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GRAPH BASED METHOD FOR CRITICAL PIPE ANALYSIS IN URBAN DRAINAGE NETWORKS AND THE EFFECT OF LOOP DEGREE

Aun Dastgir[1], Martin Oberascher[2], Sina Hesarkazazzi[3] and Robert Sitzenfrei[4]

[1,2,3,4]Unit of Environmental Engineering, Department of Infrastructure Engineering, University of Innsbruck, Technikerstrasse 13, Innsbruck, Tirol, Austria

[1] *aun.dastgir@uibk.ac.at*, [2] *martin.oberascher@uibk.ac.at*, [3] *sina.hesarkazazzi@uibk.ac.at*, [4] *robert.sitzenfrei@uibk.ac.at*

Abstract

Urban drainage networks (UDNs) are important for urban areas, to ensure protection of humans from nature and also to protect nature from anthropogenic impacts. Internal and external pressures on these systems like structural failure (e.g., pipe collapse), and functional failure (e.g., climate change and urbanization, require efficient modelling strategies for its management and maintenance. For proper functioning of the system as a whole, some elements of UDN infrastructure hold more importance than other elements. Identifying these critical elements(pipes) in UDNs is of utmost importance for forming efficient management strategies.

In this study, a graph-based method based on “runoff edge betweenness centrality” is presented for determining the critical elements due to pipe failure of a UDN. In contrast to conventional hydrodynamic modelling method, the proposed graph-based method does not rely on iterative hydraulic simulations. Instead, it takes a mathematical graph representing the structure of the network as starting point and incorporates hydraulic factors to mimic the hydraulic behavior of structural failures in UDNs. Effect of loop degree in the UDNs on this graph-based method is studied by employing the method for a fully branched network and two partially looped networks of different loop degrees. A fully branched network is employed as a case study comprising of 59 circular pipes, draining an area of 175 hectares. Loops are manually created in the same network to study the impact of different number of loops on the accuracy of graph-based method. The results from the graph-based method are compared to the ones from hydrodynamic modelling from SWMM model in terms of accuracy as well as computational time and efforts required.

Results show that the graph-based method is very accurate (98%) in case of a fully branched network but the accuracy decreases with the increase of loop degree in the network. This is due to the complex hydrodynamic effects like back-water phenomenon which cannot yet be modelled using graph-based approach. The method is hence least accurate (92%) in case of fully looped network though still very useful, because the computational time and effort required is much less than hydrodynamic modelling method. The proposed method is also less data intensive and hence can be used by utilities where quick analysis is required or a large number of evaluations have to be made.

Keywords
Complex Network Analysis, Graph Theory, Pipe Criticality, Hydrodynamic Modelling, Edge Betweenness Centrality.

1 INTRODUCTION

Urban Drainage Networks (UDNs) are an important lifeline in urban areas that are built for protection and convenience of humans. These systems are important for public health and for the protection of environment from anthropogenic impacts. Sewer networks have to be maintained and rehabilitated regularly to achieve the serviceability required from these systems [1]. UDNs are large spatial networks consisting of many elements. The overall performance of the network strongly depends on the performance of each individual element. Characteristics and position of a particular element define its importance in the network [2]. Maintaining all the elements to the same high service level is expensive in terms of resources required. Hence, it is important to recognize critical elements of UDNs to prioritize the maintenance and rehabilitation accordingly. The degree of criticality can therefore be used to make such a system more resilient.

There are very few methodologies in literature to identify critical elements in sewer networks. Arthur and Crow [3] described a strategy to find critical elements based on the serviceability loss. The ranking of pipes is done based on the combination of consequence scoring (depending on the consequence of failure) and likelihood scoring (based on likelihood of failure). Another methodology is used for identification of weak points for urban water infrastructure [4, 5]. In that approach systematic Hydrodynamic Modelling Method (HMM) is used, through which the capacity of each conduit is reduced to almost zero to mimic pipe blockage (one at a time) and the hydraulic consequences such as overall system flooding is determined and spatially mapped to the origin of the blockage. For large networks and looped systems this method requires a high computational effort.

