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Vulnerability analysis of hydrological infrastructure to flooding in coastal cities - a graph theory approach

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Abstract

Hydrological infrastructure such as pumps and floodgates are invaluable assets for mitigating flooding in coastal cities. These infrastructure components are often vulnerable to damage or failure due to the impact of flood waters, thus exacerbating the flood hazards and causing significant loss of life and destruction to property worth billions of dollars. Hence, there is a growing need worldwide to enhance the understanding of flood vulnerability and to develop key metrics for assessing it. This study proposes an approach for measuring the vulnerability of hydrological infrastructure to flood damage in coastal cities. In this approach, a hydrological infrastructure flood vulnerability index (HIFVI) is developed based on exposure, sensitivity and resilience of infrastructure assets to flooding. A graph-theoretic algorithm for implementing the proposed HIFVI is presented and applied to assess the flood vulnerability of floodgates in one of the most representative coastal cities - Jakarta, Indonesia. The application involves the construction of a graph-based spatio-topological network model of Jakarta's hydrological system, with floodgates represented as network nodes and waterways as edges. An analysis of the constructed network is carried out based on the underlying graph-theoretic algorithm to compute HIFVI for all nodes that represent floodgates. The results show that HIFVI can point to the most vulnerable hydrological infrastructure components and also highlight locations within coastal cities where additional infrastructure are required to improve resilience to flooding. These information are vital to decision makers when planning and prioritising infrastructure maintenance and resource allocation for flood preparedness in coastal cities.

Keywords

theory, graph, cities, coastal, flooding, infrastructure, approach, hydrological, vulnerability, analysis

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Vulnerability analysis of hydrological infrastructure to flooding in coastal cities - A graph theory approach

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ABSTRACT Hydrological infrastructure such as pumps and floodgates are invaluable assets for mitigating flooding in coastal cities. These infrastructure components are often vulnerable to damage or failure due to the impact of flood waters, thus exacerbating the flood hazards and causing significant loss of life and destruction to property worth billions of dollars. Hence, there is a growing need worldwide to enhance the understanding of flood vulnerability and to develop key metrics for assessing it. This study proposes an approach for measuring the vulnerability of hydrological infrastructure to flood damage in coastal cities. In this approach, a hydrological infrastructure flood vulnerability index (HIFVI) is developed based on exposure, sensitivity and resilience of infrastructure assets to flooding. A graph-theoretic algorithm for implementing the proposed HIFVI is presented and applied to assess the flood vulnerability of floodgates in one of the most representative coastal cities - Jakarta, Indonesia. The application involves the construction of a graph-based spatio-topological network model of Jakarta's hydrological system, with floodgates represented as network nodes and waterways as edges. An analysis of the constructed network is carried out based on the underlying graph-theoretic algorithm to compute HIFVI for all nodes that represent floodgates. The results show that HIFVI can point to the most vulnerable hydrological infrastructure components and also highlight locations within coastal cities where additional infrastructure are required to improve resilience to flooding. These information are vital to decision makers when planning and prioritising infrastructure maintenance and resource allocation for flood preparedness in coastal cities.

1 INTRODUCTION

With the increasing frequency and intensity of rainfall and associated floods in coastal cities, there is a need to judiciously allocate limited resources for routine maintenance and upgrade of existing hydrological infrastructure (e.g. pumping stations, floodgates), in a manner that improves their resilience and minimises their failure during extreme flooding events (Sadoff et al. 2013). Ideally, such resource allocations and investment decisions should be effectively targeted at the most vulnerable components in the hydrological infrastructure system. By so doing, the failure of the hydrological infrastructure system and the resulting loss of life and property damage associated with flood inundation can be minimised (Hall et al. 2003). Though a quantitative assessment of vulnerability can point decision makers to the most vulnerable components in the hydrological infrastructure network, this is not a straightforward task that lends itself to a standardised process of finding suitable metrics (Balica et al. 2012). In the context of coastal cities situated in developing nations, this task is further complicated by the lack of sufficient data, potentially limiting the range of possible solutions (Brecht et al. 2012).

