Development of an Integrated Urban Drainage Cycle Management Model for City of Colombo

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Abstract— *Floods are the most frequently occurring hazard event among all natural disasters. Poorly prepared compact cities have become prone to flash floods even in a small storm event. Present urbanization happening in these cities creates an imbalance between urban runoff volume and effective drainage capacity. For the survival of these cities it is vital to establish proper urban drainage systems resistant to flash floods. However, this is a complicated task for many Asian cities due to solid waste blocking drainages. Thus, Asia urge for a more comprehensive drainage design which considers present and future forms of the cities, solid waste disposing patterns, floating population and imminent prone areas of urban sprawl. This research paper introduces a novel approach in urban drainage management through the concept of "Urban drainage cycle". There, consider the storm water circulation of a city as a cycling process pertain to urban drainage. Geographical information system based computational techniques are being used to track the breakdowns of the urban drainage cycle. This step will initiate the development of "Integrated urban drainage cycle management model". It consists with Geographical information system based spatial decision support system and a mathematical model. Outputs of the model will use as inputs of "Solid waste resist urban drainage" design. Developed model and drainage design will be physically tested in Madampitiya, Nagalagam Street of City of Colombo Sri Lanka.*

Keywords— Flash floods, Solid waste, Urban drainage system, Asian cities

I. INTRODUCTION

Flooding is the most frequently occurring hazard among all natural disasters (United Nations, 2002). 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. Rate of population growth has rapidly increased in many countries in the recent past. More than half of the world's population has migrated to urban areas (United Nations, 2002). Urban flooding poses a serious challenge to development and the lives of people. A recent World Bank report titled Citied and Flooding revealed that flood events have a disproportionate impact in densely populated developing countries. The residents of the rapidly expanding cities in these countries hit hardest by the floods (World Bank, 2011).

Presently in Asia, more than 50% of urban population lives in slums and shanties (World Bank, 2011). 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.

Properly designed urban drainage infrastructure is considered as a viable solution for flash floods (Tucci, 2001). Regular maintenance of drainage infrastructure is essential to ensure continued functioning of it. But most of the countries that are affected are least capable of financing their drainage infrastructure (Maksimovic, 2001). For many countries, investing in the urban drainage alone was not an appropriate solution. In many instances costly upgrades to systems have created more issues than they had before (Tucci, 2001).

It is very clearly identified following characteristics pertain to urban drainage system in compact cities of developing Asia. Urban drainage is one of the least developed physical infrastructures for many Asian cities (Lamond et al, 2012). Existing drainage systems in many colonized Asian cities are over hundred years old (Rana, 2011; Roosmalen, 2006).This tends to minimize its efficiency and workability.

Still many Asians dump their solid waste in to the nearest drain. (Tucci, 2001; Lamond et al, 2012). This tends decreasing its drainage capacities (Zurbrugg, 2002). Today these cities have become prone to flash floods even in a very low precipitation event.

Work towards evaluating the flash flood handling abilities of drainage systems in colonized Asian cities to develop a novel urban drainage cycle management model, focusing on the city of Colombo is described in this paper.

Colombo is the commercial capital city of Sri Lanka. It is located in the flood plains of the Kelani River (Niroshinie et al, 2010). Colombo is a coastal city with very low altitude (1.5 m above Mean Sea Level) resulting in a reduced flow rate in the canal system. City network was commissioned in the year 1910 for a population of 100,000 which has now increased to 650,000 and daily floating population of 500,000. Illegal developments in canal reservations has caused difficulties in canal maintenance and thus reducing the carrying capacity. Retention areas of the city have been reduced due to legal and illegal constructions. Less open areas and more paved areas due to rapid development has resulted in faster surface runoff. Therefore Floods are common in low lying areas of the city during heavy rainfall.