Researchers have started working with a new methodology based on graph theory to model UDNs to tackle the problem of high computational efforts in case of large UDNs. Graph theory is a branch of mathematics which employs graphs to model the complex problems of real life, more efficiently [6]. For example, graph theory is used for the layout and design of UDNs [6], functional analysis of UDNs [7], to assess redundancy [8], and assessing the efficiency of different topological positions of combined sewer overflow structures in an UDN [9], in literature. A method has been proposed for finding critical elements using graph theory which focuses on finding the costs of the graph by removing a part of the network [2]. The research uses shortest path length graph measure and head loss as a weight to find the costs associated with removing a particular component (pipe). The cost associated with the graph is calculated after removing an edge (pipe) and the method is repeated for every edge. However, there is a need to extend the research to a graph method that is simpler to implement and is not iterative to save computational time on large networks and which can also be extended to multiple pipe failure or cascading failures.

Recognizing the research gap, this paper proposes a new method based on graph theory to identify the critical individual components (pipes) of a UDN. The method is based on a graph metric called "Runoff Edge Betweenness Centrality" (EBC_e^R). In contrast to conventional hydrodynamic modelling method, the proposed method does not depend on iterative hydrodynamic simulations which is a time-consuming procedure. Instead, it employs the concept of network analysis tailored to UDNs to mimic their hydraulic behaviour. Critical pipes are identified with a graph-based measure (EBC_e^R) which can be interpreted as the volume of flooding when a particular pipe is blocked. The pipes are subsequently ranked according to the caused flood volume when it is blocked. This research focuses on both branched and looped networks and discusses the impact of loop degree on the accuracy of the method. The results from the graph-based method are compared with the results from hydrodynamic modelling method in terms of accuracy as well as computational time. This paper only focuses on single pipe failure/blockage but the methodology can be extended to multiple pipe failure or cascading failure as well due to its high computational efficiency.

2 MATERIALS AND METHODS

First, theory of the graph-based method is explained along with the explanation of existing hydrodynamic method which will be used for comparison. Both methods are then applied for fully branched, semi looped and fully looped network and the results are compared.

2.1 Graph Representation of UDNs

A graph G is a set of vertices (V) and edges (E) and can be represented by G = (V,E) where the set of vertices (nodes) are denoted by V(G) and the set of edges are denoted by E(G). An edge can be represented using its source node i and target node j by an ordered pair (i,j) [6]. A graph is called directed if the edge (i,j) is directed from node i to node j or undirected if the edge has no particular direction in which case edge (i,j) is exactly the same as edge (j,i). In graph analysis, each edge can have a certain weight. A graph can be looped if there exists more than one edge originating from the same vertex or branched if there exists only one path between each pair of vertices (no loops). In UDNs, manholes, storage tanks etc. are represented by vertices and pipes, pumps etc. are represented by edges. A graph can have one or multiple outlets or in case of foul or combined sewer systems, outflows in the receiving water or wastewater treatment plants.

The graph measures that has been used in this study are modified to the functioning and hydraulic properties of UDNs. The first graph measure that has been employed is called shortest path lengths $\sigma_{i,j}$, which can be defined as a path between nodes i and j which has minimum sum of edge weights [10]. Weights can be given to edges according to the requirement of the study and as an attribute of hydraulic behaviour of UDNs. Length is used as an edge weight to find shortest paths in this study. Another graph measure that is employed in this study is, edge betweenness centrality (EBC). Number of shortest paths between every pair of nodes in a graph that pass through a particular edge *e*, represents the EBC of the edge *e* [11]. Considering the hydraulic nature and functioning of UDNs, a modification has been added to EBC graph measure to make it more suitable to the use case. We count the number of shortest paths between every inlet node i to an outlet node j that passes through a particular edge e. Further, instead of counting the number of paths, the contributing runoff area R_i of each inlet node is added to EBC values to compute the cumulative impervious area for every edge of a UDN. This measure is called runoff edge betweenness centrality (EBC_e^R) [12] and is given by:

$$\boldsymbol{EBC_e^R = \sum i,j \;\; \sigma_{i,j}(e) \, * \, R_i} \qquad (1)$$

EBC_e^R values can be multiplied with different rain volumes that gives a surrogate for potential flooding volume.

2.2 Graph Based Method

The graph-based method is used to replicate the flood volume in the system when a pipe blockage is simulated. This is achieved using the concepts of shortest paths and EBC_e^R as explained in the above section. The functionality of our approach is illustrated using a simple branched network consisting of six nodes and five edges as shown in Figure 1.

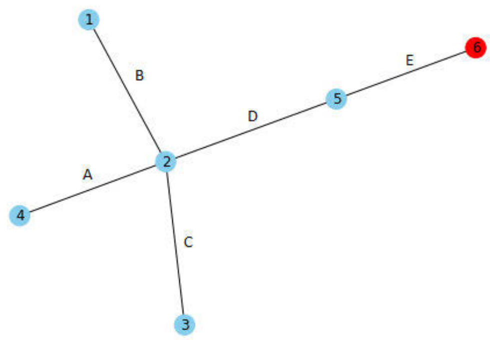

Figure 1: A simple six nodes branched network

In the first step, the shortest paths from all inlet nodes to the outlet node, node 6 shown in red in above network, are determined. Table 1 shows the results from shortest paths calculation for every node. For every node, the pipes that are part of the shortest path get a value of 1 and all other pipes get a value of 0 forming a vector of zeros and ones. Summing up the rows for each pipe in that matrix, results in a vector which gives us the classical edge betweenness centrality of every pipe shown in Table 1. To account for the functional properties of UDNs, runoff area of each node R_i calculated using the area of the sub-catchments connected to a particular node and their imperviousness, is multiplied with all matrix elements in the corresponding shortest path. When now summing up the rows in that matrix, the EBC_e^R are obtained for each edge.

Additionally, total rainfall volume can also be included in the calculation by multiplying EBC_e^R with the rainfall volume to understand the differences generated by different rainfalls (e.g., different return periods). This can be the indication of maximum possible flooding volume based on EBC_e^R values for every pipe. For a fully branched network, the EBC_e^R value multiplied with the rainfall volume corresponds to the flooding volume when that particular pipe is blocked. This flooding value is then compared with the flood volume obtained from HMM method.

Table 1: Edge betweenness centrality vector for network in Fig.1

Nodes / Pipes	**1**	**2**	**3**	**4**	**5**	**EBC**
A	0	0	0	1	0	1
B	1	0	0	0	0	1
C	0	0	1	0	0	1
D	1	1	1	1	0	4
E	1	1	1	1	1	5

In case of a looped network, the aforementioned methodology has to be adapted to include the impact of loops on flooding as well. In that case, a new measure called Capacity Edge Betweenness Centrality (EBC^c) is introduced based on the capacity of pipes.