To address this issue, this study proposes a graph-based network approach for measuring hydrological infrastructure flood vulnerability index (HIFVI), using the concepts of exposure, sensitivity and resilience. The graph theory approach provides a rigorous mathematical basis for computationally reducing vulnerability to a single metric, using very little available data within the data-starved environment and allowing for further improvement from the initial results as additional data becomes available in the future (Bunn et al. 2000). In this approach, a graph-theoretic algorithm for implementing the proposed HIFVI will be developed and applied to assess and rank the flood vulnerability of Jakarta's floodgates, using the constructed spatio-topological network model of the city's hydrological system. The following section establishes the general equation for computing the flood vulnerability index of hydrological infrastructure components.

2 DERIVATION OF FLOOD VULNERABILITY INDEX FOR HYDROLOGICAL INFRASTRUCTURE COMPONENTS

Generally, vulnerability is determined based on three main factors: exposure, sensitivity (or susceptibility), and resilience (Balica et al. 2012). This can be represented mathematically using the general flood vulnerability index (FVI) formula (Eq. 1) (Balica et al. 2012).

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

The exposure of any given floodgate is determined by the length of all waterways that flow from upstream towards it (Balica et al. 2012). Given that the number of waterways that flow from upstream towards a given floodgate can range from 1 to n, the length, l, for each of these waterways can be summed to determine the exposure, E, of the floodgate. Mathematically, this can be represented as shown in Eq. 2.

$$E = \sum_{i=1}^{n} l_i \tag{2}$$

Susceptibility is a system characteristic, which determines the degree to which the system is affected by the impact of flood waters (Balica et al. 2012). In this study the capacity of the floodgate is used as a measure of susceptibility to flood damage. During intense flood events, a floodgate with lower capacity is considered more susceptible to failure or breakdown as compared to one with a greater capacity. Hence, given that C_g is the capacity of a given floodgate, susceptibility, S would decrease as C_g increases. This relationship can be represented mathematically as shown in Eq. 3.

$$S = \frac{1}{C_g} \tag{3}$$

Resilience can be derived as a function of redundancy (Chang & Shinozuka 2004). In this study, the resilience of a given floodgate, FG, in the hydrological infrastructure network is determined based on redundancy provided by connected upstream floodgates (Chang & Shinozuka 2004). Factors considered in measuring the redundancy provided by each connected upstream floodgate include capacity, c, geometric length, l (i.e. distance along flow path(s) to FG), and the upstream network configuration. The connected upstream floodgates with higher value of c and lower value of l contribute more to the resilience of FG. In terms of upstream network configuration, a connected upstream floodgate would contribute maximally to the resilience of FG if its location in the network allows it to divert floodwater from all the different channels flowing to FG. However, with additional number of channels, w, connecting the link between the two floodgates, the contribution of the upstream floodgate to the resilience of FG reduces accordingly. Hence, given that FG has m number of connected upstream floodgates, its total resilience, R can be estimated using Eq. 4.

$$R = R_s + \sum_{i=0}^{m} \frac{c_i}{l_i * w_i} \tag{4}$$

R_s is the structural resilience of the referent floodgate based on the physical property of its material, $\sum_{i=0}^{m} \frac{c_i}{l_i * w_i}$ is the total resilience contributed by the connected upstream floodgates, where i is an element in the set of connected upstream floodgates, which may be made up of 0 to m members. 0 member means that there are no connected upstream floodgates, in which case $\sum_{i=0}^{m} \frac{c_i}{l_i * w_i} = 0$ and $R = R_s$.

