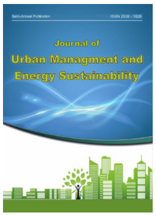
Int. J. Urban Manage Energy Sustainability, 5(4): 1-18, 2024

Journal of Urban Management and
Energy Sustainability (JUMES)

Homepage: http://www.ijumes.com



ORIGINAL RESEARCH PAPER

Enhancing Sustainable Urban Management: A Proposal for Point Sustainability Index to Optimize Water Distribution Network Performance

Darab Biranvandi[1], Hossein Hassanpour Darvishi[2*], Hossein Ebrahimi[3], Pezhman Taherei Ghazvinei[4]

1 Department of Civil Engineering, Shahr-e-Qods Branch, Islamic Azad University, Tehran, Iran.
2 Department of Civil Engineering, Shahr-e-Qods Branch, Islamic Azad University, Tehran, Iran.*
3 Department of Civil Engineering, Shahr-e-Qods Branch, Islamic Azad University, Tehran, Iran.
4 Young Researchers and Elite Club, Shahr-e-Qods Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Article History:
Received 2023-12-02
Revised 2024-04-23
Accepted 2024-08-17

Keywords:
Refurbishment, reliability, resilience, sustainability, vulnerability, water distribution network.

DOI: 10.22034/ijumes.2024.2016944.1186

ABSTRACT

Refurbishing water distribution networks necessitates simulating the impact of implementation options to enhance sustainability. The study introduces a novel point evaluation index to assess changes' effects on consumption points based on sustainability components. The results showed that in the state of maximum consumption, the point stability distribution had lower values than in other consumption states, so that the trend of changes in the total stability index of the network decreased from 0.66 to 0.41 with pressure reduction. In the same situation and at the same time, the average point index of the network had decreased from 0.8 to 0.27. Therefore, the comparison of the total and point stability indicators of the network showed that the amount and distribution of the stability index of the network points have decreased more with the increase in consumption (pressure reduction) compared to the total stability index under the same conditions. The research revealed that enhancing point index sustainability positively influences the network's overall sustainability. Notably, the point sustainability index, particularly in the maximum consumption mode, is recommended for local network improvement plans. Therefore, it can be recommended that in network reform and reconstruction programs, evaluation and promotion of point stability will provide more favorable operational results. In order to continue and further clarify the results of this research, it is suggested to evaluate the general and point stability indexes corresponding to the water pressure decimal intervals that form the basis for dividing the acceptable limits of the pressure conditions in the network.

Running Title: Point Sustainability Index to Optimize Water Distribution Network Performance

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
19	06	02

*Corresponding Author:
Email: *hhassanpour@qodsiau.ac.ir*
Phone: +982146896000
ORCID: https://orcid.org/0000-0002-9898-6298

INTRODUCTION

In order to achieve the goal of the research, it was necessary to review and summarize the records of related researches that had been done to extract the stability of the water distribution network, the methods of calculating the network stability index, the components used in extracting the stability index, as well as the effect of changes in physical and hydraulic conditions, as well as fluctuation. The performance of the network was analyzed based on this index. Also, attention was paid to how and to what extent the sustainability index has been used in the improvement and reconstruction programs or the development of the extraction network. Therefore, in order to achieve the goal of the research, the findings and records of related researches have been used and considered for the design of the research implementation method, and in the innovation of the present research, the improvement of the method of achieving the goal, as well as the presentation and development of the use of the point sustainability index, have also been presented. The following sections are presented as a summary of related records in this article.

