Transformation of urban flood modelling from hydrodynamic to system dynamics approach

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Abstract. Flood problem is one of the key issues in the urban water management practice. Currently, there is a gap between flood prediction techniques, which mostly by Hydrologic Modelling, and the water management modelling, which mostly use the System Dynamic approach. This paper evaluates the possibility of the integration of hydrodynamic modelling to System Dynamics, which is one of the most common method to develop an urban water modelling. By integrating hydrodynamic modelling within a larger system dynamics-based urban water modelling, the hazard aspect of urban water management can thoroughly be examined. In this paper, the integration of Hydrodynamic Modelling into system dynamics-based urban water modelling is achieved by implementing the flow inputs of hydrodynamic modelling as a variable in the system dynamics.

1. Introduction

One of disturbances that may occur in an urban area is when there is an unexpected body of water on the surface, due to the amount of water entering the area is higher than its capacity to discharge it. Flood problem in urban areas is induced by various factors, such as the network system of drainage within the urban area, higher rate of rainfall than anticipated, and changes of volume of water carried by rivers passing through the city. In general, causes and types of urban flooding can be categorized to [1] Lack of drainage infrastructure, Blockage of the drainage system, Flooding in low-lying areas, Backup due to elevated downstream water levels, and Inundation caused by high river water levels. Mitigation measures for those problems are related to other aspects of urban management, such as provision of freshwater, drainage system, and water storage. For example, during rainy season, most water that enter an urbanized area should be discharged to its outer part, while in a dry season, incoming water should be stored to maintain the supply of freshwater. Therefore, we can argue that flood management is an integral part of the urban water management.

Efforts to manage urban flooding problems mostly started with predicting the flood itself, by using flood modelling to produce predictions about potential flood that may occurs. The most common type of flood modelling is the Hydrodynamic Flood Modelling, which calculates the characteristics of the water flow, either in channels or on surface. Despite this approach is proven to be useful for municipalities to manage flood problems, hydrodynamic approach is not suitable to be developed as a basis for urban water management. The main drawback of hydrologic modelling is this approach considered water as a continuous flow, from inlet to outlet. It simplifies the situation by assuming that a problem occurs when the volume of water at inlet is bigger than at outlet.
Urban water management is actually beyond that, because water is not only passing, but also may be utilized for various purposes, such as household activities, water-based services, and even for industries. Therefore, there is a need to explore how hydrologic modeling can be integrated to urban water management modelling. This paper evaluates the possibility of the integration of hydrodynamic modeling to System Dynamics, which is one of the most common methods to develop an urban water modelling. By integrating hydrodynamic modeling within a larger system dynamics-based urban water modelling, the hazard aspect of urban water management can thoroughly be examined.

2. Hydrodynamic approach for flood modelling
This paper implements a Meta-Synthesis approach, which analyses and synthesizes the key elements in research related to the concept of a resilient city and the implementations of measures to achieve it. The aim of the meta-synthesis in this paper is to transform findings in each of the research and implementation to construct a new concept and generalization [10], [11]. In this paper, available methods and practices to improve or achieve the adaptive aspects of a resilient city were examined to make a categorization of those methods and practices. While previous works related to implementations of hazard mitigation measures in urban areas are abundant, a specific research that summarizes those measures and categorizes them based on their characteristic is not available.

To establish an overview of methods and techniques related to adaptability measures in urban areas, this paper first formulates the underlying characteristic of those measures. This step will produce general categories of adaptability measures. The main hypothesis of this paper is that by comparing the main characteristics of adaptability measures toward a resilient city, a pattern will emerge, that will make a categorical grouping of those measures possible. After the general categories of adaptability measures are established, the next step is to perform an in-depth analysis of each category, to explore the similarity and variance of adaptability measures that fall within the same category. The result of this phase will give a detailed explanation about types of adaptability measures, how they are implemented, and examples of their implementations.

2.1. 1D flood modelling
In the 1D approach, water flow is assumed to occur in one dominant spatial dimension aligned with the centre line of the main river channel. The geometry of the problem is represented in the model by channel and floodplain cross-sections perpendicular to the channel centreline. Measured distances between these cross-sections are also required by the computer model [2]. According to [3], 1D Flood model is capable of capturing the downstream propagation of a flood wave and the response of flow to free surface slope, which can be described in terms of continuity and momentum equations as:

\[
\frac{\partial Q}{\partial t} + \frac{\partial A}{\partial x} = q
\]

\[
S_0 = \frac{n^2 P^{4/3} Q^2}{A^{10/3}} - \frac{\partial h}{\partial x} = 0
\]