By substituting Eq. 2, 3, and 4 into Eq. 1, a general equation (Eq. 5) is obtained for estimating FVI (i.e. HIFVI) in the context of hydrological infrastructure (specifically floodgate) for flood mitigation.

$$HIFVI = \frac{\sum_{i=1}^{n} l_i}{C_g\left(R_s + \sum_{i=0}^{m} \frac{c_i}{l_i * w_i}\right)} \tag{5}$$

A graph-theoretic algorithm for applying Eq.5 to compute the HIFVI for the floodgates in a hydrological infrastructure network is shown below.

```
Begin
V = set of all nodes in the network, G.
    A node, v represents either a junction or floodgate.
E = set of all edges in the network, G.
    An edge, e is represented as ($v_s$ $v_f$), where $v_s$ = start node
    and $v_f$ = finish node.
$F_g$= set of all floodgates in the network, such that $F_g \in V$
For g such that $g \in F_g$:
Do
  1. Obtain the capacity, $C_g$ of $g$
     (Note: $C_g$ is encoded as an attribute in network nodes).
  2. Compute total length of waterways, $L_g$ connected to $g$.
        --$L_g$ = 0   (Initialisation)
        --Find $V_g$, set of all upstream nodes connected to g
        -- For e such that $e \in E$:
              if ($v_s \in V_g$) and ($v_f \in V_g$)
                  $L_g = L_g +$ (geometric length, l of e)
        --Return the value of $L_g$
  3. Compute $F_c$, the set of floodgates linked to $g$ upstream.
  4. Compute the total resilience, $R_{fc}$ contributed by the
     upstream floodgates connected to $g$ in four steps:
        $R_{fc}$ = 0   (Initialisation)
        -- For f such that $f \in Fc$:
     (i). Compute c, being the capacity of f.
     (ii). Compute the total number of additional waterways,
           $W$ joining the link between each connected upstream
           floodgate and $g$ (i.e. a measure of branchness factor).
           W = 1   (Initialisation)
           $V_{fc}$= set of all nodes in the shortest path between f
           and g.
           For p such that $p \in V_{fc}$:
               $N_e$= the number of inward edges to p
               if $N_e > 1$ (an indication of branchness)
                   $W = W + N_e$
           Return the value of W
     (iii). Compute the total length of waterways, $L$ between f
            and $g$.
            L = 0   (Initialisation)
            $V_{fc}$= set of all nodes in the shortest path between f
            and g.
            For e such that $e \in E$:
                if ($v_s \in V_{fc}$) and ($v_f \in V_{fc}$)
                    $L = L +$ (geometric length, l of e)
            Return the value of L
     (iv). Compute sum of the resilience contributed by all
           upstream floodgates connected to $g$.
             $R_{fc} = R_{fc} + \frac{c}{L*W}$
  5. Compute the total resilience, R of $g$.
        -- $R_s$ = 1 (structural resilience, $R_s$ is assigned a constant
               value of 1 for all floodgates in the network.)
        -- $R = R_s + R_{fc}$
  6. Compute the flood vulnerability index, HIFVI of $g$.
        -- $HIFVI = \frac{L_g}{C_g*R}$
End
```

3 A CASE STUDY APPLICATION: JAKARTA'S HYDROLOGICAL INFRASTRUCTURE NETWORK

Jakarta, the capital of Indonesia was selected for this study because it is one of the most exemplary coastal cities of developing nations that depend heavily on structural measures or hydrological infrastructure (e.g. floodgates, pumps, etc.) to mitigate the devastating impact of flooding on the people, property, economy, and environment (Li 2003). As a low-lying delta city served by thirteen rivers, Jakarta relies on a network of pumping stations and floodgates to control water flowing from surrounding hills and mountains, through the city to the Java Sea (Hartono et al. 2010). The frequent use of these ageing and poorly maintained hydrological infrastructure components during the annual monsoonal flooding (between November and March) exposes them to the damaging impacts of floodwaters, with possibility of breakdown or failure as a consequence (Turpin et al. 2013). Generally, the pumping stations are used to move out accumulating floodwater, particularly in low lying areas where drainage is difficult without pumping (Tingsanchali 2012). On the other hand, the action of closing a floodgate allows it to be used for diverting floodwater away from flooded areas located downstream of the floodgate. Because the acquired dataset for the pumping stations was incomplete at the time of this study, this application focuses on just the floodgates infrastructure in Jakarta.