Simulating the effect of the applied changes options to improve the sustainability of the water distribution networks (WDN) is necessary to avoid wasting costs. In this regard, in order to determine the ranges and routes of optimization, the network risk index, which is based on the prevention of accidents and the importance of consumer points (nodes) in the network, is compared and evaluated in current and future state of the network (applying changes). In addition, the network sustainability index, as a consequence of network indicators for resilience, reliability and vulnerability, is used to compare and evaluate network performance in time periods (daily, monthly, seasonally and annually) or to compare the performance of homogeneous networks performance in different geographical environments. To evaluate network operators in the performance comparison mode, a set of networks covered by the regions (cities and villages) covered by an operating company or employer organization is used (Ahmadi, Moradi, Hoseini, & Shahraki, 2022; Beker & Kansal, 2022; Tabarestani Ali, Nabi Bidhendi Gholamreza, & Baghdadi Majid, 2023). In order to evaluate the state of the distribution network state, various indicators have been defined by researchers. Four criteria—reliability, flexibility, vulnerability and sustainability—were defined to evaluate the water network performance (Azadkhani Pakzad, 2022; Behzadpoor E., Tabaeian A., & Khatibi M., 2020; Zhang, Zhang, Li, & Zhao, 2020). The first three conceptually are based on the definitions used in water resources engineering; unlike water resources studies where there is a minimum demand or network flexibility indices where the minimum pressure is determined, the proposed criteria for evaluating the drinking WDN, they do not evaluate the probability of the network gaining the minimum efficiency, but evaluate the network efficiency in different conditions.

Kuma and Abate (2021) examined the WDN performance index under multiple loading conditions. In this research, it is pointed out that the WDN performance index depends on the system efficiency in addition to the delivery of water with adequate pressure and flow rate. This level of efficiency is defined based on the system performance index by calculating the geometric average based on the four criteria; reliability, vulnerability, flexibility and the connection ability of system components when necessary. All the mentioned criteria are based on energy sufficiency, hydraulic capacity and the network structure ability to deliver water in different conditions. Based on the definition, the policy of index capability increasing, similar to other indices trend, is based on increasing the network pressure, but this approach is different from creating unnecessary high pressures in the network (Geleta Ebsa & Fufa, 2021).

In 2021, Vitan et al. determined the evaluation index of the urban water distribution network based on the pressure of the nodes in the network and the age of the water. This index was defined based on performance indicators of reliability, adaptability and vulnerability. The EPANET model was used to simulate the pressure of nodes and the age of water inside the network. Then the values of the two parameters mentioned were combined with each other to determine the target index. Also, relevant calculations were done to determine the overall score of the stability index of the desired pressure zones. Finally, this index was used to monitor the network condition and suggest upgrade options, such as changes in the operation of pumps and network modifications, in order to increase the stability of the network. In 2021, Macías et al. combined and presented a set of indicators in the form of a mathematical structure along with other known indicators in the water distribution network (Macías Ávila et al., 2021). In the published article of this research, the water index of sustainable cities is discussed. This index of composite scores based on various factors such as water stress, green space, risks related to water distribution networks, flood risk, balance and water storage was used to rank cities. In the next step, the stability of the water distribution network in 50 cities in 31 countries was measured and ranked. This index showed that most North American cities are in the upper half of this sample of cities in developed countries. It was also recommended to adopt the “One Water” approach to address water challenges, as sustainability index modeling from source to consumption was considered in an integrated manner. However, this article does not provide information on the details of the specific methods used in the research.

Borzì, Bonaccorso, and Aronica (2018) studied the WDN sustainability of the Italian city, Messina through the WDN model evaluation of this city. The WDN sustainability index was determined based on the reliability, adaptability and vulnerability of the network parameters. For this purpose, six different scenarios were prepared and implemented in the mentioned model, and the results were compared with each other.

In a research, Batten III (2018) classified 50 world-class cities based on the WDN sustainability index. The sustainability of the WDN system means supplying safe water, reliability in terms of the required quantity and pressure, and easy access to the subscribers, including residents and various businesses. Also, this criterion means the flexibility of the water network system in different weather conditions and climate change. In this classification, Rotterdam, the Netherlands, and then Copenhagen, Denmark had the highest sustainability and New Delhi, India had the lowest value in this index.