Where \( Q \) is the volumetric flow rate in the channel, \( A \) the cross-sectional area of the flow, \( q \) the flow into the channel from other sources (i.e. from the floodplain or possibly tributary channels), \( S_0 \) the downslope of the bed, \( n \) Manning’s coefficient of friction, \( P \) the wetted perimeter of the flow, and \( h \) the flow depth. One source of the technical requirements in an urban flood model is from [4], which stated that data requirements for 1D flood modelling are:

- Dynamic flow description: when urban flooding occurs, surface water can flow in both street and pipe systems with flow exchange between these two systems through manholes. This means that simulation of backwater effects is needed in modelling of urban flooding. By using a dynamic wave model, the model includes backwater effects and surcharge from manhole including rapid change of water level.
- Parallel flow routing: while surface flooding takes place, water from the pipe system flows through
manholes or catch pits to street system. Flow along the street (e.g. right above the pipes) can be in either direction along the streets, i.e. it can flow following a slope of the street or against it. It is not necessary that the flow direction in the street has to be the as the flow direction in the pipe system.

- GIS interface: GIS is important in simulation urban flooding. It is used as a tool to provide data and display simulation results. Surface storage for simulating surface flooding can be calculated by the application of GIS together with the DEM the study area, i.e. find area–elevation relation from DEM. In addition, results of the simulation can be easily understood in form of flood inundation maps. Model output in term of water along the streets are transferred to GIS and with interpolation routine, water surface is able developed. Flood inundation maps can be generated by overlaying of water surface and introducing flood depth map which is a method to visualise flood situations.

The main drawback of 1D flood modelling approach is an inaccuracy in the treatment of street channels and in the case of water flow on a surface. Both cases still considered as one dimensional. When the channels are overtopped, the flow of water is not only no longer 1D, because water move around 2D plane.

### 2.2. 2D flood modelling

As an addition to 1D flood modelling, 2D flood modelling can be used to analyse flow behaviour on a surface, both for water depth and velocity. 2D-modelling of out-channel floods clearly has the potential to revolutionise understanding of high-magnitude spatial and temporal hydraulics and high-magnitude flow phenomena, geomorphological and sedimentological processes, and hence rapid fluvial landscape change. This potential for new understanding is because of the now wide availability of high-resolution DEM data for large and often inaccessible areas, and the availability of remotely-sensed data [5]. Models to predict flood inundation based on the 2D shallow water equations are classed here as 2D approaches and solve for water level and depth-averaged velocities in two spatial dimensions. Unlike 1D models there is no need to prescribe a particular direction for the flow in 2D models. This brings advantages in terms of providing more detail on the nature of floodplain inundation but also introduces a number of limitations, e.g., difficulties in including hydraulic structures such as weirs and bridges in the models, longer computer run times and greater data requirements [2]. The system of 2D flood model consists of three equations: one equation for continuity and two equations for the conservation of momentum in the two orthogonal directions [6].

\[
\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0
\]

\[
\frac{\partial (hu)}{\partial t} + \left(\frac{h}{2}u^2 + \frac{v^2}{h^{1/3}}\right) + \frac{\partial (hu)}{\partial y} + gh \frac{\partial h}{\partial x}
= -gh \frac{\partial^2 z_b}{\partial x^2} - g n^2 \frac{u \sqrt{u^2 + v^2}}{h^{1/3}} + \nu eff \frac{\partial}{\partial x} \left( \frac{h}{\partial x} \right) + \nu eff \frac{\partial}{\partial y} \left( \frac{h}{\partial y} \right)
\]

\[
\frac{\partial (hv)}{\partial t} + \left(\frac{h}{2}u^2 + \frac{v^2}{h^{1/3}}\right) + \frac{\partial (hv)}{\partial x} + gh \frac{\partial h}{\partial y}
= -gh \frac{\partial^2 z_b}{\partial y^2} - g n^2 \frac{v \sqrt{u^2 + v^2}}{h^{1/3}} + \nu eff \frac{\partial}{\partial x} \left( \frac{h}{\partial x} \right) + \nu eff \frac{\partial}{\partial y} \left( \frac{h}{\partial y} \right)
\]

In equation above, \( h \) is water depth, \( u \) and \( v \) are velocities along horizontal \( x \) and \( y \) axes, \( z_b \) is bottom level, \( n \) is Manning’s roughness coefficient, \( g \) is gravity acceleration and \( V_{eff} \) is effective cinematic viscosity. Usually, it is assumed that the viscosity is constant throughout the flow field. Although 2D flood modelling can accurately describe the behaviour of flow on a surface, this model also has some drawbacks. First, calculation method is considerably more complicated than 1D flood model, and second, river and drainage network sometimes has a complicated morphology that cannot incorporated sufficient enough in 2D flood model.
2.3. 1D2D flood modelling