The floodgate dataset, in addition to Jakarta's waterways (i.e. rivers, canals, and streams) were acquired and processed in readiness for network construction and subsequent vulnerability analysis. The data acquisition involved the use of ground survey, GPS locations and aerial imagery analysis to capture and record the names and locations of the different floodgates and waterways in Jakarta. The resulting waterways vector data is of line geometry type while the floodgates vector data made up of 30 records is of point geometry type. Using the topology toolset and GRASS plugin within the QGIS software, these datasets were processed to remove topological and locational errors introduced during survey and digitisation of mapped data. Furthermore, edges in the waterways dataset were programmatically split into separate line features where they self-intersected or intersected with floodgate infrastructure. This is to ensure that at the construction of the hydrological infrastructure network, junctions are created were they actually exist.

The graph-based spatio-topological network model of Jakarta's hydrological infrastructure was constructed using the PostGIS spatial database schema and coupled Python interface to the NetworkX graph analysis package developed by Newcastle University (Barr et al. 2012). This software was first extended to support the proposed graph type (i.e. multidigraph), which permits multiple edges between the same source and target nodes. Topology was encoded within the data using a system of unique node and edge primary keys. In the absence of high resolution and accurate elevation data to model flow direction of Jakarta's waterways, directionality was inferred by edge orientation assuming the general condition of water flowing from the mountains of Bogor to the south of Jakarta, and through the city to the Java Sea in the north. Where exceptions to this assumption existed based on actual field observations of water flow in the city of Jakarta, corrective adjustments of edge orientation were made by re-ordering (i.e. reversing) the geometric points in the linestrings.

The completed network comprised of 628 edges representing Jakarta's waterways, with a total geometric length of 1092 km. There were 560 nodes in the network, 30 of which represent floodgate infrastructure, and the remaining 464 representing network junctions (e.g. river confluences). Figure 1 highlights the locations of the floodgate infrastructure in the network.

Following the successful construction of the network model, the NetworkX and the Pandas Python libraries were used in implementing the underlying graph-theoretic algorithm, resulting in the computation of HIFVI for all 30 floodgate infrastructure in Jakarta. In this implementation, certain assumptions were made. For instance, in the absence of relevant data to determine structural resilience, R_S this parameter was assumed to be a constant value of 1 for each floodgate in the network. Similarly, in the absence of data for floodgate capacity, the number of gates in each floodgate was used as a proxy for capacity. The computed HIFVI values were stored in a PostGIS database table and accessible for visualisation using geographical information system software (e.g. QGIS).

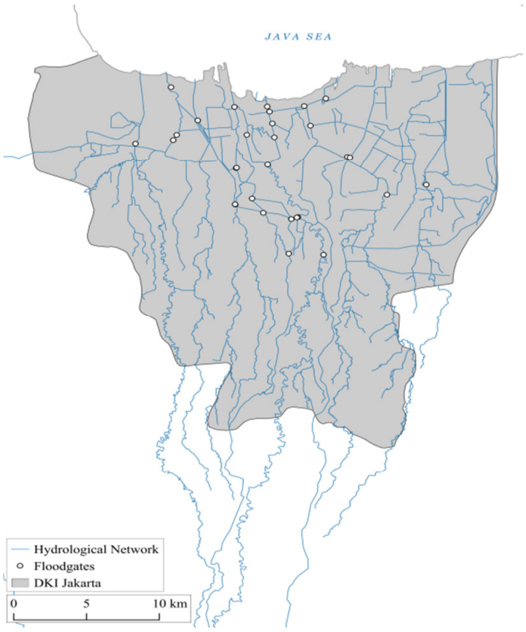

Figure 1. Jakarta's floodgate infrastructure network

4 RESULTS

The results of an application of the graph-theoretic algorithm to Jakarta's hydrological infrastructure are index values representing the degree to which each floodgate in the city is vulnerable to failure or damage due to the impact of flood waters. The index values (i.e. HIFVI) were normalised to give a number from 0 to 1, where 0 does not mean absence of vulnerability, but rather a representation of the lowest vulnerability and 1 indicates the highest in this dataset. This approach allows for a comparative assessment of infrastructure vulnerability to flood hazards (Balica et al. 2012).

