Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.25744

196 (2020) 370–376
August

Vulnerability of sewer network – graph theoretic approach

Balaraman Ganesan[a,*], Sundareswaran Raman[b], Sujatha Ramalingam[b], Mustafa Erkan Turan[c], Goksen Bacak-Turan[c]

[a]*St. Joseph's Institute of Technology, Chennai, Tamilnadu, India, email: balaramanmath@gmail.com (B. Ganesan)*
[b]*SSN College of Engineering, Chennai, Tamilnadu, India, emails: sundareswaranr@ssn.edu.in (S. Raman), sujathar@ssn.edu.in (S. Ramalingam)*
[c]*Manisa Celal Bayar University, Manisa, Turkey, emails: mustafaerkan.turan@cbu.edu.tr (M.E. Turan), goksenbacak@gmail.com (G. Bacak-Turan)*

Received 10 December 2019; Accepted 23 February 2020

ABSTRACT

One of the most important structures in urban areas is an efficient sewer system to protect humans and the environment from the detrimental effects of wastewater. Such sewer systems often consist of pipes, manholes, pumping stations, and other complementary units. Strict monitoring of the sewer system is highly essential as any leakage can cause undesirable effects on health and safety. The layout is modeled as a graph which contains all sewer links and satisfies all the restrictions of a sanitary sewer system. In this work, we apply centrality measures on the sewer network system and water distribution system and also analyze the vulnerability of these systems.

Keywords: Sewer system networks, Water supply networks, Centrality, Group betweenness centrality, Group closeness centrality

1. Introduction

Sewer systems and water supply networks are the most important structures in a modern town. The main underground infrastructure is sewer systems and water supply networks. It is not easy to determine the actual condition of the assets. The maintenance and rehabilitation of sewer systems depend on the consequences of visual inspections [1]. Sewer systems and water supply systems are networks which consist of many elements. Sewer systems involve manholes, pipes, pumping stations, and other complementary parts. It can be separated into three categories based on the water carried, such as a sanitary sewer system, a combined sewer system, and a storm sewer system [2]. The performance of the network depends on the working of the individual elements. The rank of an element for the network depends on the features of the element and its location in the network. Graph Theory is one of the important mathematical theories and it can be applied in many fields. Graph representation of sewer networks and water distribution networks are computationally very effective and, in most applications, shortest path and minimum spanning tree algorithms are used. A network is simplified by a graph and its connectivity in vertices and edges [3]. Water supply networks, sewer systems, electricity networks are typical examples of graphs consisting of links and nodes. The structure of the network can be represented by hydrological models graphs. The use of the graph theory is to analyze the criticality of conduits in sewer networks [4]. A graph can be represented by $G = (V,E)$, where $V(G)$ is the set of nodes and $E(G)$ is the set of edges. An edge can be represented by the ordered pair (u,v), where u and v are the end vertices of the edge. Adjacency matrix and Incidence matrix are used to represent the graphs. The elements of the adjacency matrix show every pair of vertices that are adjacent or not in the graph. The incidence matrix has the rows and columns

* Corresponding author.

Presented at the First International Conference on Recent Trends in Clean Technologies for Sustainable Environment (CTSE-2019), 26–27 September 2019, Chennai, India

labelled by the vertices and edges, respectively. If a value is different from zero, the labelled vertex corresponding to that row is an end vertex of the labelled edge corresponding to that column. If the edges are directed then the graphs are called directed graphs. That is, every edge (u,v) has an arrow from vertex u to vertex v, otherwise, the graphs are called undirected graphs. If the edges of a graph are related with some numerical values, then the graph is called a weighted graph. A graph is called a connected graph if there exists a path between every pair of vertices, otherwise it is called a disconnected graph. A loop is an edge that connects a vertex to itself. A sewer network system can be modeled by a graph, each manhole is represented by a node and each link represented as a edge. A graph that consists of all possible nodes (manholes) and edges (sewer links) is called a base graph [5]. A sewer system contains all manholes, and all sewer links and are not allowed to contain loops. In this work, we apply centrality measures on the sewer network system and water distribution system and also analyze the vulnerability of these systems.

