Role of Hydro GIS Tools in Hydrological Modelling and Urban Flood Management: A Literature Review

RMM Pradeep[1#] and NTS Wijesekera[2]

[1]*Faculty of Computing, Kotelawala Defence University, Rathmalana, Sri Lanka*
[2] *Construction Industry Development Authority, Ministry of Urban Development, Water Supply and Housing Facilities, Wijerama Mawatha , Colombo 07, Sri Lanka*

#pradeep@kdu.ac.lk

Abstract: *Hydrological modelling and urban floods have a strong relationship as flood management is based on hydrological calculation. GIS assists this relation by providing an easy environment to carry out difficult and time-consuming steps of hydrological calculations. However, when developing automated GIS tools for the above process, there are no guidelines available to manage the software project easily. Then developing a comprehensive guideline requires to clearly understand of the role of GIS in the urban flood and hydrological modelling relation. The present work carried out an in- depth study on; flood, land management, hydrological modelling and GIS assistance to hydrological modelling to understand the role of hydro GIS tools in urban flood management. It used the semi-systematic literature review method to review the gathered knowledge. Through the analysis, it found a close relationship between flood and land management, specially in urban areas.*
Further, it found that now GIS is assisting in performing the major functions of hydrological models than the inception, and the HydroGIS term has been introduced to identify the software tools that assist flood management through hydrology modelling. Further, it has been understood that HydroGIS tools are employed in local-level flood management activities and utilised by non-technical decision-makers for day-to-day activities. Hence the HydroGIS tools can be introduced to the local level authorities as an interface to perform complex hydrological processes when land management decision-making.

Keywords: *Urban Flood, Hydrological Modelling, state-of-art Review, HydroGIS tool, Flood Management*

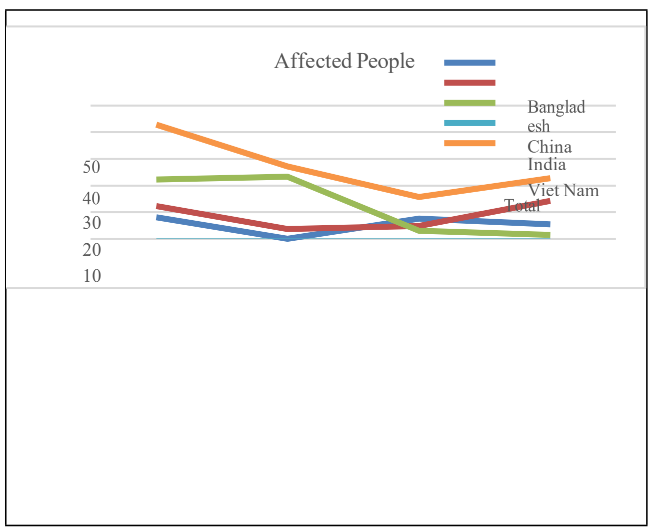
1. Introduction

A. Land and water

It has studied that, the cities are getting crowded and new urban areas are being created as a result of man-kind attention change from agriculture-based economy to industrial-based economy (Henderson, 2003; National Geographic, 2020; Weeks, 2010, p. 2). According to the statistics in 2018, 55% of the world population lived in the urban area, but UN predicted that it will reach to 78.3% by 2045-2050 (UN, 2018b, a). Same way, it has predicted that the global urban land cover would be increased to approx. 1.5 million km^2 by 2030 (Seto et al., 2011). Considering the total world land area of 148.94 million km^2, this is only 1.025%. Hence, it shows that urban population densities are getting more compressed. This situation increases the complexity in land management as repercussion of a simple failure effects on large population.

One of such critical decision making is flood management, as the cities are evolved around water ways such as rivers and bays which prone to flood. Further the notable effect of urbanization on land cover and land use resulted high direct runoff creating flood situations, while high population density increases flood risk and damage (Archer & Fowler, 2021; Feng et al., 2021) . Then the flood managers obviously pay the attention to land management and other integrated approaches when flood management. As well analysing the available flood data on four leading flood effected countries, it found that the damage to the people is reducing but the damage to economy is increasing (Figure 1). Hence, now the flood is becoming as a challenge to economic growth of most of nations (Miller et al., 2014; OSPHP, 2014; Sun et al., 2011; World Bank, 2016).