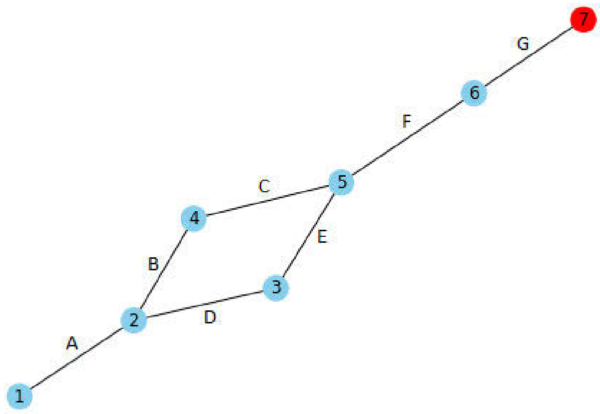

Figure 2: A simple looped network

In the looped network shown in Figure 2, nodes 2,3,4, and 5 are part of loops as they have alternative paths which means even if one of the pipes B, C, D or E are blocked, there is an alternate path for the flow to reach the outlet 7 (shown in red). The amount of flow which can be redirected to the alternate path depends on the capacity and slope of the pipe in the alternate path. For example, when pipe B is blocked, the whole EBC_e^R value of the pipe does not correspond to the flooded volume, rather a portion or all of it can be redirected to the pipe D. To find the amount that can be redirected to D, EBC^c is calculated based on Manning-Strickler formula using diameter and slope of the pipe D. Flooding when the pipe B is blocked can be calculated by subtracting EBC^c

of pipe D from the EBC_e^R of pipe B. Similarly, the procedure can be repeated for all the pipes having alternate paths/loops. The pipes are ranked on the basis of flooding volume in case of blockage or failure. The pipe with the highest flood volume in the system is ranked most critical.

2.3 Hydrodynamic Modelling Method (HMM)

To compare the proposed graph-based method with the state-of-the-art, Achilles approach introduced by [4] is used in this paper to identify critical pipes using hydrodynamic modelling implemented in SWMM. The pipes are ranked on the basis of flooding produced in case the pipe is blocked. The pipe that leads to the most flood volume in the system when it is blocked, is the most critical pipe.

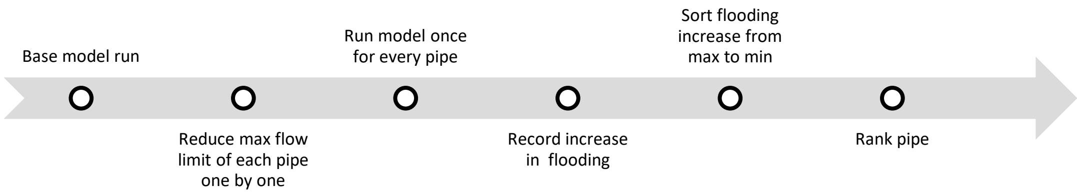

Figure 3: Process to determine critical pipes using HMM

Figure 3. describes the process of determining critical pipes using HMM. First, a base run is performed when all pipes function under normal condition, and therefore no flooding occurs in the system. Then, maximum flow limit of pipe is reduced to 0.01 to simulate pipe blockage. A new simulation is carried out for every pipe blockage one by one. The flooding volume is then recorded for every pipe. Pipes are ranked on the basis of flooding produced when it is simulated as blocked.

2.4 Case Studies

A benchmark urban drainage network is selected for this study. The network is designed by [12] for two year return period block rain of 15 minutes duration having total rain volume of 17.1 mm. It is a fully branched network that drains 175 hectares. The network is comprised of 59 circular pipes connected by 60 inlet nodes including one outlet as shown in Figure 4.

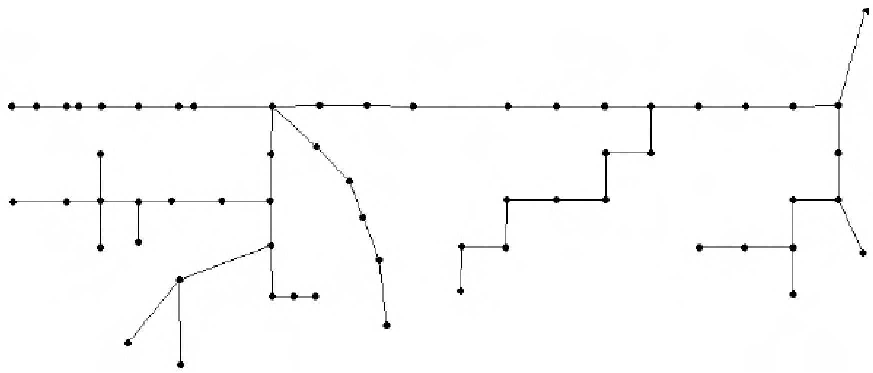

Figure 4: Benchmark Case study network [12]

To extend the study to looped networks, loops are created manually in the benchmark network in Figure 4. Two networks having three loops and six loops respectively are created to study the impact of loop degree on the method. The loops created are not designed.