2. Centrality measures

Centrality is considered as an important measure in a complex network. Centrality measures such as degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality highlight the significance of certain nodes in the networks. The measure of centrality is outlined by Bavelas [6] for connected graphs. Stress centrality is introduced based on the shortest path by Shimbel [7], Katz centrality was introduced by Katz [8] to measure the relative degree of influence of a node in the network. Freeman [9] identified three type measures: an absolute, comparative measure of centrality for locations of network and the third one which is a degree of centralization for the entire network. The idea of transmitting information between any two vertices in a connected network was developed by Stephenson and Zelen [10]. Another measure to identify centrality by the idea of network flows was explained by Freeman et al. [11]. Geodesic centrality measures were generalized for betweenness for an undirected graph to more directed graphs by White and Borgatti [12]. Everett and Borgatti [13] extended the standard three centrality measures for the application in groups and classes and also as individuals. Subgraph centrality was explained by Estrada and Rodriguez-Velazquez [14] to measure the number of times of a vertex involve in the various connected subgraph of the network. Rodriguez et al. [15] simplified the subgraph centrality as functional centrality. It is done based on the idea that closed walks are correctly weighted so that their influence on the centrality reduces as the order of the walk increases. Some unique properties were also shared by Bonacich [16] for eigenvector centrality. Opsahl et al. [17] discussed improving the measures of centrality for the weighted network. Joyce et al. [18] developed a new centrality called leverage centrality and used it to analyze the human brain network. Kitsak et al. [19] explained k-shell decomposition and proposed that the key spreaders stay within the core of the network. The mixed degree decomposition method was proposed by Zeng and Zhang [20] by using residual degree and also exhausted degrees. Neighborhood coreness centrality which ranks all the nodes of a network was introduced by Bae and Kim [21]. Liu et al. [22] discussed an nth step neighborhood centrality to find an influential node in a complex network. Thus to find a more accurate ranking list of influential nodes. Wang et al. [23] proposed weighted neighborhood centrality.

2.1. Degree centrality

The degree centrality introduced by Nieman (1974) [24] and it is defined for a node is that the number of links connected to that node. A node with higher degree centrality is assumed to be more influential because it is connected to more number of vertices. A node with higher degree centrality is in relation to many other vertices, so it has more choices to communicate with the other nodes of the network. By having many edges connected to it, this node may have access to other parts of the graph easier than the vertices with less degree. This vertex is with more possibility subject to the risk of catching the information or material flowing through the graph because of more edges and possible more paths pass-through this vertex. Let G be a connected graph. The degree centrality of a node v is defined as the number of nodes directly linked to this node. (i.e.) the degree centrality is given by $C_D(v) = \deg(v)$ and the normalization is defined as $\deg(v)/(n–1)$.

2.2. Closeness centrality

The concept of Closeness centrality [25] is that a vertex v is more influential if it can communicate with all the other vertices in the graph quickly. Closeness centrality uses the length of the geodesic distances between all pairs of vertices. The closeness centrality of a node v is calculated by $C_c(v) = \frac{1}{\sum_{u \in V} d(u,v)}$, where V is the set of vertices in the graph and $d(u,v)$ is the geodesic distance between the vertices u and v. The normalization of a closeness centrality is given by

$$C'_c(v) = \frac{|V| - 1}{\sum_{u \in V} d(u,v)} \quad (1)$$

2.3. Betweenness centrality

Betweenness centrality performs a vital role in the evaluation of social networks. Betweenness centrality is beneficial as a measure of the capacity of a vertex for manage of conversation. Betweenness centrality indicates the betweenness of a vertex in a community and it measures the quantity to which a vertex lies on the shortest paths between pairs of other vertices. In many real-global conditions it has pretty a tremendous role. Finding betweenness is easy and simple when the best one geodesic connects every pair of vertices, where the intermediate vertices can completely manipulate communication among pairs of others. But when there are numerous geodesics connecting a couple of vertices, the state of affairs becomes more complex and the control of the intermediate vertices gets fractionated. The significance of the concept of vertex centrality is in the capacity of a vertex for control of information flow in the network. Positions are regarded as structurally critical to the degree to which they stand among others and might, therefore, facilitate, obstruct, or bias the transmission of messages.

The betweenness centrality of a vertex v is defined as

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \quad (2)$$

where σ_{st} is the number of geodesics between s and t and $\sigma_{st}(v)$ is the number of geodesics between s and t that passing through the node v. The normalized betweenness centrality is given by $C'_B(v) = \frac{C_B(v)}{\text{Max}C_B(v)}$. High position scores indicate that a vertex lies in a substantial fraction of the shortest ways connecting pairs of vertices.