Zischg, Mair, Rauch, and Sitzenfrei (2017) investigated the results of applied changes to the city’s WDN in the long term and compared the results with previously analyzed hydraulic models. A case study was conducted in the city of Kirana of 20,000 inhabitants in Sweden. The change in network structure over many years and the result of these changes on the distribution network and comparison with hydraulic analyses indicated that hydraulic models should be reviewed and redesigned during the network maintenance stages (Marques & Cunha, 2020; Zischg et al., 2017).

Dziedzic and Karney (2016) proposed an implementation efficiency index. He pointed out that the ability to deliver the appropriate pressure and flow rate is related to the WDN implementation. This defined index is related to the average of four criteria: reliability, vulnerability, reversibility and connectivity. These criteria are based on the energy sufficiency, hydraulic capacity and structural ability of the system to deliver water under certain conditions. These criteria were used for the two modes of the network and its alternatives in order to evaluate their relationship, and the sensitivity of the system to changes.

The analysis and evaluation of WDNs was carried out by a group of researchers using performance criteria and a deterministic and fuzzy sustainability index. In the mentioned research, the network sustainability index is defined based on reversibility, vulnerability and reliability index criteria. The reliability index is also defined based on a combination of resilience, water age and entropy. Determining the above indicators has been done using fuzzy and deterministic logic methods. Finally, the fuzzy logic method provided better results than the other method (Bakhtiari, Safavi, & Mohammadi, 2016).

So far, it has been common to use general sustainability indicators for the entire network, while development and reconstruction plans are made for specific areas of the network. Therefore, in order to improve network performance evaluation, point stability as a significant component needs to be considered. As a result, in an innovative approach to improve the assessment of stability distribution in the water distribution network, the method of this research was proposed, and in order to connect the stability characteristics from general calculations to point calculations in the network, point stability extraction relationships in the distribution network were designed and proposed. The implementation of this research required the completion and improvement of the general stability extraction relationships in the network for the possibility of extracting the point stability index of the network as well, which was not found in the records of past researches.

The review of the records indicated that the point index, which can represent the changes effect on the consumption point and at the same time is formed based on the sustainability index's correlations, can be very effective in improving the indices used in the plans in order to enhance the WDNs' performance. This means that the design process and the desired analyses (based on pressure or demand) should be done in such a way that, in addition to improving the overall stability index, the point indices also have a significant improvement. In other words, this research evaluates the possibility of obtaining point indicators related to sustainability in the network, so that, by creating a practical and research history, it can be used for the design of networks for modification, reconstruction, or the development of the attention of researchers and designers. Therefore, in the present research, along with providing research records and related projects, point index extraction relations were proposed for the first time as a research innovation and were extracted and analyzed in the hydraulic simulation of a real water distribution network.

The purpose of this research is the design and extraction of a point sustainability index in order to provide a decision-making option for improving the WDN operation as a basic step towards stable urban water management. Therefore, in the absence of a formal method in order to evaluate the distribution of sustainability in a WDN, the present research is designed and proposed as a new approach to link the characteristics of system sustainability to a substitute action. In order to evaluate the characteristics of system sustainability in a dynamic system model of the water network (accessible domain) under different scenarios of water accessibility, a sustainability distribution index corresponding to the urban WDN was established and evaluated based on its structure.

MATERIALS AND METHODS

Area of studies

Abyek city is one of the Qazvin province cities, with an area of, 1534 square kilometers. It is located on the eastern border of the province, and its center is Abyek city. This city has 2 Besharayat and central parts, which include 2 cities, 5 villages and 79 inhabited villages (Figure 1). Abyek city is located in the easternmost point of Qazvin province and between the center of this province and Karaj city. The distance to this city is 50 km from Qazvin, 45 km from Karaj and 85 km from Tehran. Abyek city is located at 36 degrees and 2 minutes of latitude and 50 degrees and 32 minutes of longitude. The general slope of Abyek city is from northeast to southwest.