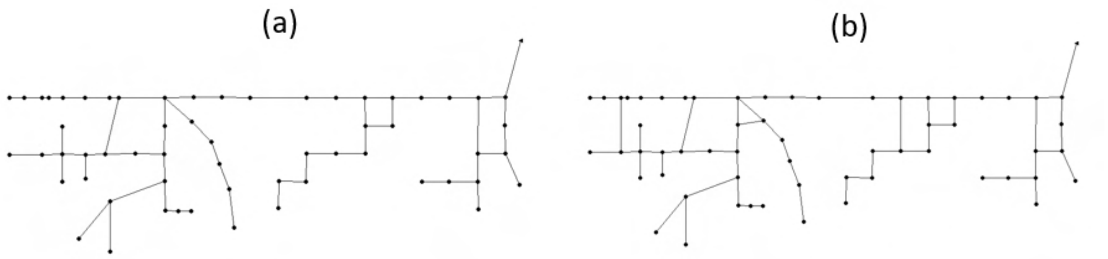

Figure 5: Manually created looped networks (a) Three loops (b) Six loops

2.5 Software and Hardware:

For hydrodynamic modelling, Environmental Protection Agency (EPA's) Stormwater Management Module (SWMM) version 5.1 is used. For graph-based method, Python's module NetworkX version 2.6.2 developed specifically for network analysis is applied. In terms of hardware, a laptop having an Intel® Core™ i7-10610U CPU @ 2.3 GHz processor and 8 GB RAM is used. The system has 64-bit Windows 10 operating system.

3 RESULTS AND DISCUSSION

All three case study networks are analysed using both graph method and HMM and the accuracy of the graph-based method is compared with that of HMM along with the computational time required for both methodologies. 20 most critical pipes given by both methods are compared to give an idea of how well the graph-based method can identify the most critical parts of the sewer networks.