2.4. Eigenvector centrality

Eigenvector centrality was proposed by Bonacich [16]. This measure is based on the idea that existing edges between v and other vertices that are powerful and influential makes v more powerful than existing edges between v and less influential vertices. This measure can be easily calculated based on the eigenvectors of the adjacency matrix.

Let A be the adjacency matrix such that $a_{ij} = 1$ if node i is connected to node j and $a_{ij} = 0$ if i is not connected to j, then the eigenvector centrality of vertex i is defined as

$$\text{A}x = \lambda x, \quad \lambda x_i = \sum_{j=1}^{n} a_{ij} x_j, \quad i = 1,2,\ldots,n, \quad \lambda \text{ is a constant} \quad (3)$$

2.5. Example

Consider a small network (Fig. 1), which consists of seven nodes and eight edges. We compute the centrality measures of this network. Fig. 2 shows a comparison of this network.

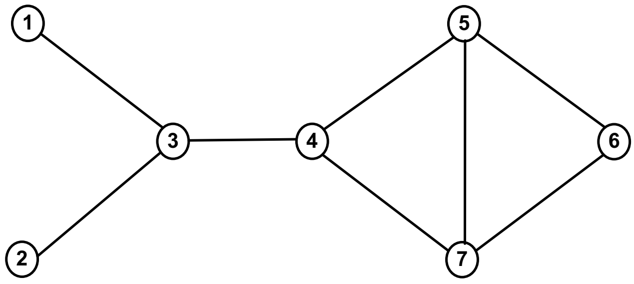

Fig. 1. Illustration of centrality measures.

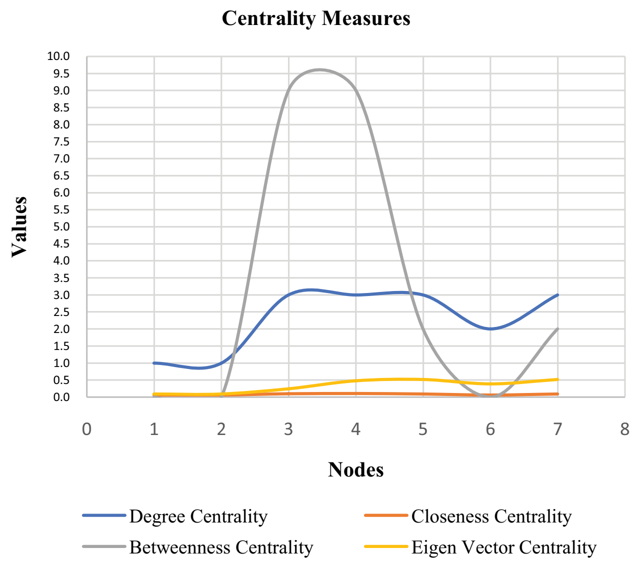

Fig. 2. Comparison of centrality measures.

3. Group centrality measures

In many real-life situations, it is important to measure the centrality of a group of nodes rather than that of a single node. Everett and Borgatti [13] extended the centrality measures to a group of nodes.

3.1. Group degree centrality

Group degree centrality is defined as the number of non-group nodes that are connected to group members. Multiple ties to the same node are counted only once. The normalized group degree centrality is given by dividing the group degree by the number of non-group actors.

3.2. Group closeness centrality

Group closeness is defined as the sum of the distances from the group to all vertices outside the group. As with individual closeness, this produces an inverse measure of closeness as larger numbers indicate less centrality, we can normalize group closeness by dividing the distance score into the number of non-group members, with the result that larger numbers indicate greater centrality. Let G be a connected graph and a set $S \subseteq V$ of nodes, the group closeness centrality is defined as:

$$G_C(S) = \frac{|V \setminus S|}{\sum_{v \in V \setminus S} d(S,v)}, \quad \text{where} \quad d(S,v) = \min_{u \in S} d(u,v). \quad (4)$$

3.3. Group betweenness centrality

Group betweenness centrality gives the proportion of geodesics connecting couples of non-group members that pass through the group. Let G be a connected graph and a set $S \subseteq V$ of nodes, the group betweenness centrality of S defined as:

$$C_B(S) = \sum_{s,t \in V/S,\, s<t} \frac{\sigma_{st}(S)}{\sigma_{st}}, \quad (5)$$

where σ_{st} is the number of shortest paths between s and t and $\sigma_{st}(S)$ is the number of shortest paths between s and t that passing through the set S.

