

# A THEORETICAL DISCUSSION AND CASE STUDY ON THE DEVELOPMENT OF SMART STORM DRAINAGE UNIT FOR COMPACT CITIES

## Article history

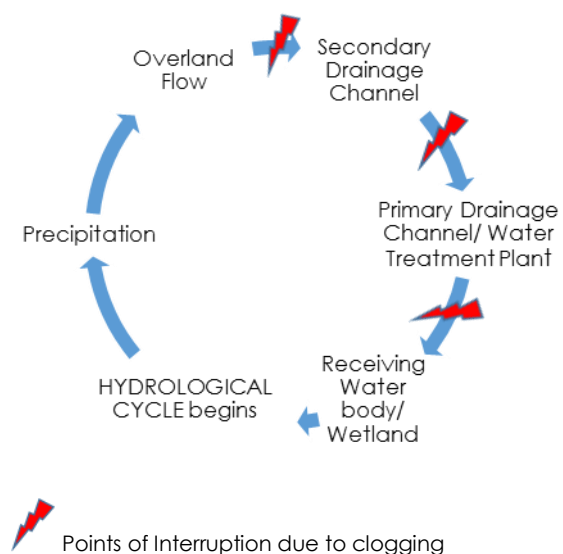
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## Graphical abstract



A Schematic representation of Urban Drainage Cycle

## Abstract

A moderate rainfall event can lead to harsh flash floods in most of the compact cities. Present urbanization happening in these cities creates an imbalance between generated urban runoff volume and effective drainage capacity. For the survival of these, it is vital in enhancing the efficiency of an urban drainage system. However, it is a complicated task due to the accumulation of solid waste in drainage channels. These drainage systems are super sensitive to some external factors caused by their immediate surroundings. This study found out the impact of the urban form, population agglomeration, floating population, imminent prone areas of urban sprawl and waste disposing patterns of settlers can be highly influenced to the efficiency of a storm drainage system. Hence, Geographical Information System based computational techniques and weighted fuzzy sets are being used to track the attention need areas of the system. These particular zones to be treated through the design of "Smart Storm Drainage Unit". By this, it is expected to maintain a clear drainage channel for transportation of surface runoff all the time. Thus, by Smart Storm Drainage will be fixed into the breakdown areas or highly sensitive areas of a drainage system. This paper discusses the impact of surrounding urban area to the breakdown of drainage system and fixates the problem by bypassing "Smart Storm Drainage Unit".

Keywords: Clogging, Drainage, Compact cities

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## 1.0 INTRODUCTION

Flooding is the most commonly occurring recurrent hazard event among all natural disasters[1, 2]. It causes enormous damages to socio-spatial settings of the affected cities. There are several significant

manmade factors which trigger the frequent occurrence of floods. The rate of population growth has rapidly increased in many countries in the recent past. More than half of the world's population now living in urban areas[1, 3]. Disastrous pluvial floods pose a serious challenge on the lives of those people. A recent World Bank report titled "Cities and

Flooding" revealed that flood events have a disproportionate impact in densely populated developing countries. In there, people who live in informal settlements are generally receives the hardest hits by urban pluvial floods[4].

Presently in the world, more than 30% of the urban population lives in informal settlements [1, 3].They tend to occupy hazard prone areas in low-lying lands. These settlements are obvious victims of natural hazards especially flash floods that could attack a city without pre-warning[5].

Properly designed urban drainage infrastructure is considered as a practical solution for flash floods [6-8]. Regular maintenance of drainage system is essential to ensure continued functioning of it. But most of the countries affected are least capable of financing their drainage infrastructure[9]. For many countries, investing in the urban drainage alone is considered not an appropriate solution. In many instances, costly upgrading to systems have created more issues than they had before[10, 11].

The following characteristics pertain to the urban drainage system in compact cities can be clearly identify as one of the least developed physical infrastructures[7, 10]. These drainage systems are commonly dilapidated and over hundreds of years old [6]. Drainage is one of the least considered factors in urban development[7, 12]. This tends to minimize its efficiency and workability. Aside from this, people still use to dump their solid waste into the nearest open space and that will end up in a nearby open drainage [7, 10, 13-17]. This tends to decrease its drainage capacity[18]. As a result, these areas become obvious victims of pluvial floods even in a small rainfall event.

