Sustainable Cities and Society 28 (2017) 53–66

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Assessing the vulnerability of pumping stations to trash blockage in coastal mega-cities of developing nations

R.I. Ogie[a,*], S. Dunn[b], T. Holderness[a], E. Turpin[a]

[a] Smart Infrastructure Facility, University of Wollongong, Northfields Ave, Wollongong, NSW, 2522, Australia
[b] School of Civil Engineering & Geosciences, Newcastle University, Newcastle, Tyne and Wear, NE1 7RU, UK

ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form 17 August 2016
Accepted 25 August 2016
Available online 30 August 2016

Keywords:
Vulnerability
Network
Mega-cities
Coastal cities
Jakarta
Trash blockage
Flood
Pump
Solid waste
Graph theory

ABSTRACT

Pumping stations are important flood mitigation infrastructure used in coastal cities to remove accumulating floodwater from low-lying areas, where drainage is naturally poor due to very low slope gradient. In coastal mega-cities situated in developing nations, these pumping stations are often vulnerable to trash blockage as a result of frequent dumping of solid waste in water bodies. Given that blocked pumps are common causes of drainage infrastructure failure, the inability to identify the most vulnerable pumping stations can lead to inefficient allocation of limited resources for preventative maintenance of the drainage system. This study proposes an approach for measuring and ranking the vulnerability of pumping stations to trash blockage. In this approach, a trash blockage vulnerability index (TBVI) is developed based on the concepts of exposure, sensitivity and resilience. Using a graph-based network analysis technique, the proposed TBVI is applied to assess and rank the vulnerability of pumping stations in one of the most representative coastal mega-cities – Jakarta, Indonesia. The results show that TBVI can point to the pumping stations that are most vulnerable to trash blockage. Such information are vital to decision makers when planning and prioritising infrastructure to be serviced or upgraded as part of flood preparedness in coastal cities.

1. Introduction

Coastal mega-cities in developing nations are facing ever-increasing challenges, including rapid urbanisation, inadequate infrastructure and the lack of basic amenities to meet the demands of an increasing population (Gasper, Blohm, & Ruth, 2011; Li, 2003). The geography of these coastal mega-cities makes them vulnerable to natural hazards, particularly flood events (Dewan, 2013). It has been shown that the average number of victims from natural hazards, including flooding, is 150 times greater in developing countries and economic losses are around 20 times higher than those in developed nations (Wenzel, Bendimerad, & Sinha, 2007). Furthermore, many of the densely populated coastal cities in developing nations lack affordable housing and sanitation facilities for low-income households (Alam, 2014). As a result, there is an uncontrolled sprawl of informal settlements or slums, many of which expand into flood plains and unprotected areas situated along the waterside (De Sherbinin, Schiller, & Pulsipher, 2007; Laronne & Shulker, 2002;; Li, 2003). Without access to adequate waste collection and handling facilities urban trash often end up in waterways (De Sherbinin et al., 2007; Laronne & Shulker, 2002). Consequently, solid wastes flow freely into the drainage network to further aggravate the flooding problem by reducing the carrying capacity of the channels and clogging the pumping infrastructure (Bankoff, 2003; Laronne & Shulker, 2002).

When a pumping station is blocked, its functionality in the flood mitigation process is jeopardised, leaving the possibility of flooding (Bankoff, 2003), particularly in low-lying areas where drainage is difficult without the use of a pump (Tingsanchali, 2012). Clogged pumps are common causes of drainage infrastructure failure in various coastal mega-cities, with resultant inundation claiming human lives, damaging urban property and disrupting economic activities (Bankoff, 2003; Li, 2003). This challenging problem, if not effectively addressed will leave these coastal mega-cities continuously trapped in a reinforcing cycle of infrastructure fragility and flood-related losses (Gasper et al., 2011).

The key challenge in addressing this problem stems from the fact that governments of developing nations lack adequate funding to cater for the basic needs of many of their urban residents including provision and maintenance of a functional drainage system (Gasper et al., 2011; Laronne & Shulker, 2002). Similarly, the use of engineer-

* Corresponding author.
E-mail addresses: rogie@uow.edu.au, korporateperformer@yahoo.com (R.I. Ogie).

http://dx.doi.org/10.1016/j.scs.2016.08.022

ing interventions for combating pump blockage (e.g. trash screens, channel dredging, etc.) have not been particularly effective due to poor maintenance arising from the mismanagement and inefficient targeting of limited resources allocated for the upkeep and upgrade of the drainage infrastructure system (Laronne & Shulker, 2002;; Wallerstein & Arthur, 2012). Hence, in planning for maintenance and upgrade of the drainage infrastructure system, there is need for a structured solution that facilitates informed decisions on where limited resources should be judiciously spent in order to prevent pump blockage (Ogie, Holderness, Dunn, & Turpin, 2016b). Ideally, such resource allocations and investment decisions should be effectively targeted at the pumping stations that are most vulnerable to trash blockage (Kumar, 2007).

A quantitative assessment of vulnerability can enable decision makers to highlight, and therefore prioritise their efforts towards the most vulnerable components within a system (Balica, Wright, & van der Meulen, 2012). However, no standardised processes yet exist for ranking pumping stations according to their vulnerability to trash blockage. The lack of a standardised process of finding suitable metrics (Balica et al., 2012), combined with the data scarcity in developing nations (Brecht, Dasgupta, Laplante, Murray, & Wheeler, 2012) complicate this task.

