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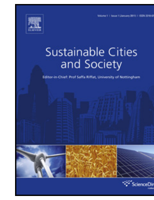

Towards high resolution and cost-effective terrain mapping for urban hydrodynamic modelling in densely settled river-corridors

K. Shaad[a,b,*], Y. Ninsalam[a,c], R. Padawangi[a,d], P. Burlando[b]

[a] Future Cities Laboratory, Singapore ETH Centre, Singapore
[b] Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland
[c] Department of Architecture, National University of Singapore, Singapore
[d] Asia Research Institute, National University of Singapore, Singapore

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ABSTRACT

With nearly 590 km of waterfront along the main rivers of Jakarta, a significant proportion of population is exposed to frequent flooding. Further, extensive engineering works on these systems are changing the nature and magnitude of risk. 2D hydrodynamic modelling can play a central role to plan and manage short and long term interventions for Jakarta and cities in similar circumstances in South and South-east Asia but require detailed description of terrain as input. Further, the dense urban fabric of these cities and its interaction with flows adds an additional source of complexity in modelling flood propagation patterns. This paper examines the developments in the field of collecting cost-effective high resolution terrain data that can contribute in the growing area of urban hydrodynamic modelling. These are aerial and ground based methods that can generate high resolution point clouds of coarse and fine grain respectively. We have applied these technologies on a case study along a 7 km stretch of the River Ciliwung in central Jakarta and we have evaluated the scope of providing coverage for large segments of the city. In the context of this urban and densely settled river corridor, the challenge of obtaining "hydraulically representative" ground description and influence of representation of structures in hydrodynamic models is explored, alongside identifying the future work required to allow scaling of the methods and acquired datasets beyond the limits of the test site.

1. Introduction

Probability of economic damage and hazard to life due to flooding in urban areas is acknowledged to be much higher than other forms of flooding (Fewtrell, Bates, Horritt, & Hunter, 2008). However, at the same time, managing flood risk in densely settled regions is constrained due to limited management options as well as due to uncertainty associated with interventions in the complex environment. Further, with liveability and sustainability becoming increasingly part of the consideration in developing urban river management strategies, tools and approaches for holistic evaluation of the river system – capable of evaluating designed interventions for river rehabilitation and restoration – are also required.

Flood hazard mapping by use of modelling has become an established component of flood risk management in urban areas (Jha, Bloch, & Lamond, 2012). The approaches used for modelling flood hazard has been categorised (FLOODsite, 2008) as ranging from judgemental and empirical (non-mathematical based approaches, cellular automata/black box models, etc.) to numerical models accounting for the physical process with varying degrees of simplifying assumptions. Further, based on the spatial characteristics, numerical hydrodynamic models can be categorised as one-dimensional (1D) models, coupled 1D/2D models, purely two-dimensional (2D) or even three-dimensional (3D) models. The dimensionality is in the degrees of freedom allowed for flow, where a 1D model for instance, allows only a single level, discharge and direction of flow at a specific cross-section of a river while 3D models allows flow along all three axis of motion thus, capturing more closely the 'real' flow patterns. The data requirements and computational load increases significantly with higher spatial characteristics – with full 3D models currently only practical for small durations and/or small spatial extent. While numerical modelling can potentially provide a valuable tool for hazard mapping, the complexity of the fluvial dynamics in urban areas demands at least a 2D representation of the hydrodynamics. A 2D hydrodynamic model 'representative' of an urban area in such circumstances, can

* Corresponding author at: Future Cities Laboratory, Singapore ETH Centre, Singapore.
E-mail address: shaad@ifu.baug.ethz.ch (K. Shaad).

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Table 1
Terrain mapping enabling techniques/technologies.

	Description	Cost	Coverage
LiDAR	LiDAR is a remote sensing technology that offers state-of-the-art high resolution mapping of terrain and is typically operated from an aircraft. Affords coverage of large areas (~10–100 sq km) but operation costs are high.	High	High
TLS	Terrestrial Laser Scanners can capture terrain data at close distance with extremely high resolution and accuracy, but being a ground-based technology has limited coverage. Attempts to expand range by mounting on vehicles have been seen in literature and practice.	High	Low
UAVp	Unmanned Aerial Vehicle based photogrammetry uses light weight drones to collect aerial imagery that via post-processing can be used to derive terrain models.	Low	High
CRP	Digital camera, as a low-cost image/video capturing technology is used to collect ground image-based data via a close-range photogrammetry (CRP) technique. These images obtained from camera positions are post-processed using Structure from Motion (SfM) algorithm.	Low	Low

provide not only useful information about flood propagation, but also allows developing and testing design alternatives for long term intervention for risk management, which are more suitable for the local conditions, as well as for building consensus of 'desirable' interventions (see Vollmer et al., 2014 and Grêt-Regamey et al., 2014 for details).