Then todays passion is to manage the flood through integrating land and stakeholder management approaches and institutions such as Integrated Water Resource Management (IWRM), Organisation for Economic Co-operation and Development (OECD) and Low Impact Development (LID) (OECD, 2015; Piyumi et al., 2020; WMO, 2013).



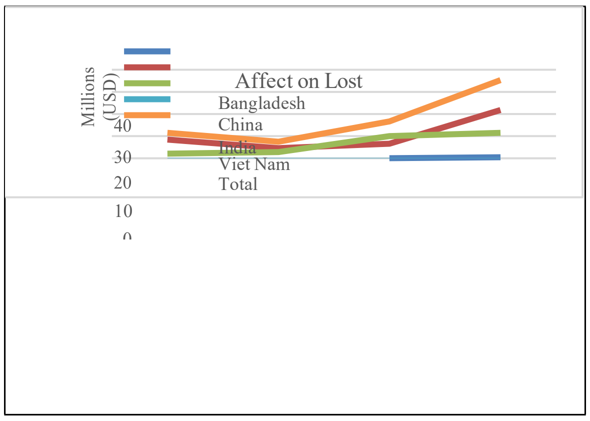


Figure 1: Comparison of flood affect
Source: created using (EM-DAT, 2020)

A. Water and GIS

Flood is natural phenomena which gather excessive water than normal situation. Hence, to manage the flood it requires to manage the water. For the purpose, the decision makers need to understand the natural water behaviour, or scientifically the hydrological cycle. Then to understand the water behaviour in different situation, the hydro models are being developed (Solomatine and Wagener, 2011; Devi, Ganasri, and Dwarakish, 2015). The curiosity on water led to human to understand the water cycle process since ancient times, i.e., 1200 B.C. However, since A.D. 1800s, the water experiments started to flourish, and hydrologists have been utilised such timely-tested hydrologic models to water resource management. Further, these hydrological models are now considered as mature to provide accurate flood management information (Chow, Maidment, and Mays, 1988, pp.12–17).

However, when consider the three main components in water cycle in urban situation (precipitation, runoff, and infiltration/evaporation) (Jacques, Stergios, and McPherson, 1980), the land cover critically effect on runoff, and infiltration. Hence, when hydrological process, it required the accurate information regarding the land cover conditions to calculate accurate output. However, the main difficulty is, the accuracy is dependent on the resolution of spatial information. This required higher computational power as it needs to manipulate high-resolution and large amount of spatial data.

In such scenario, the development of Geographic Information Systems (GIS) which evolved about a half-century ago could be able to efficiently handle the foresaid problems and simulate the models dynamically. Hence GIS become a one of the tools of hydrology modellers and further flood managers (Ogden et al., 2001).

Even though GIS had the poor usability problems, the technological boost has solved all those presently (Barik et al., 2016; Bhor, 2015; Chappell, 2010; Goodchild, 2016; Kar et al., 2016; Yang et al., 2017). With the advancement of GIS in handling complex and massive data sets (Devi, Ganasri, and Dwarakish, 2015; Coskun et al., 2010), the spatial-oriented distributed hydrological models now become a lumped model to the users which is essential in today's water management decision-making functionality (Alcaraz et al., 2017; Paudel, 2010; Pullar & Springer, 2000; Shamsi, 1999).

Therefore, the now, the GIS has become a sine-quo-none component of the Hydro model and the term 'HydroGIS' refers to a common ground between hydrology and GIS components. The HydroGIS model is preferred to the hydrology and GIS model integration for water simulation. HydroGIS tools are designed for practising scientific hydrology models using the spatial information management process of GIS (M. J. Clark, 1998). HydroGIS tools, on the one hand, provide GIS capability to capture, compute, and deliver inputs to Hydrologic models. On the other hand, it captures, computes, and delivers the Hydrologic model outputs to users as spatially distributed map-based information (Maidment, 1996; Pradeep & Wijesekera, 2020a).