The objective of this paper is to examine the flash flood handling ability of the drainage system in compact and high-density cities. Thus, by developing a novel technical solution, a "Smart Storm Drainage Unit" to restore the dysfunctional zones of the drainage system is discussed. The concept of "Smart Storm Drainage Unit" considers the effects of urbanization in storm drainage design. Hence, it examines four novel parameters in urban drainage management additional to the conventional design considerations.

- a) Changing phase of the city structure/ urban form
- b) Consuming patterns and disposing habits of settlers
- c) Population agglomeration, floating and commuting population
- d) Imminent prone areas of new development

**1.1 Description of the Case Study**

Colombo is the commercial capital city of Sri Lanka. It is located in the flood plains of the Kelani River [19]. The entire area of this city is situated at 1.5 m above Mean Sea Level, a very low altitude, resulting in a low flow rate in the canal system. The drainage system of the Colombo city has been constructed in 1910, to

cater a population of 100,000. Now the city population has increased to 650,000.The city of Colombo is also accommodates 500,000 daily floating population.

Figure 1 shows micro drainage channel, secondary drainage channel and receiving water body of the study area. due to the migration into city in the last decades, the land area for canal reservations of the city have been disturbed by illegal developments. this caused enormous difficulties in canal maintenance and reduced in the carrying capacities of the canals. Rapid development happens within the municipality has created more impervious areas. It caused less infiltration and increased surface runoff volumes. Dilapidated drainage infrastructure was unable to handle the increased volume of surface runoff. This situation leads to pluvial floods even after a small rainfall event.



**Figure 1** Micro Drainage Channel, Secondary Drainage Channel and Receiving Water body of the study area

The case study area of this research is located in Colombo 14 ward. Four Grama Niladhari divisions were considered for this study named Madampitiya,

Stadium watta Kimbula ela and Nagalagam Street. This is one of the densely populated low-income residential areas of the city. It consists of dilapidated drainage infrastructure which was constructed over 100 years ago, for a gridiron pattern settlement development. This area is regularly affected by pluvial floods and flash floods due to blockage in micro drainage channels. The slum upliftment program is currently in progress and the pattern of urban settlement is about to be changed.

## 2.0 LITERATURE REVIEW AND METHODOLOGY

### 2.0 Why do Drainage Systems Fail in Densely Populated Compact Cities?

The combination of unplanned urbanization and haphazardly dumped solid waste makes drainage a complicated issue for compact cities. Urban drainage systems in densely populated compact cities are often filled with garbage and sediments since people still use the urban drainage as a garbage dumping space irrespective of the economic status of the countries [7, 10]. Ironically while solid waste produces flash floods by blocking drainages, in the aftermath of any flood event; another stock of solid waste is generated as flood debris [16]. If not removed properly, this debris will act as the immediate cause of the next flash flood.

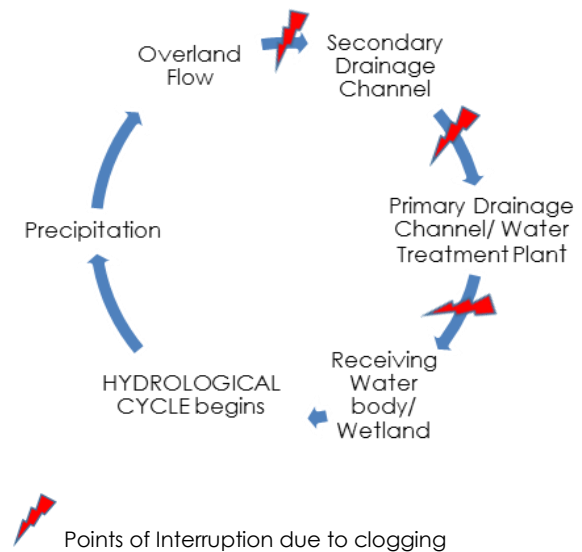
Tucci [7] has studied urban drainage issues in developing countries situated in the humid tropical climate zone for twenty years. According to his conclusions; densely populated Asian cities can be vulnerable to flash floods due to unplanned urbanization and floodplain encroachments. Many of the urban squatter settlements are built in flood-prone areas and steep hillsides. These shelters are built out of improvised materials. They shift to permanent building materials after some time, but the shelters are still not provided with basic physical infrastructures such as water supply, waste disposal, and drainage. These squatter settlements are usually made without building approvals by the Municipal authorities. Thus, Municipal authorities are not bound to provide infrastructure facilities for settlers in those areas. Therefore, squatters obviously tend to dispose of their waste in the nearest drain or open space.