3.1 Fully Branched Network

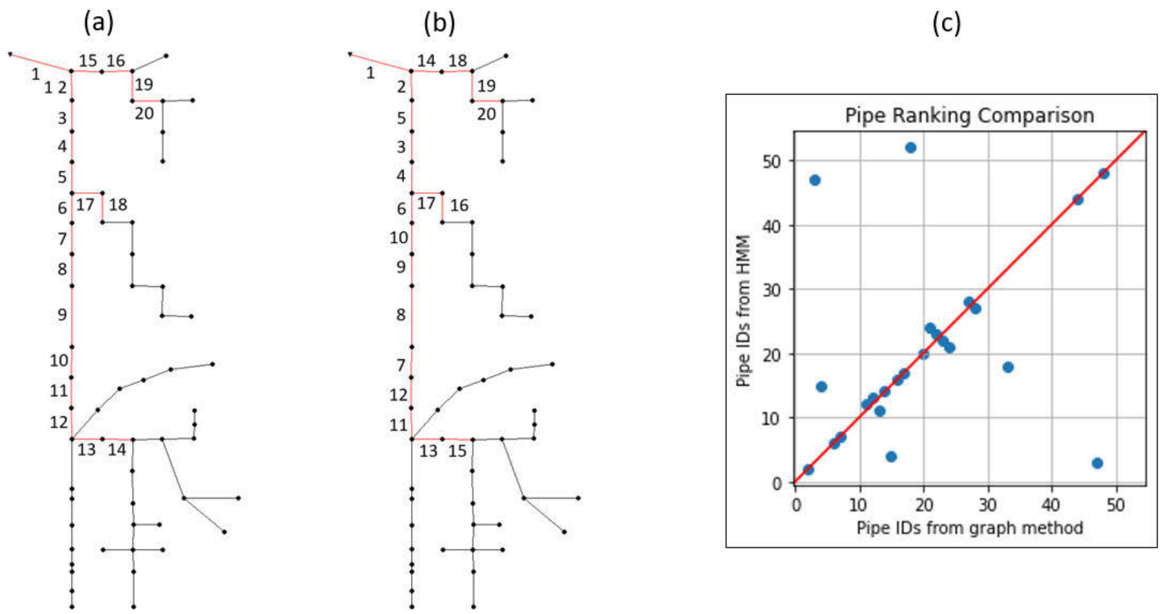

Figure 6: Critical pipes shown in red and in the order of criticality (a) from Graph method, (b) from HMM (c) comparison of pipe rankings

Figure 6 shows the difference between critical pipes identified using graph method and HMM for the branched network. It shows top 20 most critical pipes in red colour and ranked in the order of criticality, (a) obtained from graph method and (b) obtained from HIGA. It can be seen that in case of a fully branched network, all 20 pipes identified by both methods are same. The order of criticality is the same for 6 out of these 20 pipes. To better understand the accuracy in terms of order of criticality, a scatter plot comparing the rankings of pipes from these two methods is shown in Figure 6(c). The plot shows the number of pipes having the same rankings out of first 25 pipes. It can be seen that 9 out of 25 most critical pipes are ranked the same by both methods. This shows that the order of criticality of around 35% of the pipes is identified accurately by the graph method.

3.2 Looped Networks:

Critical pipes identified from both methodologies in case of looped networks are shown in figure 7, wherein (a) and (b) of the figure show the results for network with three loops and (c) and (d) show the results for network with six loops. For network with three loops, graph method identifies 18 out of the 20 most critical pipes the same as identified by HMM. The order of criticality is different starting from 3rd most critical pipe. In case of network with six loops, graph method identifies only 15 of the 20 most critical pipes identified by HMM method. This shows that the methodology is not as accurate as in the case of fully branched network. Additionally, the accuracy of the method decreases as the loop degree increases. The reason is that in case of looped networks, graph-based method cannot mimic all the entailed complex hydraulic properties e.g., backwater effect. Also, the graph method considers the impact of loops on flooding for pipes immediately next to the loops but in reality, the impact also propagates further downstream which means that the graph method cannot predict rerouting of water as accurately as HMM method. Increasing the loop degree increases the magnitude of these complexities resulting in less accurate results.