C. Problem Statement

Then as described, the land, water and GIS are relating each other's, and it understood that today hydrological models must be integrated with the GIS while making decisions in flood management. However, this critical workflow is needed to be automated on the platform of GIS (Pradeep & Wijesekara, 2018). Nevertheless due to computing discipline guidelines, it requires a suitable modelling framework to automate the workflow related to input-process-output of Hydro-GIS model (Pradeep & Edirisuriya, 2021; Pradeep & Wijesekera, 2021). Then, the fundamental requirement in development of any framework is understand the state-of-art in the research area.

Therefore, it searched the review-articles for the year 2022 (up to June) via Google scholar for AND joining key words of "GIS", "hydrological model", "flood management" and "Review". It resulted 162 articles, however it found that only seven articles are related to the present scenario. Nevertheless, those seven are on hydrological modelling practices for flood management, applications of GIS in water resources, disaster management and flood risk management, urban flood models in flood mitigation strategies, hydrological modelling practices for flood management, flood modelling for urban flood risk management and GIS technology for mapping and modelling urban floods. Then, as those articles are in out of focus, it required to review the available knowledge on the present interest.

D. Aim

Then the aim of the present work is to review the role of GIS tools in flood management and hydrological modelling. Then such understand will provide the required background information to build a suitable framework for Hydro-GIS model development.

2. Methodology

Due to the present research attention is fallen on multiple disciplines it decided to use semi-systematic literature review method (Snyder, 2019). There are three research questions were developed and utilised to collect literature through searching the relevant keywords for each question. The questions are (1) What are the interesting relations between Flood and land management, (2) What are the interesting relations between Hydrological modelling and GIS, and (3) What are the importance of GIS tools in flood management. Then the collected answers were divided in to five main themes such as (1) Flood, (2) Land, (3) Hydrological Modelling, (4) GIS tools, and (5) Implementation of Hydro GIS tools; and developed the review based on those themes.

3. Literature Review

A. Flood

The floods are events of the natural water cycle and based on the floods' nature, those are classified into 6 different types, as shown in Table 1. According to Kocornik-Mina et al., (2016), the urban flood is the most important to humans as those reduce the cities' annual economic activities by 2 to 12%. Further several studies retrieval that, the cities are always subjected to flood with flood damage worth more than Trillion USD and devastating factor to economies (OSPHP, 2014; Sun et al., 2011; Miller et al., 2014; Gunaruwan, 2016; Huizinga, Moel, and Szewczyk, 2017; World Bank, 2016).

Table 1: Different flood types

Types of flooding	Causes (Natural)	Causes (Human activity)	Onset time Duration
Urban flood	All other floods	Drainage problems, Land permeability, Lack of management	Varies. Hours - Days
Pluvial and overland flood	Extreme rains, Jamming in water bodies, landslides	Land cover changes	Varies. Varies
Coastal (Tsunami, storm surge)	Extreme Natural reasons	No direct action but harm for Coastal living	Rapid. Minutes to Months
Groundwater	Increase in the water table	Influence on natural aquifers	Slow. Longer
Flash flood	Quick release of blocked streams	Collapses in retaining, Obsolete Infrastructure	Rapid. Few hours
Semi-permanent flooding	Sea Rise, Land Subsidence	All the above	Slow. Long/ permanent

Source : (Jha et al., 2012, p. 57)

When considering the fundamental circumstances of floods, climate change is the most prominent, as human activities contribute to global warming and promoting climate change such as CO_2 emission and global greenhouse gas (GHG) emission (Aalst, 2006; Milly et al., 2002; World Bank, 2019).

However, some studies show that, flood is a natural phenomenon to manage the equilibrium. Nevertheless, human tend to locate in flood plains and their activities on behalf of economic reasons such as businesses and poverty, block the natural cycle. Then it develops floods even in regular rain events (Lee & Jung, 2014; Loucks et al., 2006). Even though there are concepts, policies, and regulations to control the human activities, due to less integration of governors and inhabitants, and gaps, political influences and poor enforcement of the available law structure; those are limited to documentation (Baker et al., 2014; Jha et al., 2012; Zhou, 2014).