4. Vulnerability in sewer system

Detection of vulnerability is the most important tool in network analysis. It can be used for water distribution systems, natural disaster management, ecological protection, climate change influence assessment, land use management, development of industrial production and property [26–34]. Davidson and Shah [35] established a comprehensive municipal earthquake disaster risk index that allows direct assessment of the relative complete earthquake disaster risk of cities universally and defines the relative contribution of assorted factors to complete risk. Turvey [36] set forward an abstraction methodology for vulnerability calculation in emerging countries by creating a composite vulnerability index. Ezell [37] established an Infrastructure Vulnerability Assessment structure to measure the vulnerability of water supply management systems and developed a comprehensive index method which can also be used to quantify the vulnerability of the systems by establishing the comprehensive evaluation index. Vulnerability analysis is mostly conducted from distinguishing varied threats that will occur, testing the response of the system, and distinguishing the weakest elements. In the field of water distribution management systems, different numerical analysis methods have been established for vulnerability calculation, for example, Markov latent effects modeling methods, probability and statistics methods, comprehensive index methods. Murray et al. [38] established a probability and statistics method which can be applied to measure the vulnerability of a water utility to a large range of contamination attacks. Pinto et al. [39] presented the concept of vulnerability of water pipe network which is to help in designing water pipe networks that can be more strong against the impairment to the pipelines. The above analysis methods have played a very important role within the vulnerability of water distribution network systems, however, there have been some studies for city drainage systems [40–47]. Poulter et al. [41] presented an application of graph-theoretic algorithms to proficiently examine network properties that is applicable to the management of a large artificial drainage system in coastal North Carolina, USA. A few investigations concentrated on the structure or water-driven states of a solitary funnel to make wellbeing assessment [47], however, a higher order of disappointment is considered in a few studies [48]. Though, few vulnerability calculation studies investigate the vulnerability of the whole drainage systems [49], particularly the virtual analysis of the vulnerability for pipe networks that have different layouts, for instance, tree and loop drainage systems [42,44,49–52].

5. Case study 1

5.1. Centrality measures of sewer system

Consider the sanitary sewer systems of the residential area of Shengli Oilfield, Shandong Province, Peoples Republic of China (Li and Matthew) [53]. This sewer network consists of 79 pipes and 57 manholes, designed to collect the sewage flow of a 260 ha housing area. Fig. 3 shows the base graph of the sewer system. Now to find the centrality measures of the base graph. From the computation of centrality measures

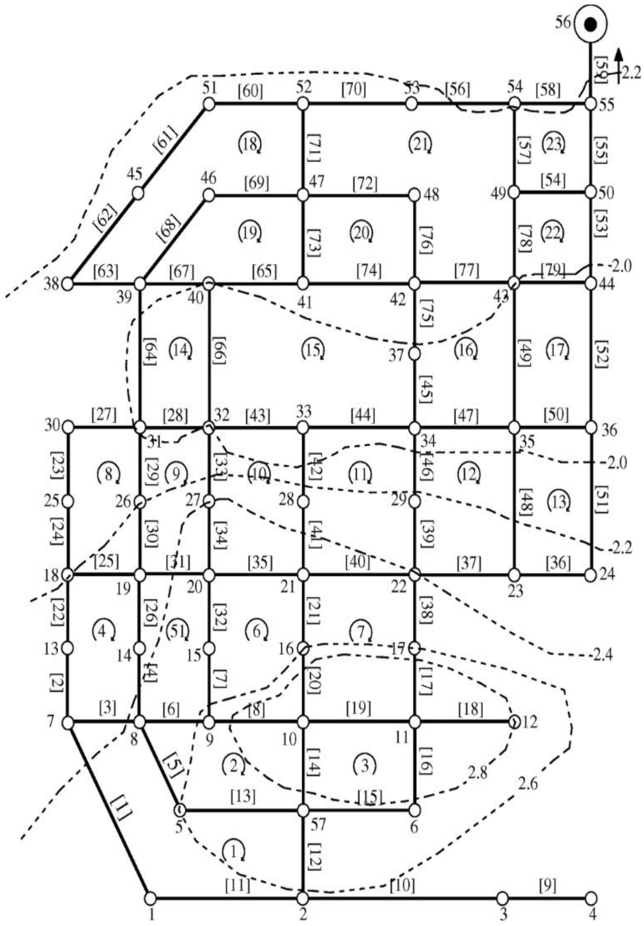

Fig. 3. Base graph of the sewer network.