### 2.2 Description of the Urban Drainage Cycle

The natural hydrological cycle starts with precipitation. It forms raindrops and creates overland flow. Overland flow is subjected to initial loss by evaporation. It again matters to ground recharge by infiltration. The rest is conveyed as natural overland flow.

The Urban drainage cycle begins with the natural overland flow supplemented with a quantity of synthetic wastewater discharges from industrial,

commercial and residential establishments. It could flow through an artificial or a natural drainage network till it leads to a wastewater treatment plant or a receiving water body. The effluent water flow of a waste water treatment plant too will ultimately end up in a receiving water body. Water in the receiving water body will again connect with the hydrological cycle. Therefore, operationally the urban drainage cycle can be defined as a continuous exchange of storm water and wastewater between the hydrological cycle and the urban drainage network. Urban flash floods occur as a result of interruptions to the urban drainage cycle. Haphazard dumping of solid waste, floodplain encroachment and reclamation of low-lying lands for development purposes, etc. are identified as primary causal factors of such interruptions in the cyclic process of drainage water. Due to these causal factors, the cyclical process of the urban drainage network tends to break at several points.



**Figure 2** A Schematic representation of Urban Drainage Cycle

#### 2.2.1 Detecting System Breakdowns with Reference to Urban Drainage Cycle

Development oriented physical impacts cause interruptions to the natural circulation of urban drainage water [20]. Here it is identified as "breaking of the circulation process of urban drainage cycle". This subheading describes how to detect the system breakdowns of urban drainage cycle which caused by development-oriented physical impacts.

#### 2.2.2 How Impervious Cover Affects the Urban Drainage Cycle

Imperviousness of the ground increases with the development. As imperviousness increases,

groundwater recharge volumes decreased. It eventually leads to increased runoff volumes and peak flows [21].

$$\text{imperviousness} \propto \text{runoff volume} \quad (1)$$

$$\text{imperviousness} \propto \frac{1}{\text{Infilt. volume}} \quad (2)$$

Runoff volume increases proportionally to imperviousness. In rapidly developing cities, enormous volumes of rainfall will be converted as overland flow. Moreover, it would be a considerable increase in the rate of discharge of overland flow. The increase of such, demands an additional drainage capacity for conveyance. Failure of accommodating the increased surface runoff volumes, maximize the risk of flooding.

### 2.2.3 How Asymmetrical Form of Present Urban Structure Affects the Urban Drainage Cycle

Existing drainage systems in most of the compact cities are dilapidated and inefficient. Those were constructed for a Gridiron shaped urban locality [13, 22, 23]. Present urban form of most of the compact cities is entirely different from Gridiron pattern. This happens due to unplanned urbanization and rapid changes in socio-spatial settings. As a result, existing urban drainage networks in many colonized cities have become operationally dysfunctional. This is a crucial factor to consider in evaluating the flood handling ability of drainage networks. As a result of the changes in urban form, drainage systems breaks the cycle process of surface runoff conveyance.

### 2.2.4 How Population Agglomeration Affects the Urban Drainage Cycle

Densely populated cities in compact cities act as development hubs. Generally, they consist of mixed developments. Administrative, industrial, and commercial establishments are scattered over the cityscape without considering the formal zoning plans. There is a considerable volume of floating population that travels back and forth to the city for regular activities such as employment and administrative matters. A significant number of low-income settlements could also be found stagnated on hydrological sensitive areas. These agglomerations result in significant negative effects to the urban drainage cycle such as disposing of solid waste into critical areas.

### 2.2.5 Mapping of Drainage Network Breakdowns Using Geographical Information System Software

The increase in a number of impervious areas, asymmetrical form of present urban structure, population agglomerations and solid waste disposing patterns are four novel parameters that will be

considered in the development of the integrated urban drainage cycle management model. It is intended to be developed in three stages based on the factors impacting the urban drainage cycle.