B. Land

The surface runoff is the main source to flood and proved that there is a relation between urbanisation and the surface runoff increase (McGrane, 2016; Odunuga, 2008; Prachansri, 2007; Shrestha, 2003; Wakode et al., 2018). It has identified that surface runoff increasing activities in urbanizations are cover with impenetrable materials over the land, changes made to soil, slope and specially divert natural water paths. (Marshall & Shortle, 2005, pp. 63–70; Prachansri, 2007). Then those changes are also observed as 3 spatiotemporal changing patterns; "grow", "shrink", and "normal" (Ping, Xinming, and Huibing, 2008). However, according to the universal truth, the water is flowing from high grounds to the low ground under the gravitational influence, but not under the human's importance. Hence, when manage the flood water it required to consider both the natural and human land scenarios (Douglas et al., 2019, p. 30; IWA, 2013).Therefore, land management become a key activity in flood management and requires hydrologically planned land management (Pradeep & Wijesekera, 2020a).

C. Hydrological Modelling

Then the foundation of "hydrologically-planned land development" is reliable water flow calculation method and hydrologic modelling assist such (Burges, 1986; Ogden, 2021). As the present scenario is about urban land management, the urban hydrology, which consider the water relationship with human needs picked the attention (Shrivastava, 2016). Unlike general hydrological modelling, the urban hydrological modelling appeared in later in 1960's for urban land management (Leopold, 1968). Since then, researches are observed on the subject such as Mcpherson and Schneider, (1974) attempted to identify the problems on the urban watershed, Chan and Bras, (1979) analysed the flood volumes in urban extends, Jacques, Stergios, and McPherson, (1980) modelled the runoff process of the urban and Maidment and Parzen, (1984) analysed the urban water use. Since 1980s urban water management become a popular study and being treated as a most critical activity for modern water management (Chow et al., 1988; Shaw, 1994; Smart & Herbertson, 1992). Fuelling with the swift urbanisation since 1990s, global level initiatives such as UNESCO Urban Water Management Program (UWMP), have been set up to manage urban water to share the knowledge among nations (Makarigakis & Jimenez-Cisneros, 2019).

There are two types of hydrological models; lump and distributed. The distributing modelling are more realistic but due to the land's undulation nature; it required higher resolution in spatial data. With the increased resolution it gives more accurate results but reduces the model performance (Becker & Serban, 1990; Ficchì et al., 2016; Ichiba et al., 2018). To increase the model performance it required to make the summation and averages of the parameters, then it generates considerable deviations from the reality (Afouda & Szolgay, 1987; Becker & Serban, 1990, p. 26). Even though it created a distributed type of output with higher effort, then calibrations required same effort to be paid again. Hence the trial-and-error processes, communicate the output to non-technical persons and improved visual outputs are become the hydro modelling a tedious and unthinkable work (Becker & Serban, 1990; Eger et al., 2017; Fatichi et al., 2016).

D. GIS Tools

However, utilising the technologically advanced GIS, those tedious task could successfully managed. Todays GIS is capable to model the multi-criteria and multi-model analysis and those are used as process automaton agents, data handlers, and visualisers in hydrological modelling (Cordão et al., 2020; Kubwarugira et al., 2019; Moncada et al., 2020; Ogden et al., 2001; Ramkar & Yadav, 2019; H. T. Su et al., 2018; W. Su & Duan, 2017; Thakur et al., 2017).

Further It evaluated 10 key research in the hydrological modelling since 1986 to 2020 for assess the level of GIS assistance in hydrological process as shown in Table 2.

Consider the close bond and attractive scientific models' integration between the Hydrological model and GIS: The HydroGIS93 conference in April 1993 at Vienna introduced the term "HydroGIS" (Kovar & Nachtnebel, 1993). Even though the ample number of tools are developed using hydro and GIS, the term rarely appears in the articles (such as Nhan et al., 1995; and Shokoohi, 2007). Then it observed that Pradeep and Wijesekera have introduced the term "Hydro-GIS tool" for flood management software tool, which facilitates the local authority to manage the urban land with the flood management capability enhanced by GIS and hydrology models (Pradeep & Edirisuriya, 2021; Pradeep & Wijesekara, 2017, 2019, 2015a, 2015b; Pradeep & Wijesekera, 2011, 2012, 2014, 2016, 2018, 2020a, 2021, 2020b).