To further characterise hydrological infrastructure based on computed HIFVI, index values were classified into 5 different levels of vulnerability as follows: 0-0.2 = very low vulnerability, 0.2-0.4 = low vulnerability, 04-0.6 = moderate vulnerability, 0.6-0.8 = high vulnerability, and 0.8-1 = very high vulnerability (see Table 1).

The results show that "Sunter C" topped the category of very high vulnerability floodgates, thereby ranking as the most vulnerable floodgate with computed HIFVI value of 1. On the other hand, "Sunter

Utara” had the lowest computed HIFVI value of 0, making it the least vulnerable to failure or damage arising from the impact of flood waters. Overall, Table 1 shows that 10% (i.e. three) of Jakarta’s floodgates were classified as having very high vulnerability to failure or damage due to the impact of flood waters. Another 3.33% (i.e. one) of the floodgates was moderately vulnerable, but 0% (i.e. none) was classified as highly vulnerable based on computed HIFVI. Most floodgates (i.e. 17) came under the category of very low vulnerability, representing 56.67% of the entire sampled infrastructure. This is closely followed by another 30% (i.e. 9) classified as having low vulnerability to failure or damage due to the impact of flood waters. These results and their implications are discussed further in the subsequent section.

Table 1: Vulnerability ranking of Jakarta’s floodgate infrastructure based on computed HIFVI

Name of floodgate	**Susceptibility** (1/no. of gates)	**Resilience**	**Exposure**	**HIFVI**	**Ranking**
Sunter C	1.00	1.45	199.89	1.000	VH
Ciliwung Lama	1.00	1.05	133.65	0.921	VH
Kebon Baru	1.00	1.00	122.59	0.890	VH
Muara Angke	0.50	1.43	203.95	0.518	M
Cakung Drainase	0.33	1.00	164.23	0.397	L
Karet 2	0.50	1.39	150.31	0.391	L
Pasar Ikan	0.25	1.51	307.40	0.370	L
Hailai	0.50	1.78	169.77	0.346	L
Istiqlal	0.33	1.13	160.47	0.343	L
Tangki	0.50	1.94	164.02	0.306	L
Jembatan Merah	0.25	1.10	163.09	0.268	L
Kali Cideng	0.33	1.50	157.59	0.253	L
Citra Land	0.33	1.75	153.79	0.212	L
Cengkareng Drain	0.25	1.00	101.23	0.182	VL
Pulogadung	0.17	1.00	143.50	0.172	VL
Ancol	0.20	1.52	176.82	0.168	VL
Pekapuran	0.20	1.64	170.12	0.149	VL
8	0.13	1.26	151.23	0.108	VL
Sogo	0.50	1.53	36.24	0.084	VL
Poglar	0.33	1.00	33.81	0.080	VL
Warung Pedok	0.50	1.00	12.81	0.045	VL
Manggarai	0.33	1.19	21.79	0.043	VL
Setia Budi	0.33	1.15	19.70	0.040	VL
Minangkabau	0.50	1.64	15.94	0.034	VL
Kampung Gusti	0.50	7.25	34.29	0.016	VL
Kalimati	0.50	1.00	3.04	0.009	VL
Honda	0.17	1.00	6.84	0.007	VL
Duri	0.33	1.00	3.09	0.006	VL
Karet	0.25	63.26	150.34	0.003	VL
Sunter Utara	0.25	1.00	0.92	0.000	VL

VH= Very High, M = Medium, L = Low, and VL = Very Low.