### 2.2.6 Generation of Present and Future Impervious Landscape Scenarios

Primary data obtained from urban development authority and the land Reclamation Corporation will be used to generate the past and present impervious cover changes into a digital map. This trend will be used to project the prospective changes of present and future impervious cover percentages of the area.

### 2.2.7 Generation of Population Agglomeration Scenarios

Projected total population will be calculated in 10-year intervals to mark the congested areas in cities. Future population agglomerations and floating population (E.g.: location of proposed industrial sites, shopping complexes, administrative complexes) can be plotted using the details available in urban development plans of the respective cities. Urban drainage requirements in these areas need more attention since development will obviously contribute to an increase in the percentage of urban litter from these areas.

An observational study would be used to assign solid waste disposing patterns. This approach will allow critical areas to be mapped. Urban litter percentage in storm drains will be estimated by using the undermentioned formula. Armitage (1998) [24] developed this formula for calculating the clogged solid waste percentage in drainage canals.

$$T = \sum f_{sci} \cdot (V_i + B_i) \cdot A_i \quad (3)$$

In this formula;

T = Total litter loads clogged in waterways (m<sup>3</sup>/yr)  
 $f_{sci}$  = street cleaning factor for each land use (This number varies from 1.0 for regular street cleaning to about 6.0 for non-existent street cleaning / complete collapse of services)

$V_i$  = vegetation load for each land use (varies from 0.0 m<sup>3</sup>/ha\*yr for poorly vegetated areas to about 0.5 m<sup>3</sup>/ha\*yr for densely vegetated areas)

$B_i$  = basic litter load for each land use

(Commercial 1.2 m<sup>3</sup>/ha\*yr; industrial 0.8 m<sup>3</sup>/ha\*yr; residential 0.01 m<sup>3</sup>/ha\*yr)

$A_i$  = area of each land use (ha)

### 2.2.8 Building Sensitivity Scenarios of the Urban Drainage Network by Application of Fussy Logic Approach to Develop Cause and Effect Function for an Urban Drainage Network

A fuzzy logic is an intelligence system that is used to

approximate a crisp output from an input features based on fuzzy rules [25-27]. One of the application of fuzzy logic system is to develop a cause and effect function for an urban drainage network. In order to analyze the effects on urban drainage network caused by the factors belong to the immediate urban environment, for instance, population agglomeration, floating population, imminent prone areas of urban sprawl and waste disposing patterns of settlers will be evaluating through fuzzy set theory. In this application the fuzzy set theory and related functions are used to illuminate the sensitivity factors which are not expressed in numerical or deterministic values. Markopoulos[26] has used this method to map uncertainty causing factors in urban water management.

Fuzzy logic system consists of three basic elements namely, fuzzier, inference engine and defuzzifier[28]. Fuzzier: used to calculate the degree of membership of the input variable in the input sets.

Inference engine: is the mechanism used to integrate the antecedent with consequent based on IF/THEN statements.

Defuzzifier: is the fuzzy element used to determine the crisp output from the inference engine fuzzy output.

Therefore, in this work, fuzzy logic system, in Matlab environment, will be applied to estimate the crisp output and the output of the analysis will be used to generate GIS maps that indicate attention needed areas of the urban drainage system.

Different levels of uncertainties or sensitivity factors can be numerically expressed as fuzzy sets themselves.

$$\mu_x : A \rightarrow [0,1] \quad (4)$$

Where;  $\mu_x$ : A = Membership function, "A" represent the member of the universe x

### 3.0 UPCOMING RESEARCH AND PROSPECTS

#### 3.1 Development of Smart Storm Drainage Unit

The next phase of this research study is to develop the solid waste resistant "Smart Storm Drainage Unit". The "Smart Storm Drainage Unit" is a novel method of constructing a drain by adding an upper layer with a suitably perforated bottom to collect and separate solid wastes disposed into the drain. Thus, by ensuring storm water handling capacity during excessive precipitation events to provide adequate conveyance of storm water to prevent pluvial flooding. Solid waste collection layer is equipped with removable perforated containers to;

- collect and trap solid waste
- function as manual collection points of solid waste
- the inbuilt sensor technology used to inform garbage collectors/ neighborhood when the waste container need to be emptied

This design will be fixed to restore the breakdown zones of a drainage network. This decision is based on the outcomes of Geographical Information System (GIS) maps and fuzzy sets evaluation of the sensitivity of the surrounding environment to the drainage network failures. It is expected that these outputs will map the critical areas and attention need spots of the urban drainage network in a compact city.