(Fig. 4) we observed that in the sewer system the manhole 21 is the suitable location that can spread information fast, and manhole 22 which controls the information among other manholes via connection paths. Finally, manhole 35 is the best location for emergency purposes.

5.2. Group closeness and group betweenness centrality of a branch of sewer network

Consider a branch of the sewer network system shown in Fig. 5. This branch has 18 nodes. Now to find the more influential subgroup within this network. The subgroup {2,8,10} has the more group betweenness centrality, which gives this group has more influential than other groups. And according to group closeness, the minimal cardinality sets {3,7,8,9,10,11} and {3,7,8,10,11,15} are the highest influential subgroups of the network. The same concept can be applied into the entire Sewer system to find the influential groups.

6. Case study 2

6.1. Centrality measures of Apulian network

The case study is planned to demonstrate the methodology as applied to a real network. Consider the Apulian network (Southern Italy) (Antonietta et al.) [54] which consists of 24 nodes, and 34 pipes whose layout is shown in Fig. 6.

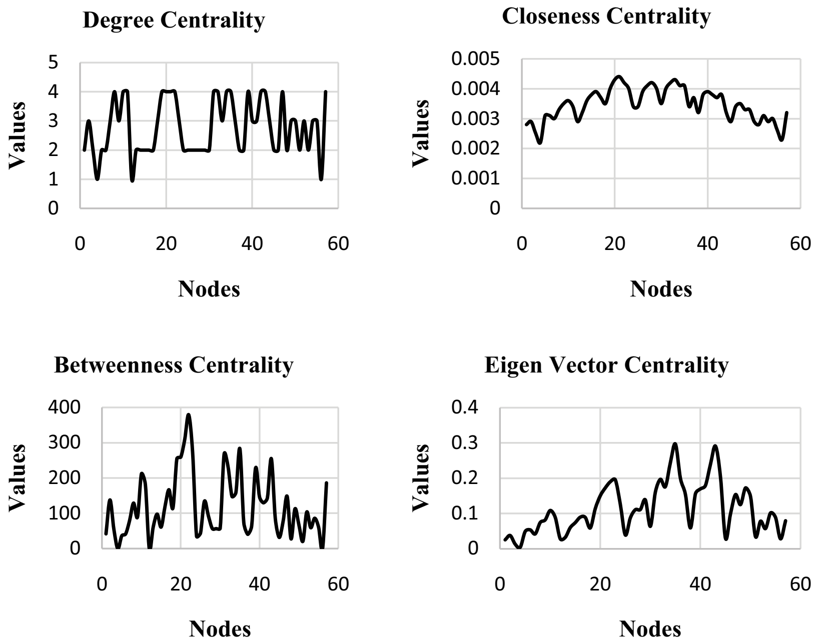

Fig. 4. Centrality measures of the sewer network system.

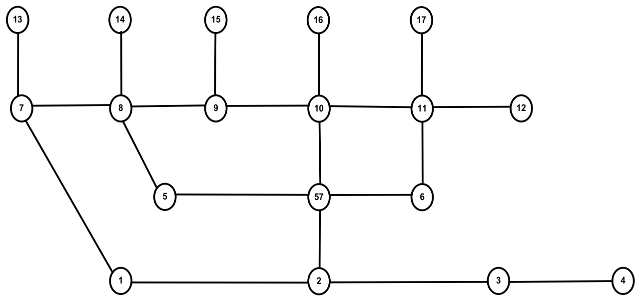

Fig. 5. Branch of a base graph of the sewer network.

From Fig. 7 node 6 is the most influential position than the other nodes.

6.2. Group closeness and group betweenness centrality of Apulian network

In the Apulian network, the group consisting of nodes {1,6,8,9,17} of cardinality 5 having higher group betweenness centrality. This indicates that this group is more influential than the other subgroup. Based on group closeness centrality, the most influential subgroups of an Apulian network which has minimal cardinality are listed in Table 1.