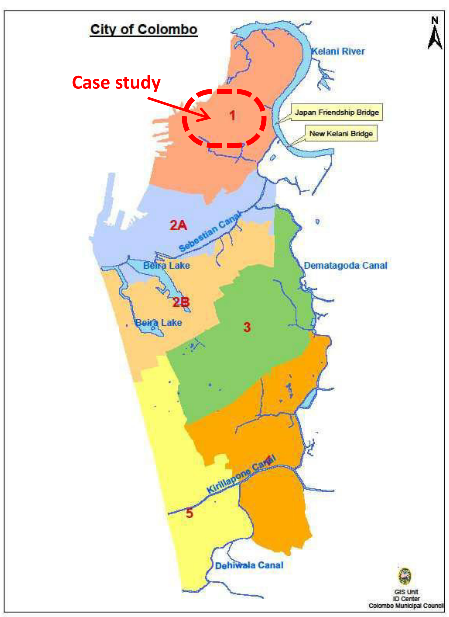

Figure 1. Map of the study area

Case study description; Colombo 14 ward Madampitiya, Stadium watta Kimbula ela and Nagalagam Street.

This is one of densely populated low income residential area of the city. It consist with dilapidated drainage infrastructure which constructed over 100 years ago, according to a gridiron pattern settlement development. This area is regularly affects to flash floods since encroachments of natural drainage paths and solid waste blocking micro drainages. Slum upgradation program is currently in process and the settlement form is about to be changed.

II. WHY DRAINAGE SYSTEMS FAIL IN DENSELY POPULATED ASIAN CITIES?

The combination of unplanned urbanization and haphazardly dumped solid waste makes drainage a very complicated issue for cities in Asia. Urban drainage systems in densely populated Asian 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 (Lamond et al, 2012; Tucci, 2001). Ironically while solid waste produce flash floods by blocking drainages, in the aftermath of any flood event; another stock of solid waste is generated as flood debris. If not removed properly, this debris will act as the immediate cause of the next flash flood event.

Tucci (2001) 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 flood plain encroachments. Many of the urban squatter settlements are built in flood prone areas and steep hill sides. These shelters are built out of improvised materials. They shift to permanent building materials after some time but shelters are still not provided with basic physical infrastructure such as water supply, waste disposal and drainage. These squatter settlements are usually made without building approvals by the local councils and the Municipal authorities are not bound to provide infrastructure facilities for them. Therefore, squatters obviously tend to dispose their waste in the nearest drain or open space.

III. WHAT IS URBAN DRAINAGE CYCLE?

The natural hydrological cycle begins with precipitation. This precipitation in the form of rain drops on the land surface is subjected to some initial loss through evaporation and interception by vegetation. The excess rainfall is available for infiltration in to earth, overland flow and depression storage.

Urban drainage cycle begins with the natural over land flow supplemented with a quantity of synthetic waste water discharging from industrial, commercial and residential establishments. It could flow through an artificial or a natural drainage network till it leads to a waste water treatment plant or a receiving water body. Output from a waste water treatment plant too will ultimately end up in a receiving water body. Once at the receiving water body the water will again connect with the hydrological cycle.

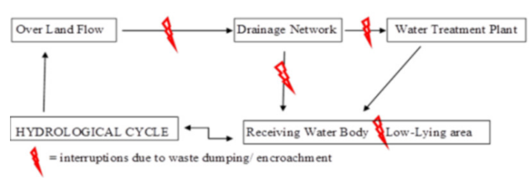

Figure 2. A schematic representation of Urban Drainage Cycle

Therefore, operationally the urban drainage cycle can be defined as a continuous exchange of storm water and waste water 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, flood plain encroachment and reclamation of low lying lands for development purposes etc. identified as primary causal factors of such interruptions to the cycling process of urban drainage water. Due to these causal factors the cyclic process of the urban drainage network tends to break at several points.

A. Detecting system breakdowns with reference to urban drainage cycle

Development oriented physical impacts cause interruptions to the natural circulation of urban drainage water. Here it identified as “breaking of the circulation process of urban drainage cycle”. This sub heading describes how to detect the system breakdowns of urban drainage cycle which caused by development oriented physical impacts.