Smart Storm Drainage will be a location specific entity. It is intended to design this considering following characteristics of the locality.

- The pattern of flash flood occurrence
- The pattern of solid waste disposal
- Failing factors of existing storm drainage system

#### 3.1.1 Usability of the Design of the City of Colombo Sri Lanka

Technical details of present storm water drainage system in the city of Colombo, Sri Lanka as follows[29];

Average rainfall November 2013	=375mm/h
Area of Colombo Municipal Council	= 37 000 m <sup>2</sup>
Runoff coefficient for urban area	= 0.6

Runoff volume = rainfall X Area X Runoff coefficient  
Runoff volume = 8,325,000 m<sup>3</sup>

This would amount to a volume of 8,325,000 m<sup>3</sup> from a 375 mm of rainfall.

Drainage capacity calculation;

Total length of drainage area of CMC is 350,000 m. The drainage section is rectangular and the dimensions varying from 1m-0.6m. Average width and depth of micro drain canal is about 1m.

Drainage capacity	= length X width X depth
	= 350x 10 <sup>3</sup> m x 1 m x 1 m
	= 350, 000 m <sup>3</sup>

Drainage capacity: Runoff volume	= 0.0420
	= 4%

### 4.0 CONCLUSIONS

The existing drainage system of the Colombo Municipal Council can only handle 4% of runoff volume generated in the city. The rest is handled by natural retention systems. In general, storm drainage system and a retention system will be able to accommodate 40% of the surface runoff volume. Therefore, the natural retention system of the city cannot handle 36% of runoff as an individual entity. So, it is essential to increase the hydraulic capacity of existing urban drainage system.

Development of the "Smart Storm Drainage Unit" is considered as the significant outcome of this research study. This design will be increase the hydraulic capacity of existing urban drainage system. Furthermore, the Fuzzy logic approach and GIS based spatial decision support system can also assist to storm flow management, hydro catchment management, and low-lying area management. The aforesaid analysis will lead the formulation of policy guidelines on urban drainage. It can play a credible role in municipal urban drainage management and design.

Once the "Smart Storm Drainage Unit" is designed and tested in hydraulics laboratory, it is planned to be physically constructed in Madampitiya and Nagalam Street area of ward 14 of the City of Colombo. This design element is expected to act as a solid waste management entity as well as the pluvial flood mitigation object. It is anticipated that this could be incorporated into sustainable drainage networks of future urban development areas to ensure effective solid waste management and pluvial flood control abilities.

