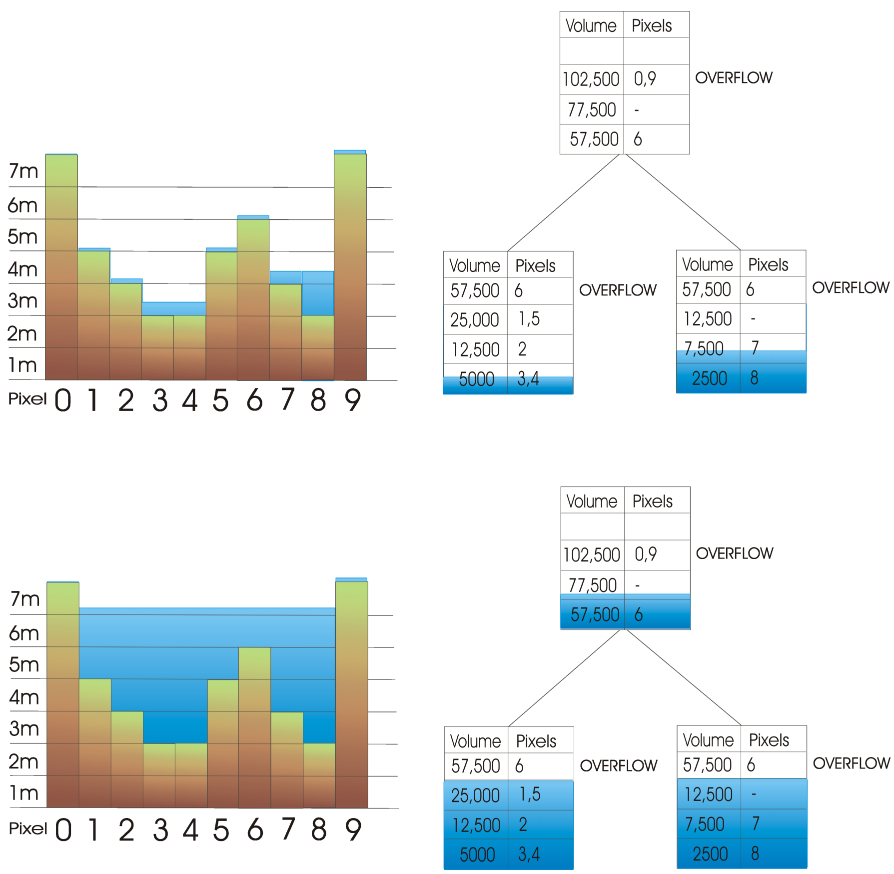
Catchments When surface run-off is generated and made to flow down slopes it might end up in some areas where there is no escape. Water flowing into parts on the terrain that are contained start to fill up and thus change completely the dynamics of the flow. Catchments, as defined in the context of Simulo Tempestas, are areas on the terrain that take water in to form 'pools'. This filling process happens because of the existence of pixels that are lower than the rest. The discretised terrain provides height values to the nearest metre, therefore when catchments start filling up, changes occur only at intervals of one metre. At these intervals, with incoming water flow increasing the height level, the surface area of the catchment grows bigger as it consumes new cells on the catchment brim. These cells are not regarded anymore as a separate pump with the previous slope gradients to lower pixels, but as cells that share the same water level with all the neighbouring cells that are part of this new catchment surface.

At one point, when the water level reaches the 'brim' of the catchment and makes contact with the rim of other neighbouring catchments, the water will start to overflow accordingly. Once these neighbouring catchments fill up to the brim too they merge into one bigger catchment forming a bigger surface area and once again the dynamics of the flow changes as they now share common boundaries. Mimicking such interconnectivity between catchments is possible through the use of a tree structure. These catchments are interconnected in such a way that help us keep track of the water in these pits. The purpose of such a tree is to store a hierarchy of these catchments as they fill up with water. The idea behind this approach came from a paper by Lee Vincent and Pierre Soille [1]. The authors of this paper discuss simulating a flooding process as if water is coming out of the ground, moving upward. They do this to delineate the watershed areas on the terrain without any pre-processing of the pits on the ground. To establish these catchment areas they process the pixels one altitude at a time starting from lowest going up to flooding the entire terrain.

3.2 Climate

Just as nature has its clouds and wind, our system too has its virtual clouds and wind. These clouds are stored in a climate layer in the layering system mentioned before. The precipitation process is responsible for feeding the hydrological model with rain. The rain data is fed into each individual cell on the ground by the simulation engine. Due to the nature of our DEM data i.e. the fact the cells have a large surface area of 50m by 50m, an assumption must be made that water is dropped

Fig. 5. *Simplified catchment tree at work*



as a thin sheet over the cell surface. Depending on the precipitation rate and the cloud coverage, the volume 'emitted' by the cloud can be easily calculated. Raining on the terrain is done in three phases;

1. Raining on catchment areas
2. Raining on flat lands
3. Raining on the individual flow cells

The reasons behind the introduction of these three particular objects into our system have already been discussed. The flat lands and catchments, both comprised of many flow cells, are now seen as a group of cells that have to be all treated in the same way as they share the same water surface. They have to be viewed as different-sized 'particles' and thus have to be rained upon differently. Since each ground cell is defined as a flow cell and acts in an autonomous fashion the climate must feed water to them individually.

4 Conclusions and Future Work

Simulo Tempestas allows an engineer to effectively plan the development of a region so as not to disrupt the natural course of storm water. Better still, it could actually be used to improve an area, by making changes that will allow it to cope with extraordinary heavy downpours. All the four project primary objectives that were set at the outset have been achieved since the end product:

- allows the creation of a customisable terrain complete with its climate
- it is fully capable of simulating storms
- it presents such storms and its effects graphically in three dimensions
- it captures and presents statistics and results in a useful format for hydrologists and engineers.

It gives the user the possibility to examine hypothetical weather scenarios and their impact over time. At the same time it is structured in such a way that future add-ons can be plugged in with very minor modifications. The simulator can be developed further into an early warning system for flood prone areas if it is integrated with live satellite DEMs and weather forecasting software. Such a package could be radio-linked to earth stations in vulnerable areas from where evacuation plans can be triggered to mobilise communities in danger and move them to safer zones.

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