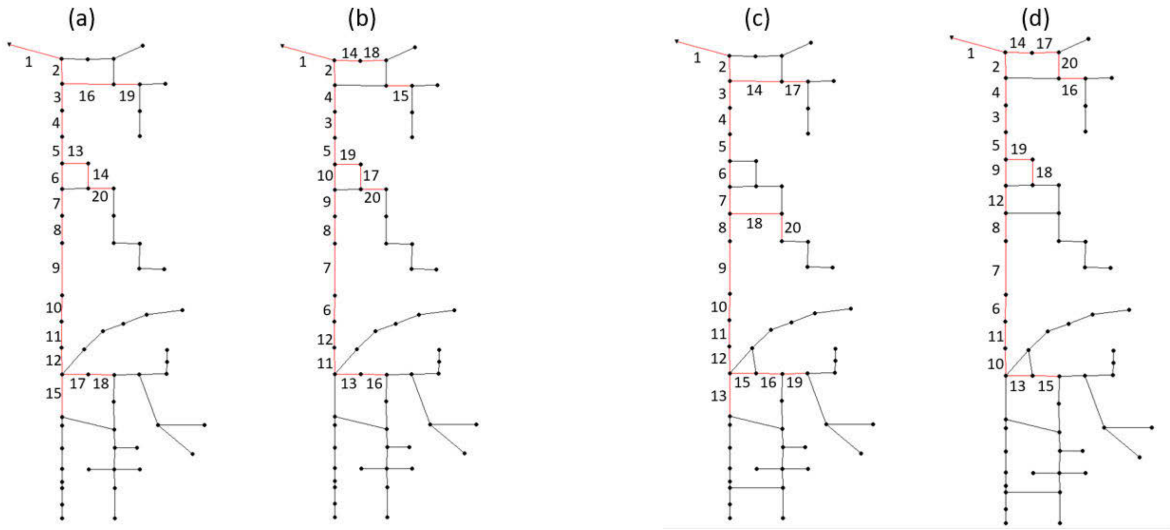

Figure 7: Critical pipes shown in red and in the order of criticality from network with three loops using, (a) graph (b) HMM and from network with six loops using, (c) graph (d) HMM

To get a better idea of the differences in both methods, Figure 8 compares flooding obtained from graph method using EBC_e^R and flooding obtained using HMM, based on a linear regression trendline for every network. In Figure 8(a), the flooding volumes from HMM and based on the graph-based method for the branched networks are shown. It can be seen, that the graph-based method, besides identifying the criticality of the pipes, also quite sufficiently reproduces the flooding volume.

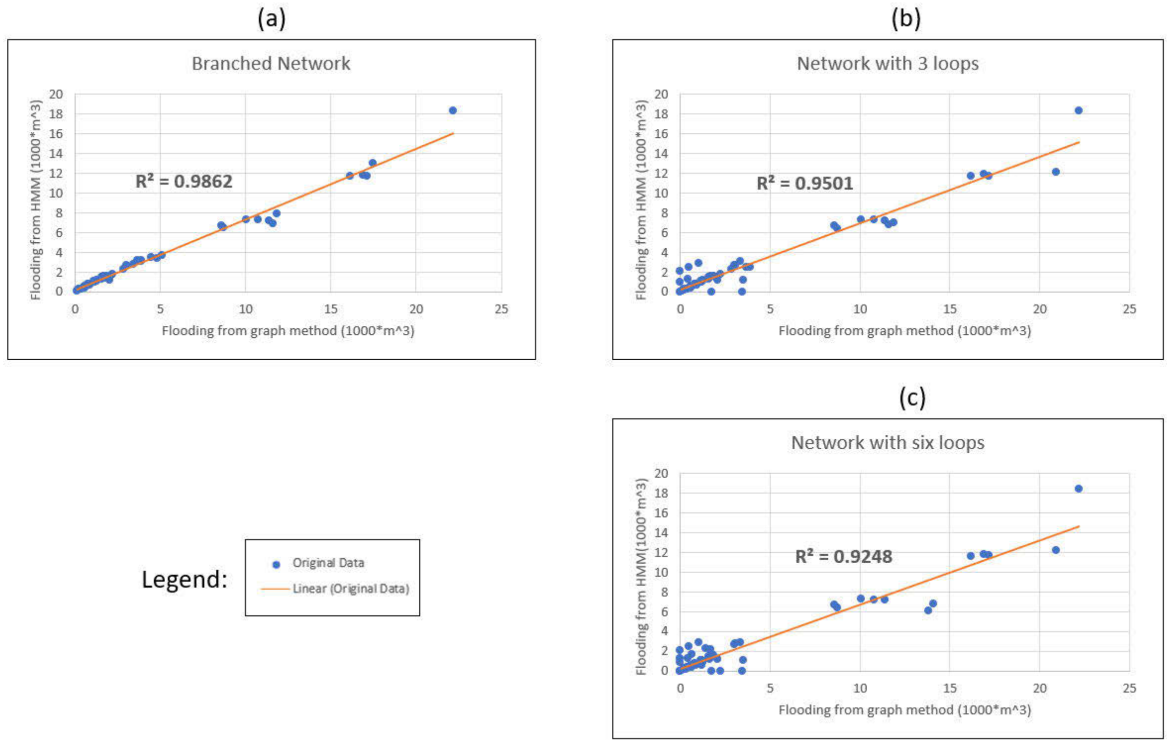

Figure 8: Results of flooding from graph method and HMM for fully branched network (a), network with three loops (b) and six loops (c)