Because both 1D and 2D flood modelling has its own advantage and disadvantages, there are extensive approaches to integrate 1D and 2D models resulting in hydrodynamic model of floodplains and integrated 1D (channel flow) and 2D (overland flow), or widely known as 1D2D flood modelling. The main idea of 1D2D flood modelling is integrating 1D hydrodynamic modelling technologies, Digital Elevation Models and GIS systems is to take advantage of the best combination of 1D hydrodynamic data for rivers together with 2D terrain data, and presenting them in the GIS as maps [3].

The integrated one-dimensional and two-dimensional (1D-2D) model development focuses on the extension of model capabilities in order to simulate flooding situations more accurately. This includes improving flood wave propagation over initially dry land, improving the presentation of hydraulic control (levees and embankment) in the floodplain and integration of one-dimensional hydraulic elements (pumps, bridges and regulator gates). The combined 1D-2D modelling opens up the possibilities for studying flood control measures, flood forecasting, and development of flood evacuation plans. Main advantages of 1D2D flood modelling model are [7]:

- Flow computation on initially dry land, without using any special drying or wetting procedures.
- Accurate and stable flow computation on very steep slopes, such as dike walls and other manmade structures.
- Especially suitable for short event predictions (hours and days).
- Realistic flood predictions of dike break due to heavy rainfall or other natural hazards.
- Pre- and post-processing within a GIS environment.

For 1D-2D flood modelling, there are four parameters needed for the input which are [8];

- Digital Elevation Model to represent topography and river cross sections.
- Roughness data to represent the resistance to water flow on.
- Embankment and other artificial structure to make the model work as close as to the real-world condition.
- Boundary data in which time series of flow or water levels or Q-H relation can be defined.

3. System dynamics

System dynamics is method of thinking that can help to understand a complicated relationship in a system that consists of multiple key factors, constructing and visualizing the dynamic relationship between those factors within the system. [9]. After the system is constructed and visualized, users can modify the values of the factor to evaluate the behaviour of the system, and even find the optimum setting for each factor. System dynamics approach is unique from other method to construct a complex system in a way how its simulates and predicts a complex nonlinear system, and has been widely implemented in scientific research and engineering application. System dynamics is also already applied in solving the difficulties in researches, modelling and simulation is implemented during the analysis [10]. System dynamics was developed based on systems theory, which is a scientific field that tries to understands a system by focusing on its key components, relationship between components, and its internal mechanism. Implementation of System dynamics to represent real-world systems gain a worldwide attention when it is proven effective to develop an efficient management strategies for private companies.

In a computer-based construction of System dynamics, key factors or components in a complex system are represented as Stocks, Flows, Converters, and relationship among those components. The relationship among components are represented graphically, and modelled by a mathematical finite difference equations. A specific value of each component is calculated for each time step that pre-defined during the construction of the model. Computer-based simulation for system dynamics methodology mostly constructed using software modelling that are object-oriented in nature, such as Powersim, Vensim, Stella, and AnyLogic [11].

In visualizing a complex system of urban water management, system dynamic can be used to
integrate a various types of sub model both from quantitative and qualitative data. System dynamic analysis respects the complexity of relationships between research objects by accommodating them through an arrow pointed from one subsystem as represented by a variable to others. The arrows reflect the relationships between variables. The positive marks signal the reinforcing value of relationships while the negative marks are utilized for balancing the relationships. The relationships resemble the reality of a multi-system within the community. Figure 1 below shows a simplified version of relationships in system dynamic analysis.

In order for a system dynamic analysis in urban water infrastructure to be conducted, first a modelling process should be completed. (Sterman 2014) suggests that there are five major steps of modelling, as follows:
- Problem articulation
- Formulation of dynamic hypothesis
- Formulation of a simulation model
- Testing
- Policy design and evaluation.

Models in system dynamics are continuous, with a constant time steps. The time advancement is regular, the values of the components changes during the time advance, and the system records those values at any time the simulation run [12]. Therefore, System dynamics simulation models can be considered as discrete-time models. At any time-step $t$, the state of the model and the values of its components is an exact value, and must be unambiguously can defined. This model’s state at time-step $t$ will determines the state of the model at time-step $(t+dt)$, where $dt$ is the later time-steps.