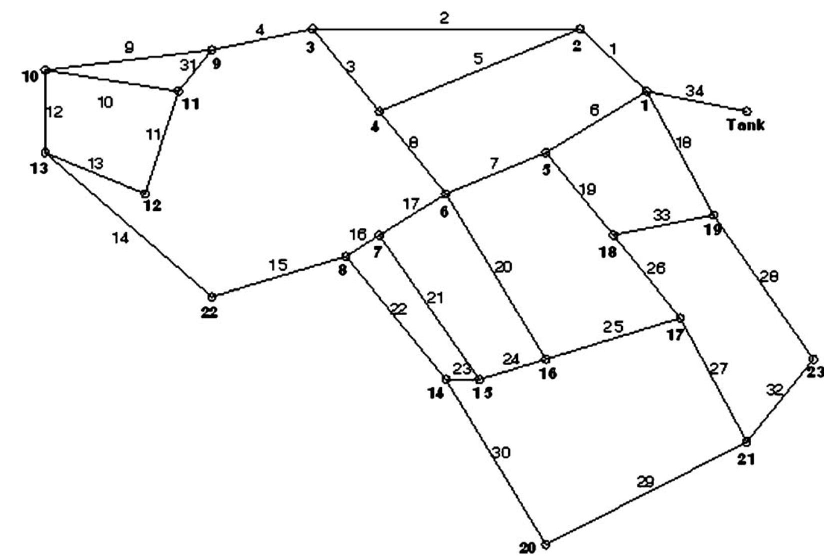

Fig. 6. Apulian network layout.

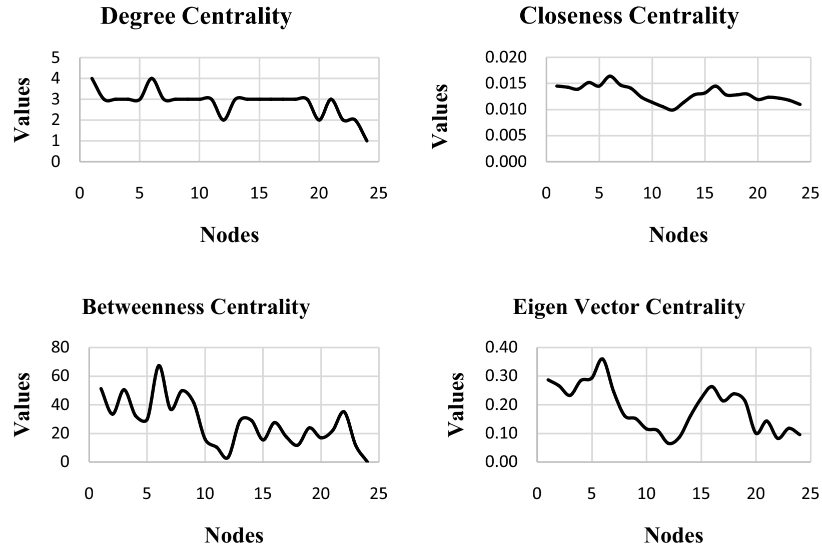

Fig. 7. Centrality measures of an Apulian network.

Table 1
Group closeness centrality of Apulian network

Group closeness centrality
{1, 2, 5, 11, 15, 21, 22}{1, 3, 5, 11, 15, 21, 22}{1, 4, 5, 11, 15, 21, 22}
{1, 4, 11, 15, 17, 21, 22}{1, 4, 11, 15, 18, 21, 22}{1, 4, 11, 15, 19, 21, 22}
{1, 5, 6, 9, 13, 14, 21}{1, 6, 9, 13, 14, 17, 19}{1, 6, 9, 13, 14, 17, 21}
{1, 6, 9, 13, 14, 17, 23}{1, 6, 9, 13, 14, 18, 21}{1, 6, 9, 13, 14, 18, 23}
{1, 6, 9, 13, 14, 19, 21}{4, 11, 15, 18, 21, 22, 24}

7. Conclusion

Vulnerability analysis is one of the most important concepts of an urban sewer system. Different methods have been established by different researchers to obtain the most influential node in a Sewer network. In the sewer system, we analyzed the more important roles in different aspects. In the network, not only finding a most influential node but also finding a group of nodes which have more influence within the network. In this work, we studied the vulnerability of sewer network systems and water distribution systems using graph theory parameters, which is very helpful to identify the most important nodes within the network and also we identified the subgroups which have more central in the network. Further, by using group closeness and group betweenness centrality concepts, we can also apply in the field of Sensor placement in water distribution systems and monitoring sewer network systems.