It is evident from this figure that most values are on this line for fully branched network while more values go further from this line as the loop degree increases. Coefficient of determination (R-squared) is calculated for all three networks to check the accuracy of the method. R-squared values clearly describe the impact of loop degree on the accuracy. Value of 0.98 in case of fully branched network shows that the method is very accurate. The values decrease to 0.95 and 0.92 for three loops (Fig. 8(b)) and six loops (8(c)) respectively, showing that the accuracy of the method is decreasing with increasing loop degree.

3.3 Computational time and Data Requirements

The benefit of using the graph method explained in this study, lies in the difference in computational time required to run both methodologies. HMM run time for simulating all pipe blockages is 5 minutes and 20 seconds as the model has to run 59 times, once for each pipe blockage scenario. In comparison, graph method only takes 5 seconds to run thus having a computational gain factor of 64 (320/5) as compared to HMM. This factor will increase with the size of the network. Because for a complex and very large drainage network, HMM method requires a long time to run whereas graph-based method based on time efficient graph techniques does not exhibit the same behavior. To confirm this hypothesis, the method was applied to a real case study having 430 pipes. HMM method in that case took 45 minutes while graph method only took 10 seconds showing graph method having a computational gain factor of 270 (45*60/10). It is thus evident that as the size of UDN increases, the computational gain factor increases non-linearly. Thus, the graph method is much more efficient in case of large UDNs.

Graph based method is also significantly less data intensive as compared to HMM. Methodology presented in this study, although not as accurate as HMM especially for looped networks, can still be used by utilities for a preliminary analysis where all the data is not available. The graph method used in this study has its limitations as well. For example, it cannot model complex hydraulic behaviour (yet), including backwater effect and re-routing of water to parallel pipes as HMM does.

Both these factors contribute to decreasing the accuracy of the method when more loops are introduced in the network, all of which will be tackled in future research.

4 SUMMARY AND CONCLUSIONS

In this study, a new graph-based method was proposed based on network analysis techniques called runoff edge betweenness centrality (EBC_e^R). The method was applied to three case studies with varying loop degree. Results from graph-based method were compared with a hydrodynamic model (HMM) to determine the accuracy of the graph method. Additionally, impact of loop degree on the accuracy of the methodology was investigated. Following main conclusions can be drawn from the study:

- A graph-based method can be used to successfully identify the critical elements of a UDN using network analysis techniques updated to consider the hydraulic behaviour of UDNs.
- The method is applied to three case studies with varying degree of loops. Results indicate that the graph method is almost fully accurate for a branched network. It identifies all 20 critical pipes identified by the HMM method. R-squared value of 0.98 in case of branched network, also shows the high accuracy of the proposed method.
- Accuracy of the graph method decreases with increasing loop degree in the network. The graph method identifies 18 and 15 out of 20 most critical pipes as compared to HMM for three loops and six loops, respectively. R-squares values are also reduced to 0.95 and 0.92 for three loops and six loops.
- The main advantage of using graph method lies in the difference of computational time as compared to HMM. Graph method has a computational gain factor of 64 (5 seconds vs 320 seconds) as compared to HMM. Additionally, graph method is also less data intensive.
- The graph methodology proposed in this study can be used by utilities for a quick analysis where conventional hydrodynamic modelling method becomes too time consuming and where enough data is not available to setup a hydrodynamic model.

5 ACKNOWLEDGEMENTS

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