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### References

- [1] UN, International Migration Report. 2002.
- [2] Alfieri, L., Salamon, P., Pappenberger, F., Wetterhall, F., and Thielen, J. 2012. Operational Early Warning Systems For Water-Related Hazards In Europe. *Environmental Science & Policy*. 21: 35-49.
- [3] UN-Habitat. 2013. STATE OF THE WORLD'S CITIES 2012/2013.
- [4] Jha, A. K., Bloch, R., and Lamond, J. 2012. Cities And Flooding: A Guide To Integrated Urban Flood Risk Management For The 21st Century: World Bank Publications.
- [5] Rana, A. 2011. Avoiding Natural Disaster In Megacities—Case Study For Urban Drainage Of Mumbai, VATTEN. 67: 55-59.
- [6] Karamouz, M., Hosseinpour A., and Nazif S. 2010. Improvement Of Urban Drainage System Performance Under Climate Change Impact: Case Study. *Journal of Hydrologic Engineering*. 16: 395-412.
- [7] Tucci, C. 2001. Urban Drainage In Humid Tropics. Volume I In Maksimovic, C. Urban Drainage In Specific Climates.
- [8] Tucci, C. E. 2001. Urban Drainage Issues In Developing Countries, Urban Drainage In Humid Tropics. 23-40.
- [9] Maksimović, Č., Prodanović, D., Boonya-Aroonnet, S., Leitao, J. P., Djordjević, S., and Allitt, R. 2009. Overland Flow And Pathway Analysis For Modelling Of Urban Pluvial Flooding. *Journal of Hydraulic Research*. 47: 512-523.
- [10] Lamond, J., Bhattacharya, N., and Bloch, R. 2012. The Role Of Solid Waste Management As A Response To Urban Flood Risk In Developing Countries, A Case Study Analysis.
- [11] Parkinson, J. and Mark, O. 2005. *Urban Stormwater Management In Developing Countries*. IWA publishing.
- [12] Taleb, M. A. 2012. Comparative Study of Urban Area Extension and Flood Risk in Dhaka City of Bangladesh, *Global Journal of Human Social Science. Geography & Environmental GeoSciences*. 12: 37-40.
- [13] Caljouw, M., Nas, P. J., and Pratiwo, M. 2005. Flooding in Jakarta: Towards a blue city with improved water management, *Bijdragen tot de taal-, land-en volkenkunde/Journal of the Humanities and Social Sciences of Southeast Asia*. 161: 454-484.
- [14] Chandrasena, D. C. N., Khamaruzaman Wan Yusof, M., and R. U. Mustafa. 2014. An Investigation on Failure Mechanisms of Urban Drainage System in Colonised Asian Cities. *13th International Conference on Urban Drainage (ICUD 2014), Kuching, Malaysia*.
- [15] Gupta, A. K. and Nair, S. S. 2011. Urban Floods In Bangalore And Chennai: Risk Management Challenges And Lessons For Sustainable Urban Ecology. *Current Science(Bangalore)*. 100: 1638-1645.
- [16] Melosi, M. V. 2004. *Garbage In The Cities: Refuse Reform And The Environment*. University of Pittsburgh Pre.
- [17] Nijman, J. 2010. A study of space in Mumbai's slums, *Tijdschrift voor economische en sociale geografie*, 101: 4-17.
- [18] C. Zurbrugg. 2002. Urban Solid Waste Management In Low-Income Countries Of Asia How To Cope With The Garbage Crisis. Presented for: Scientific Committee on Problems of the Environment (SCOPE) Urban Solid Waste Management Review Session, Durban, South Africa. 1-13.
- [19] Niroshinie, M., Babel, M., and Herath, S. 2011. A Methodology To Analyze Extreme Flooding Under Future Climate Change Scenarios For Colombo. *Soc. Soc. Manage. Syst*. 1-10.
- [20] Karnib, A., Al-Hajjar, J., and Boissier, D. 2002. An Expert System To Evaluate The Sensitivity Of Urban Areas To The Functioning Failure Of Storm Drainage Networks. *Urban Water*. 4: 43-51.
- [21] How Urbanization Affects the Water Cycle, a publication of California Water and Land Use Partnership. 2007. <http://www.coastal.ca.gov/nps/watercyclefacts.pdf>.
- [22] Hassan, A. S. 2009. The British Colonial 'Divide And Rule' concept: Its Influence To Transport Access In Inner City of George Town, Penang, *Transportation*. 36: 309-324,.
- [23] Van der Heiden, C. 1990. Town planning in the Dutch Indies. *Planning Perspective*. 5: 63-84.
- [24] Armitage, N. and Rooseboom, A. 2000. The Removal Of Urban Litter From Stormwater Conduits And Streams: Paper 2- Model Studies Of Potential Trapping Structures. *Water S. A.* 26: 189-194.
- [25] Zimmermann, H.-J. 2001. *Fuzzy Set Theory—And Its Applications*. Springer Science & Business Media.
- [26] Makropoulos, C., Butler, D., and Maksimovic, C. 2003. Fuzzy Logic Spatial Decision Support System For Urban Water Management. *Journal of Water Resources Planning and Management*. 129: 69-77.
- [27] Tseng, M.-L. and Lin, Y. H. 2009. Application of Fuzzy DEMATEL To Develop A Cause And Effect Model Of Municipal Solid Waste Management In Metro Manila. *Environmental Monitoring And Assessment*. 158: 519-533.
- [28] Zimmermann, H. J. 2010. Fuzzy Set Theory, *Wiley Interdisciplinary Reviews: Computational Statistics*. 2: 317-332.
- [29] Ariyananda, T. 2013. Controlling Floods In Colombo City Through Rain Water Harvesting, In *The Island*, Ed.