E. Implementation of Hydro GIS tools

Water is flowing over the ground without considering the man maid boundaries. Hence in most countries the flood water management is distributed to different administrative levels, based on the geographical area such as (1) Local, (2) Regional, and (3) National levels (Zermoglio, Scott, and Said, 2019, p.67). Apart from that when the water flow over the nations the Transboundary level has introduced as the fourth to the list (APFM, 2013, p. 2). In urban scenario, the local level is interested and stakeholders at the level are, (1) The individuals: Responsible to adhere to the local government's rules and regulations on the lands and water, (2) local decision-makers / Water Service Provides (WSP) control and permit individual activities, and (3) the Water Resource User Association/Water User Association (WUS), is a local group of people (such as farmers) who negotiate with WSP on water and land demands. The WUS provides the link between stakeholders of regional levels (Dukhovny et al., 2009; Gandhi et al., 2020; IUCN, 2015). However, at the chain of command, the local level becomes the operationalisation agent of the management options made by the upper levels. Hence day to day quick decision making has to be done by local levels under the rules, regulations and norms imposed by regional or national level. (Bandaragoda, 2000, p. 9; IWRM, 2009, p. 5).for an example, when consider Sri Lanka, the local authorities such as Municipal councils (MC), Urban councils (UC), and Pradeshiya Sabha (PS) are given the controlling power of all the lands and erections, by the law to look after the water and other resources of the area (Urban Councils Ordinance, 1940; Municipal Councils Ordinance, 1947; Pradeshiya Sabhas Act, 1987).

The regional level decisions are based on the states or basins level (Gandhi et al., 2020, pp. 9–18) while the national-level authorities manage the nation-wise policies on water. (Bandaragoda, 2000; IUCN, 2015; Song et al., 2010; Zermoglio et al., 2019). In transboundary level, the nations among the watershed are responsible for collectively make decisions on water (APFM, 2013).

4. Results and Discussion

A. Urban Flood Management and Land Management

It found six types of floods (urban, coastal, groundwater, flash, semi-permanent, and pluvial & overland) and identified those act as natural causes for an urban flood. However, urban floods occur due to deficiencies in drainage systems, land permeabilities, and poor management. Cities lose 10% of economic activities and annually experience over 500 million economic damage due to these floods. Hence, urban floods have to be suitably managed.

For managing the flood, it is necessary to identify the reasons for the flood. For urban floods, the causal reasons are identified as higher CO_2 & GHG emissions, cities erected in flood basins, higher population clustering, disturbing the natural cycles in flood sensitive lands, activities of the poor in the urban population, and political influences on policies & regulations. As all those are related to land utilisation, hance land management is highlighted as the main activity of urban flood management.

A closer look will indicate that urbanisation has resulted from land modifications. When considering the influence on the runoff, apart from the direct modifications on soil, slope and land cover, land's spatiotemporal patterns such as grow, shrink, and shape changes also increase the flood (Figure 2). Reviewing this situation shows that land modifications, directly and indirectly, increase the damage and occurrence of urban floods. Hence, attention should be paid to present land/infrastructure development practices for reducing the effect on flood generation for sustainable flood management.

B. Role of GIS in Hydro modelling

Managing floodwater is essential for flood management. It utilises hydro models, which are mature to provide substantial accurate predictions. Hydro models have problems with the model's requirements, but GIS could handle those issues accurately and efficiently (Table 3). Further, analysing ten generic hydrology models it found that GIS can "highly" assist in both the model's process and visualisation requirements (last column of Table 2). The tern HydroGIS was evolved in 1996 and since 2011 it has been researched under computing discipline. Noe the HydroGIS tools known as fully automated or semi-automated hydrology processing tools which use GIS.