1) How impervious cover affects the urban drainage cycle

Imperviousness of the ground increases with the development. With natural groundcover, 25% of rain infiltrates into the aquifer and only 10% ends up as runoff. As imperviousness increases, less water infiltrates and more and more end up in the runoff (Ruby, 2007).

Since runoff volume increases proportionally to imperviousness, in urban areas with large amounts of impervious cover, a larger volume of rainfall is diverted to over land flow. There would be a corresponding increase in the rate of discharge as well. The increased surface runoff demands additional drainage infrastructure to minimize the risk of flooding.

2) How asymmetrical form of present urban structure affects the urban drainage cycle

Existing drainage systems in many colonized Asian cities are over hundred years old. These were constructed following a Grid-iron patterned urban form. However the present urban form has grown into a pattern completely different from the Gridiron pattern due to unplanned urbanization. As a result of this existing urban drainage networks in many colonized Asian cities have become operationally dysfunctional.

This is a critical factor to consider in evaluating the ability of drainage networks in these cities to handle current flash flood threats. As a result of the changes to urban form, solid waste and sediment clogging tends to interrupt these drainage systems breaking smooth functioning of the urban drainage cycle.

3) How population agglomerations affects the urban drainage cycle

Densely populated cities in developing Asia act as multipurpose hubs. Generally they consist of mixed developments. Administrative, industrial, and commercial establishments are all scattered over the city scape with no consideration of 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 results in significant negative effects to the urban drainage cycle such as disposing of solid waste in to critical areas.

B. Development of an integrated urban drainage cycle management model using GIS

Increase in the amount 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.

1) Generation of present and future impervious landscape scenarios

Digital "Noilli maps" will be used to evaluate the impact of land use changes in buildable areas of the city. The "Nolli map" provides an immediate and intuitive understanding of the city's urban form through the simple yet effective graphic method of rendering solids as dark and rendering voids as white. Proposed "Nolli map" can use to calculate the present and future impervious cover percentage of the area. Future probable impervious areas can premeditated using urban design dimensions in urban development plans of respected cities.

2) 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 (Eg: location of proposed industrial sites, shopping complexes, administrative complexes) can be plotted using details available in urban development plans of 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 following formula developed by Armitage et al (1998) from the study of springs and Robinson Canal data, which was tentatively suggested for South Africa:

$$T = \Sigma f_{sci}.(V_i + B_i).A_i \quad (1)$$

where:

- T = total litter load in the waterways (m^3/yr)
- f_{sci} = street cleaning factor for each land use (varies from 1.0 for regular street cleaning to about 6.0 for nonexistent street cleaning / complete collapse of services)
- V_i = vegetation load for each land use (varies from 0.0 m^3/ha·yr for poorly vegetated areas to about 0.5 m^3/ha·yr for densely vegetated areas)
- B_i = basic litter load for each land use (commercial = 1.2 m^3/ha·yr industrial = 0.8 m^3/ha·yr residential = 0.01 m^3/ha·yr)
- A_i = area of each land use (ha)

3) Building hydrological scenarios

In order to analyse the effects on hydrology of the area caused by land use changes due to urbanization, hydrological scenarios will be built considering rainfall excesses and soil property data.

Soil data of study areas are to be generated from existing soil survey maps. Boundaries of different soil textures will be digitized, to generate hydrological soil maps for cities.

Data on soil moisture, evaporation, pervious and impervious areas, length and slope of the sub catchment will be used to calculate rainfall excess estimates using a parameter optimization approach. This will allow calculation of total annual urban runoff in 10 year intervals with consideration of probable impervious area scenarios and future land use scenarios.

Proposed "integrated urban drainage cycle management model" will assist in storing, processing and analysing of urban drainage data and formulation of drainage design guidelines. Rendering to the model solutions, "solid waste resist urban drainage" is to be physically designed. Model outcomes will use as a "spatial decision support system" pertain to urban drainage of the respected municipality.