To address this issue, this study proposes a graph-based network approach for measuring and ranking the vulnerability of pumping stations to trash blockage. The graph theory approach is considered suitable because it provides a rigorous mathematical basis for computing vulnerability (Dunn & Wilkinson, 2012; Dunn, Fu, Wilkinson, & Dawson, 2013), using very little data obtainable at the time and allowing for further improvement from the initial results as additional data becomes available in the future (Bunn, Urban, & Keitt, 2000). In exploring this approach, a general equation for computing the vulnerability of pumping stations to trash blockage is first established, based on the concepts of exposure, susceptibility and resilience. The derived equation is then implemented in a case study application to assess and rank the pumping stations in the city of Jakarta, Indonesia, according to their vulnerability to trash blockage. The remainder of this paper is organised as follows: In Section 2 the methods followed to derive the equation for computing the Trash Blockage Vulnerability Index (TBVI) of pumping stations are presented, including the use of the Jakarta's study area as a demonstration of the activities leading to network construction and application. Section 3 presents the application of the underlying equation to compute TBVI for Jakarta's pumping infrastructure. In Section 4, the results are presented and their implications discussed. Section 5 concludes the paper and presents major limitations. Finally, Section 6 provides suggestions for future research.

2. Methods

This section presents the methods followed to derive the equation for computing the Trash Blockage Vulnerability Index (TBVI) of pumping stations. It includes the use of the Jakarta's study area as a demonstration of the activities leading to network construction and application. In this application, suitable metrics for implementing the equation are systematically derived using the constructed spatio-topological network model of the city's drainage infrastructure system. The results of the application are TBVI values representing the degree to which each pumping station in the city of Jakarta is vulnerable to trash blockage failure. The computed TBVI values are stored in a PostGIS database table (Obe & Hsu, 2015) and accessible for visualisation using geographical information system software (e.g. Quantum GIS or QGIS for short) (Gray, 2008). Such detailed analysis results are useful to decision makers in coastal communities when planning and prioritising infrastructure maintenance and resource allocation for flood preparedness.

In this paper, we narrow our scope to focus solely on fluvial (or riverine) flooding as this is the most likely to impact or aggravate trash interference to the pumping stations. Many coastal cities are also impacted by pluvial (or surface water) and coastal flooding (Douglas et al., 2010). Pluvial flooding occurs during intense rainfall as a result of surface water runoff associated with low permeability in urban areas that may be lying above and far from coastal and river floodplains (Douglas et al., 2010). Considering that pluvial floods are normally only a few centimetres deep, pumps are not often used to mitigate such type of floods (Yin, Yu, & Wilby, 2016). Coastal flooding is associated with high tides/waves, storm surges and sea-level rise that result in overtopping or breaching of coastal defences and the consequent inundation of areas lying on the coast of the sea or ocean (Wolf, 2008). Coastal floods happen less frequently than fluvial or pluvial floods and pumping stations have limited use in this scenario because they are not as effective as traditional coastline defences (e.g. dunes, groynes or seawalls) (Bates et al., 2005). However, pumping stations play a crucial role in defending against fluvial floods (Quan, 2014). This type of flooding is caused by inundation from river flows and can occur either due to intense, high velocity flash floods or excessive rainfall that causes river channels to overflow their banks (Fernandez et al., 2015). During fluvial flooding events, pumping stations are often used to pump out water from low-lying urban areas into storage basins or drainage channels flowing to larger water bodies such as the sea (Van Andel, Price, Lobbrecht, & van Kruiningen, 2010). Therefore, fluvial flooding is the most likely to be catalysed and aggravated by trash flowing in rivers. On the one hand, the flow of trash in rivers reduces their carrying capacity and increases the likelihood of fluvial flooding during days of extensive rainfall (Laronne & Shulker, 2002). On the other hand, the clogging of pumping stations by trash can result in their failure to defend low-lying urban areas against the impact of fluvial flooding (Bankoff, 2003). Hence, given that this study focuses on trash and their blockage to pumping stations, further reference to flooding, including for purpose of analysis will be based on fluvial floods.

2.1. Trash blockage vulnerability index (TBVI)

Vulnerability is the degree to which a system is susceptible to and is unable to cope with hazards (Adger, 2006). Its measurement depends on a number of factors within and outside the given system, which often appear to be complicated and with many dimensions that are difficult to capture in a single metric (Adger, 2006). These factors often vary from one system to another. They may also vary according to the conceptualisation of vulnerability, a term that seems to defy consensus usage (Adger, 2006; Few, 2003). In this study, the vulnerability of pumping stations to trash blockage (i.e. Trash Blockage Vulnerability Index, *TBVI*) is conceptualised as being made up exposure, *E*, sensitivity (or susceptibility), *S*, and resilience, *R* (modified from: Balica et al., 2012). This relationship is represented mathematically using the general formula (Eq. (1)).

$$TBVI = \frac{E * S}{R} \tag{1}$$

2.1.1. Exposure

Exposure, a key element of vulnerability, is the degree to which a system is in contact with, or subject to perturbation (Gallopín, 2006). In the context of flood hazards, pumping units are exposed to blockage from trash in all river reaches that flow from upstream to the given pumping station. In this regard, longer and large-size rivers or drainage channels pose greater risk to downstream pumps because they have more room and avenue for trash uptake. Given