5 DISCUSSIONS

This study has proposed a new flood vulnerability index and an underlying graph-theoretic algorithm to comparatively assess and rank floodgates in coastal cities based on their exposure, susceptibility, and resilience to flooding. An application of the graph-theoretic algorithm to Jakarta’s hydrological infrastructure produced index values that point to the most vulnerable floodgates in the network (see Table 1). “Sunter C” ranked as the most vulnerable floodgate in Jakarta, followed by “Ciliwung Lama”, and “Kebon Baru” in that order. These three floodgates are characterised as having very high vulnerability and they represent the top 10% of Jakarta’s floodgate infrastructure that are most likely to fail during a flood event. Hence, they should be prioritised during infrastructure maintenance and resource allocation for flood preparedness. To minimise their vulnerability to flood damage, limited resources can be judiciously spent on increasing their capacities by adding extra gate units where possible. No doubt, this outcome will be useful to coastal communities and external funding bodies who often require structured vulnerability assessment techniques that facilitate transparent and efficient decisions on where the limited resources allocated for flood mitigation should be invested.

Furthermore, because “Kebon Baru” does not currently have any upstream floodgate connected to it, its vulnerability can also be further minimised by improving its resilience through the installation of additional upstream floodgates. This way the pressure on “Kebon Baru” created by accumulating floodwaters can be controlled using the additional upstream floodgates, thereby reducing the probability of structural failure due to infrastructure fragility (Turpin et al. 2013). This demonstrates the usefulness of the adopted approach in highlighting locations where additional infrastructure may be required.

In addition, this approach to vulnerability assessment can be useful to decision makers who require justification for vulnerability attribution. For example, “Sunter C” ranked as the most vulnerable floodgate partly because of its huge exposure to 199.89km length of waterways as compared to very low vulnerability ranking floodgates like “Duri” and “Sunter Utara”, which are only exposed to 3.09km and 0.92km length of waterways respectively. Another reason is because of its high susceptibility to flood damage, which can be attributed to the fact that it only has one gate unit compared to very low vulnerability ranking floodgates like "Sunter Utara", "Honda", and "8" which has 4, 6, and 8 gates respectively. Similarly, the very low vulnerability of 56.67% of Jakarta's floodgates is mainly due to their low exposure to flood waters when compared to other floodgates in the city. However, in the case of "Karet", it is its high resilience attained through redundancy provided by connected upstream floodgates that makes it rank as a very low vulnerability floodgate. No doubt, such detail of vulnerability attribution can leave clues as to what actions can be taken to minimise infrastructure vulnerability.

6 CONCLUSION

This paper has proposed a graph-based network approach for measuring hydrological infrastructure flood vulnerability index (HIFVI), using the concepts of exposure, sensitivity and resilience. An application of the proposed method produced HIFVI values for Jakarta's floodgates, demonstrating its usefulness in ranking and comparing the vulnerability of hydrological infrastructure components to flood damage in coastal cities. The results will facilitate transparent and efficient targeting of limited resources towards routine maintenance, future investments and upgrades to the flood control infrastructure within coastal cities situated in developing nations. Importantly, the method was found to be useful in highlighting locations where additional infrastructure may be required to improve resilience to flooding. This will enable coastal cities in developing nations plan for more resilient future and to improve the outcome of their structural response to flood hazards.

One limitation of this study is the absence of additional data to improve the quality and reliability of the technique. This issue can be addressed by taking advantage of the graph theory feature, which allows for incremental integration of additional data into the network model as they become available in the future (Bunn et al. 2000). Hence, future study will seek to improve the quality and reliability of the technique by introducing additional data related to hydrological infrastructure components (e.g. asset age, flood height capacity, maintenance and failure history). Moreover, the impact of flood waters on the hydrological infrastructure can be more accurately accounted for if additional data such as elevation, width, depth, roughness, and flow rate of river channels are available.

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