Availability of detailed spatial description of terrain and their integration with highly demanding 2D hydrodynamic models to reflect both real terrain conditions and flow behaviour have traditionally been the Achilles' heel of this approach (Horritt & Bates, 2001; Marks & Bates, 2000). While high resolution LiDAR data and terrestrial laser scanners (TLS) have become increasingly accessible, their operation and deployment in dense urban settings remains a costly exercise. However, in lieu to these high resolution but high cost technologies (see Table 1), developments have been made in the production of low cost digital imaging alternatives from unmanned aerial vehicles (UAVs) surveys and ground based close-range photogrammetry (CRP) techniques that have the potential to provide more effective alternatives and can possibly offer new direction to developing 'representative' 2D hydrodynamic models for densely settled river corridors.

The main objective of this paper is to provide an overview of the new capabilities offered by these low cost technologies and gauge the challenges still remaining for their integration with 2D hydrodynamic modelling, especially in the context of scaling of these technologies to provide coverage for large and densely populated urban conglomerates. To this end, we investigated the flood hazard in the urban area of Jakarta in relation to the different management scales, urban expansion and coping strategies it has generated at institutional and community levels (Section 2). A brief overview of the traditional constraints of 2D hydrodynamic modelling in these circumstances (Section 3) leads into the case study where the technologies are deployed on a ~2 km^2 area in Central Jakarta (Section 4) and urban hydrodynamic models constructed and evaluated from the resulting data (Section 5). Finally, Section 6 summarises these results and links to the further required work that could allow 2D hydrodynamic modelling based on advanced but still cost-effective terrain mapping technologies to emerge in urban areas as a robust, versatile yet scalable and attractive platform not only to incorporate elements of basic flood management planning, but also to address long term plans for river rehabilitation.

2. Floods in Jakarta, policy and interventions

2.1. Recent history of flooding and possible causes

Floods are not new in Jakarta. The Dutch colonial government has recorded recurring occurrences of floods in the city since the 1600s (Zaenuddin, 2013). A city in a deltaic plain, Jakarta counts 13 rivers flowing through the city. The link between urban development and floods, however, has only been established more firmly since the considerably rapid growth of the economy and the population since 1945. The amount of impervious surface has grown continuously due to the dramatic increase of Jakarta's urban development. This has led to the lack of groundwater recharge and more surface runoff (Abidin et al., 2011; Remondi, Burlando, & Vollmer, 2015; Texier, 2008). The reduction of forested areas in the upstream area of Ciliwung River has also been blamed for the increasing frequency of floods and the Ciliwung to be known as the source of flood problems rather than as a valuable resource (Akmalah & Grigg, 2011; Caljouw, Nas, & P, 2004; Texier, 2008).

Besides reduction of forested and green area, Jakarta's urban development has also been associated with land subsidence due to the scale of urbanisation and over-extraction of groundwater. In general, the city's annual land subsidence is 1–15 cm per year, but the distribution of this subsidence is uneven (Abidin et al., 2011). Thus, tidal floods have increasingly become a more serious threat in Jakarta due to the heavy land subsidence in the coastal area and to the fact that 40% of the city is already below sea level (Steinberg, 2007; Firman, Surbakti, Idroes, & Simarmata, 2011). The worst recorded flood in Jakarta in recent history was the 2007 flood, which displaced more than 400,000 people and brought 60% of the capital under water.

The city's shortage of affordable housing and unconsolidated control of land is another factor exacerbating flood risk. Density of urban *kampungs* – local neighbourhoods that consist of mostly self-built houses – has continuously increased, as they provide strategic locations in the city with relatively affordable rents compared to other private-driven real estates that have grown tremendously in and around Jakarta, particularly in the 1980s (Rimmer & Dick, 2009). Although riverbanks are state-owned land, the lack of control and often negotiable bureaucratic actors turn them into one option for affordable land within the city. Therefore, even when building on riverbanks is considered illegal, it is not uncommon to find residents who have some form of ownership of parts, including documentation in form of land and property tax payment slips (Hellman, in press). Thus, the use of riverbanks as settlements in a mega-urban region exposes more livelihoods to flood risk, especially because these settlements are typically multifunction, often combining work space and residential use (see Tunas, 2008).

2.2. Planned intervention and making space for the river

To respond to the emerging needs generated by riverbanks settlement, the Ministry of Public Works has issued, in the case of Ciliwung River, a plan for flood management, which includes the building of retention basins in the upstream area. These measures would be complemented by river dredging and concrete embankment carried out by the Government of Jakarta, and by the digging of a deep tunnel that would channel water overflow to the eastern flood canal (Widagdo, 2013). A press release in 2012 by JICA (Japan International Cooperation Agency), the Ministry's collaborator in