References

[1] W.V. Riel, E.V. Bueren, J. Langeveld, P. Herder, Decision-making for sewer asset management: theory and practice, Urban Water J., 13 (2017) 57–68.
[2] J. Ellis, B. Chocat, S. Fujita, J. Marsalek, W. Rauch, Urban drainage: a multilingual glossary, Water Intell. Online, 5 (2015) 528.
[3] J.P. Rodrigue, C. Comtois, B. Slack, The Geography of Transport Systems, Routledge, New York, NY, USA, 2013.
[4] T. Laakso, S. Ahopelto, T. Lampola, T. Kokkonen, R. Vahala, Estimating water and wastewater pipe failure consequences and the most detrimental failure modes, Water Sci. Technol. Water Supply, 18 (2018) 901–909.
[5] E.T. Mustafa, B.T. Goksen, C. Tulin, A. Ersin, Feasible sanitary sewer network generation using graph theory, Adv. Civ. Eng., 2019 (2019) 1–15.
[6] A. Bavelas, Communication patterns in task-oriented groups, J. Acoust. Soc. Am., 22 (1950) 725–730.
[7] A. Shimbel, Structural parameters of communication networks, Bull. Math. Biophys., 15 (1953) 501–507.
[8] L. Katz, A new status index derived from sociometric analysis, Psychometrika, 18 (1953) 39–43.
[9] L.C. Freeman, Centrality in social networks conceptual clarification, Soc. Networks, 1 (1978) 215–239.
[10] K. Stephenson, M. Zelen, Rethinking centrality: methods and examples, Soc. Networks, 11 (1989) 1–37.
[11] L.C. Freeman, S.P. Borgatti, D.R. White, Centrality in valued graphs: a measure of betweenness based on network flow, Soc. Networks, 13 (1991) 141–154.
[12] D.R. White, S.P. Borgatti, Betweenness centrality measures for directed graphs, Soc. Networks, 16 (1994) 335–346.
[13] M.G. Everett, S.P. Borgatti, The centrality of groups and classes, J. Math. Sociol, 23 (1999) 181–201.
[14] E. Estrada, J.A. Rodriguez-Velazquez, Subgraph centrality in complex networks, Phys. Rev., 71 (2005) 056103 1–9.
[15] J.A. Rodriguez, E. Estrada, A. Gutierrez, Functional centrality in graphs, Linear Multilinear Algebra, 55 (2006) 293–302.
[16] P. Bonacich, Some unique properties of eigenvector centrality, Soc. Networks, 29 (2007) 555–564.
[17] T. Opsahl, F. Agneessens, J. Skvoretz, Node centrality in weighted networks, Generalizing degree and shortest paths, Soc. Networks, 32 (2010) 245–251.
[18] K.E. Joyce, P.J. Laurienti, J.H. Burdette, S. Hayasaka, A new measure of centrality for brain networks, PLoS One, 5 (2010) 1–13.
[19] M. Kitsak, L.K. Gallos, S. Havlin, F. Liljeros, Identification of influential spreaders in complex networks, Nat. Phys., 6 (2010) 888–893.
[20] A. Zeng, C.J. Zhang, Ranking spreaders by decomposing complex networks, Phys. Lett. A, 377 (2013) 1031–1035.
[21] J. Bae, S. Kim, Identifying and ranking influential spreaders in complex networks by neighborhood coreness, Physica A, 395 (2014) 549–559.
[22] Y. Liu, M. Tang, T. Zhou, Y. Do, Identify influential spreaders in complex networks: the role of neighborhood, Physica A, 452 (2015) 289–298.