![Figure 1. An Example of Relationships Between Factors in System Dynamics.](image)

4. Results

From the discussion in the previous section, we can assume that system dynamics approach may be applied to develop a dynamic hydrodynamic systems such as urban flood modelling. Characteristics of elements of system dynamics, one of them is Flow, is directly compatible with the concept of hydrodynamic modelling. The key aspect of System dynamics, which is the constant time-step, is also linear with the concept of hydrodynamic modelling, because the time-step is associated with periodic nature of observations on urban water infrastructures. The principle of interconnection between components also can be used for realistic modelling and simulation of urban flooding. Example of System dynamics in urban flood and water management can be seen in [13], which developed a simulation of the operation of reservoirs for managing flood hazard. Another example is shown in [14], where a System dynamics-based hydrodynamics model is constructed in order to evaluate the system performance, especially its loss, due to flooding that caused by extreme rainfall, as well as how they can
potentially recoverd due to a city’s adaptive measures.

Key components of System dynamics can be used to construct a complete hydrodynamic model. Flow component of System dynamics can be used to model simulate a wide array of water infrastructures that carry water into the city or discharge it to outer part of the city. Stocks are implemented to calculate the volume of the water that collected in the urban area. Connections can be implemented to model the water and drainage network within the area. The conceptual method of how hydrodynamic model is constructed in a System dynamics approach can be seen in figure 2 below.

Figure 2 shows the key components of hyrdologic modelling that represented as a flow diagram, a method that widely used to sketch the model of complex system. The inflow of water into the urban area is primarily from local rain that may collected in the drainage system or became a run-off water on the surface of the terrain. The inflow water can also from rivers that entering the city that connected to the drainage system. Even when there is no local rain, an excessive amount of water from incoming rivers can also caused flood in the urban areas. After the flow diagram is constructed, the next step is to develop a computer-based model of the flow, as seen in figure 3.

![Diagram](image1)

**Figure 2.** Conceptual Method of Flood Modelling in System Dynamics

![Diagram](image2)

**Figure 3.** Example of Flood Modelling in System Dynamic Software (Powersim)

In Figure 3 above, The main components of the model are:

(a) Levels or Stocks, which consists of Inflow Water, Outflow Water, and Surface Water

(b) Flows, that consists of Inflow Rivers, Rainfall, Drainage Network, and Water Storage

(c) Connectors that simulating the flow of water from one components to another.
The values of those three components can be calculated by a 1D Hydrologic model. The volume of water can be entered directly from data source to the system dynamic model, while the capacity of water infrastructures must be calculated first by using equation (2) before implemented as an input for the System dynamic model. The functionality of System dynamic approach for flood modelling cannot extend to evaluate the water behaviour above the terrain surface. Hence, 2D or 1D2D hydrologic modelling cannot transformed into a System dynamics model. However, this drawback should be compensated by the increased accuracy and the visualization of the water system within the System dynamics model.

5. Conclusions
Adaptive aspects were seldom given priority in promoting a resilience city, due to those aspects’ complexity compared to the vulnerability aspects. Because a city’s resilience is measured in both adaptive and vulnerability values, the lack of adaptive efforts was not emerged as a concern, as long as the vulnerability-reducing efforts were adequate. By focusing not only on vulnerability but also towards adaptive aspects, the quest to make a city resilient will be improved. Recently emerging technologies provide an opportunity to further increase and promote the adaptive measures in facing disturbances and disasters. With these technologies, various applications, either desktop or mobile, can give suggestions to users to avoid disturbances, such as traffic jam, flood, etc. It is up to the user whether to use these suggestions or not.

The main challenges of utilization of those technologies are the security aspect of the technologies itself because the implementation of applications to increase a city’s adaptability will also increase in its vulnerability, because technologies, especially in form of computer systems, are prone to malicious attacks, i.e. from hackers and computer viruses. Therefore, implementation of new technologies in promoting a resilient city must be taken very cautiously.

This paper shows the possibility constructing a System dynamics-based flood modelling based on input both from raw data and 1D flood modelling. The visualization funcionality of System dynamics should give an added value to the flood modelling practice, because planners and decision makers can evaluate the existing condition of flood hazard and generate scenarios to various possible conditions. Even though the 2D and 1D2D hydrologic modelling is not possible to be transformed into a System dynamics, the visualization of the water network can give a lot of advantages.

For our future work, we planned to construct a complete model of System dynamic-based flood modelling, based on the existing 1D flood models for a particular city. By contructing a multiple System dynamics-based flood modelling from various 1D flood, we hope that we can evaluate the accuracy of the flood modelling if it is constructed using a System dynamic approach. An integrated model of System dynamics and 1D flood modelling is also possible, that would bring a complete new approach in flood modelling for urban environment.

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