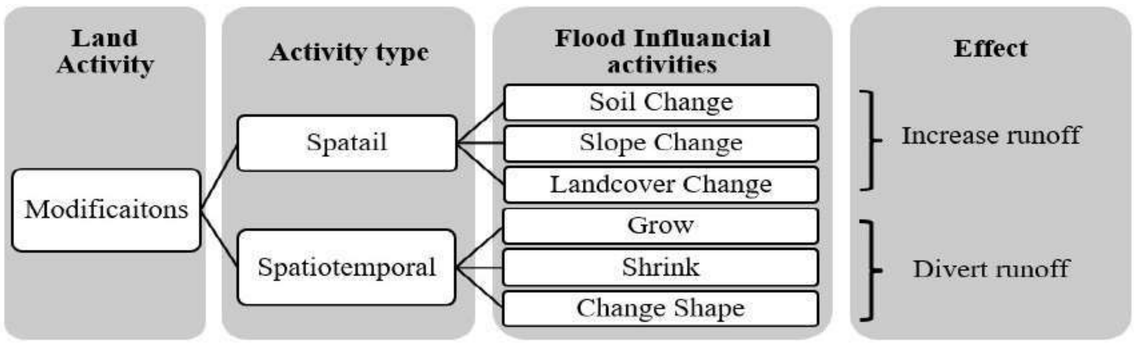


Figure 2: Important Land Activities to Urban Flood
Source: Author

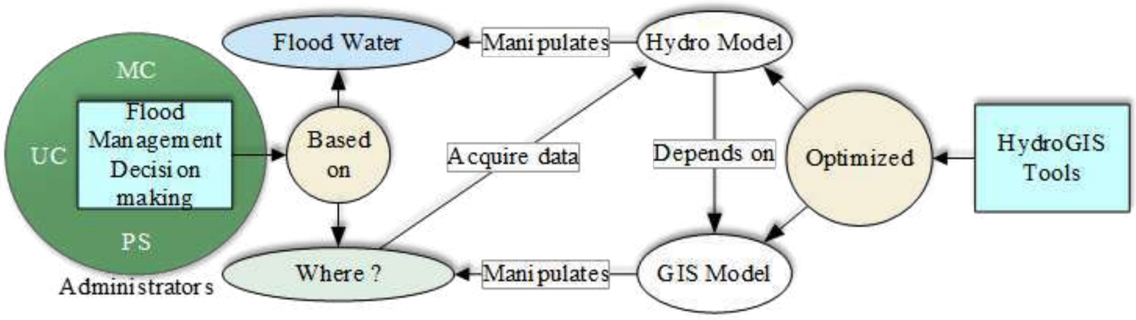


Figure 3: The Dependence of the Flood Management and HydroGIS tool
Source: Author

C. Role of GIS Tool in Urban Flood Management

Flood management has four different levels: Transboundary, National, Regional, and Local. The local level administration holds the decision-making authority on lands and properties of a significant land area of a country. The present work has realised that local level consisting of the day-to-day decision-makers. Then automated HydroGIS tool will assist them make land management decisions as the local administrators are non-technical decision makers. Reviewing the present situation, it developed an illustration to show how local administrators' flood management decision-making process can be assisted by the HydroGIS tools (Figure 3).

5. Conclusion

Urban floods research has peaked and found that poor land management is the direct and foremost reason to flood generation as it increased the runoff. Further studies proved that increased runoff boosts the flashiness and gathering of the population and economic activities increase the urban flood damages. Hence, land management is a crucial activity in urban flood management.

Since flood is a water phenomenon, flood can be modelled using hydrology. Thousand years of research has made these hydro models well-established and time proven. Nevertheless, the accuracy of the models depends on the spatial information resolution. Such massive spatial data requirement reduces the model performance.

This complex undertaking in the last decades could easily be made with the GIS advancements fuelled with modern technology. Today GIS assists in executing all the core steps in a hydro model. The term "HydroGIS" is used to integrate approaches in GIS-hydro modelling. Since 2012, the term

"HydroGIS tool" has described the automated Hydro model in the GIS environment.

As water management is based on land, land management has different levels with the political administration. In most countries, the smallest management unit is the Municipal/urban/rural council, and they are being powered by land authority. Then the local authority is entrusted to accurately implement any water decision taken from the top authorities and grant under commands with accurate decisions for sustainable flood management. Since non-technical decision-makers in the local authorities make these decisions, the HydroGIS tools become a vital tool for quick decision-making.

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