[23] J. Wang, X. Hou, K. Li, Y. Ding, A novel weight neighborhood centrality algorithm for identifying influential spreaders in complex networks, Physica A, 475 (2017) 88–105.
[24] J. Nieminen, On the centrality in a graph, Scand. J. Psychol., 15 (1974) 322–336.
[25] A. Bavelas, A mathematical model for group structures, Appl. Anthropol., 7 (1948) 16–30.
[26] H.M. Fussel, R.J. Klein, Climate change vulnerability assessments: an evolution of conceptual thinking, Clim. Change, 75 (2006) 301–329.
[27] P. Timmerman, Vulnerability, Resilience and the Collapse of Society: A Review of Models and Possible Climatic Applications, Institute for Environmental Studies, University of Toronto, Toronto, ON, Canada, 1981.
[28] H. Li, P. Zhang, Y. Cheng, Concepts and assessment methods of vulnerability, Prog. Geogr., 27 (2008) 18–25.
[29] M.J. Metzger, R. Leemans, D. Schroter, A multidisciplinary multi-scale framework for assessing vulnerabilities to global change, Int. J. Appl. Earth Obs. Geoinf., 7 (2005) 253–267.
[30] B.C. Ezell, J.V. Farr, I. Wiese, Infrastructure risk analysis of municipal water distribution system, J. Infrastruct. Syst., 6 (2000) 118–122.
[31] J.J. McCarthy, Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2001.
[32] G.F. White, Natural Hazards, Local, National, Global, Oxford University Press, Oxford, UK, 1974.
[33] C. Vogel, Vulnerability and global environmental change, LUCC Newsl., 3 (1998) 15–19.
[34] S.L. Cutter, B.J. Boruff, W.L. Shirley, Social vulnerability to environmental hazards, Soc. Sci. Q., 84 (2003) 242–261.
[35] R.A. Davidson, H.C. Shah, An Urban Earthquake Disaster Risk Index, Stanford University, Stanford, CA, 1997.
[36] R. Turvey, Vulnerability assessment of developing countries: the case of small island developing states, Dev. Policy Rev., 25 (2007) 243–264.
[37] B.C. Ezell, Infrastructure vulnerability assessment model (I-VAM), Risk Anal., 27 (2007) 571–583.
[38] R. Murray, R. Janke, J. Uber, The threat ensemble vulnerability assessment (TEVA) program for drinking water distribution system security, World Water Environ. Resour. Congress, (2004) 20–24, doi: 10.1061/40737(2004)482.
[39] J. Pinto, H. Varum, I. Bentes, J. Agarwal, A theory of vulnerability of water pipe network (TVWPN), Water Resour. Manage., 24 (2010) 4237–4254.
[40] M. Moderl, M. Kleidorfer, R. Sitzenfrei, W. Rauch, Identifying weak points of urban drainage systems by means of VulNetUD, Water Sci. Technol., 60 (2009) 2507–2513.
[41] B. Poulter, J.L. Goodall, P.N. Halpin, Applications of network analysis for adaptive management of artificial drainage systems in landscapes vulnerable to sea-level rise, J. Hydrol., 357 (2008) 207–217.
[42] M. Moderl, R. Sitzenfrei, J. Lammel, M. Apperl, M. Kleidorfer, W. Rauch, Development of an urban drainage safety plan concept based on spatial risk assessment, Struct. Infrastruct. Eng., 11 (2015) 918–928.
[43] E. Friedrich, D. Kretzinger, Vulnerability of wastewater infrastructure of coastal cities to sea-level rise: a South African case study, Water SA, 38 (2012) 755–764.
[44] M. Kleidorfer, M. Moderl, R. Sitzenfrei, C. Urich, W. Rauch, A case-independent approach on the impact of climate change effects on combined sewer system performance, Water Sci. Technol., 60 (2009)1555–1564.
[45] R. Sitzenfrei, M. Mair, M. Moderl, W. Rauch, Cascade vulnerability for risk analysis of water infrastructure, Water Sci. Technol., 64 (2011) 1885–1891.
[46] M. Mair, R. Sitzenfrei, M. Kleidorfer, M. Moderl, W. Rauch, GIS-based applications of sensitivity analysis for sewer models, Water Sci. Technol., 65 (2012) 1215–1222.
[47] Q. Hou, Study on Vulnerability Assessment and Emergency Measures of Storm Sewer System; Qingdao Technological University, Qingdao, China, 2014.
[48] S.N. Mugume, D.E. Gomez, G. Fu, R. Farmani, D. Butler, A global analysis approach for investigating structural resilience in urban drainage systems, Water Res., 81 (2015) 15–26.
[49] L. Hao, L. Cuimei, Vulnerability assessment of urban storm sewer systems, J. Shenzhen Univ. Sci. Eng., 6 (2014) 006.
[50] Y. Seo, Y.H. Seo, Y.O. Kim, Behavior of a fully-looped drainage network and the corresponding dendritic networks, Water, 7 (2015) 1291–1305.
[51] Z. Ji, General hydrodynamic model for sewer/channel network systems, J. Hydraul. Eng., 124 (1998) 307–315.
[52] L. Feng, Study on the Hydrodynamic and Wastewater Quality Transformation Model in Urban Sewer Networks, Dalian University of Technology, Dalian, China, 2009.
[53] G. Li, R.G.S. Matthew, New approach for optimization of an urban drainage system, J. Environ. Eng., 116 (1990) 927–944.
[54] S. Antonietta, R. Luca, B.L. Daniele, B. Luigi, Centrality metrics for water distribution networks, EPiC Ser. Eng., 3 (2018) 1979–1988.