C. A "Solid Waste Resist Urban Drainage Design"

Purpose of this design is regeneration of existing drainage system of a compact city. It will not change the existing capacity of the urban drainage system but will include a waste trapping mechanism and solid waste clogging area to the default design. It will act as a dumping space as well as drainage water circulation point. Prime objective of this design is to secure the hydraulic capacity of the drainage system and ensure preservation of drainage water cycling process. For that, extensive solid waste traps and solid waste clogging points designed to separate waste from drainage water. By this step it is proposed to enhance the hydraulic capacity of the urban drainage system. Pressure pumping positions will includes at critical areas to pull out the drainage water in to forward lines. By introducing this, it is expected to enhance the flood peak attain time of overland flow. Proposed design will also to minimise water flowing time from a given spot to the nearest receiving water body.

This will be designed based on the outcomes of Integrated Urban Drainage Cycle Management Model. It is expected that model outputs will map the critical areas and attention need spots of the urban drainage cycle in a respective city. Then it will generate design guidelines of extensive solid waste traps. This will include pressure pumping positions and design dimensions of solid waste clogging areas. All other physical parameters pertain to "Solid Waste Resist Urban Drainage Design" develop according to the proposed drainage model outputs.

This will be a location specific structure. It is intended to design this considering following characteristics of the locality.

i. The pattern of flash flood occurrence
ii. The pattern of solid waste disposal
iii. Failing factors of existing storm drainage system

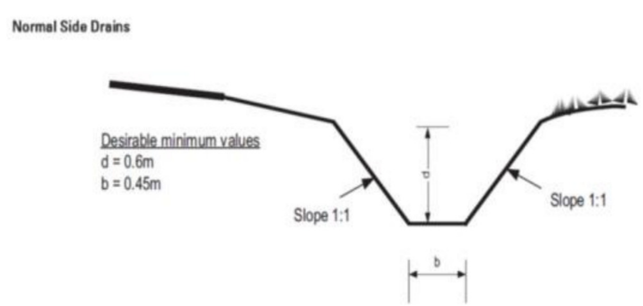

Figure 3. Technical details of present road side drainage, Sri Lanka

Source: Road and Drainage Maintenance service delivery training module 3 of 4, (2008), A publication of Ministry of Local government and provincial councils

D. Usability of the design to the city of Colombo Sri Lanka

A. Technical details of present storm water drainage system in city of Colombo Sri Lanka

Average rainfall November 2013 = 375 mm/h (Meteorological Department, 2013)

Area of Colombo Municipal Council = 37 000 m^2

Runoff co efficient for urban area = 0.6

Run off volume = rainfall X Area X Runoff coefficient

Run off volume = $.375\ m \times 37 \times 10^6\ m^2 \times 0.6$

= 8,325,000 m^3

This would amount to a volume of 8,325,000 m^3 from a 375 mm of rainfall.

Drainage capacity calculation

Total length of drainage area of CMC = 350,000 m (Ariyananda, 2011)

Drainage capacity = length X width X depth

= 350x 10^3 m x 1 m x 1 m

= 350, 000 m^3

Drainage capacity: Runoff volume

$\frac{350,000}{8,325,000} \times 100$ = 0.0420

= 4%

IV. CONCLUSION

Existing drainage capacity of Colombo Municipal council can only store 4% of runoff volume of the city. Rest is handled by natural retention system. It is expected that existing drainage system and retention system will be able to cope 40% of run off volume generated in the city. (Ariyananda, 2011). City is developing and impervious cover.Therefore, natural retention system of the city cannot handle 36% of runoff volume as an individual entity. So, it is essential to increase the hydraulic capacity of existing urban drainage system.

The outcome of this research study will be an "Integrated Urban Drainage Cycle Management Model", Spatial Decision Support System on urban drainage and a "Solid Waste Resist Urban Drainage Design". This design can increase the hydraulic capacity of existing urban drainage system. Furthermore, the urban drainage model and spatial decision support system can also assists to storm flow management, hydro catchment management and low-lying area management. 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 "Solid Waste Resist Urban Drainage Design" is finalized, it is planned to be physically tested at 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 a flood mitigation object. It is anticipated that this could be incorporated into drainage networks of future urban development areas to provide effective solid waste management and flood control.

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