The highest altitude value is 1390 meters above sea level in the north of the city, and the lowest altitude value is 1215 meters above sea level in the southern part of the city. According to the population census of 2016, the population of Abyek city included 29,234 households, including 94,536 people, 49,129 men, and 45,407 women. Accordingly, the population of Abyek city is 60,107 people with an annual growth rate of 1.5%. According to the population density maps of the Iran Statistics Center, in 2016, the city of Abyek had an area of 1836 hectares, and the average density of this city in the mentioned year was 32/7 people per hectare. According to the detailed project of Abyeke City in 2015, the area of the city is determined to be 817 hectares for 1425 years, and the average density of this city in the mentioned year is estimated to be 122.5 people per hectare. The statistical reports of the Qazvin Province Regional Water Company indicate that the amount of per capita consumption in the period of 2016–2021, excluding lost, is 211.5 liters per person per day in Abyek city. Based on the methods of per capita calculation in consumption's different sectors and consumption management and loss reduction, it is predicted that the total amount of consumption per person for a day will reach 202 liters in 1425 and the total amount will reach 7.4 million cubic meters in that year. The arrangement of the distribution network in Abyek city is shown in Figure 2. Abyek WDN was considered for refurbishment to enhance the sustainability of the water distribution. Therefore, the WDN was selected for the simulation of the enhancement options. Although, the optimum option will be driven by the refurbishment project, despite the optimization of the options' evaluation, the method of the overall simulation of sustainability is within the scope of the current research.

Figure 1: Study area.

Methodology

For the structural classification of measuring and understanding the sustainability index of the distribution network system, the ranges of the network's response to changes, including absorption, adaptation and restoring (the network failure due to change and the need to restore), were simulated. For this purpose, the hydraulic model of the water distribution system was established using WaterGems software. Then the relationships between the effective components in the network sustainability index are possible after the quantitative and qualitative evaluation stages of the collected data. According to Figure 3, the main stages of the research are as follows:

- Data collection
- WDN Hydraulic simulation
- WDN Sustainability index identification
- Redefinition WDN Sustainability index
- Extraction Sustainability indices
- Evaluation

The reversibility index of the network is suggested as below (Macías Ávila et al., 2021):

$$I_R=1-\frac{P_D}{P_{D\max}}=\frac{\sum_{i=1}^{n}=1\left(q_i h_i-q_i^{*} h^{*}{}_{i}\right)}{\sum_{k=1}^{r} Q_K H_K-\sum_{i=1}^{n} q_i^{*} h_i^{*}} \qquad 1$$

Figure 2: Water distribution network of Abyek city.

In this relation, q and h are flow and Head (height equivalent to pressure), respectively. R is the number of water supply tanks in the scope, and I is nodes in the WDN. This relation is defined based on the energy delivered to the nodes (Elshaboury, Attia, & Marzouk, 2021). The calculated number based on this relation will be between the minimum value of zero and a maximum of one. Also, the system reliability rate is defined using the following relation (Dziedzic & Karney, 2016; Prasad, 2021):

$$P_{rel} = \sum_{i}^{s} \sum_{t}^{h} \frac{e_{t,i}}{sh} \qquad 2$$

In which pres is reliability rate, h is the hydraulic model simulation hours and S is a number of scenarios. These scenarios must be defined in normal and emergency conditions. Parameter e is calculated using the following relation, which is the ratio of delivered energy to the supplied energy.

$$e = \frac{E_{delivered}}{E_{\sup plied}} \qquad 3$$

The amount of system vulnerability was defined using the following relationship:

$$P_{vul} = \min\left(e_t, i\right) \qquad 4$$

The system’s vulnerability severity is the minimum efficiency of the system during emergency events or normal conditions of operation.

In this study, the sustainability index is a criterion that indicates the satisfaction of the WDN performance. The amount of satisfaction or utility of the network performance using a mathematical function is distinct from dissatisfaction. In this research, the optimal pressure in

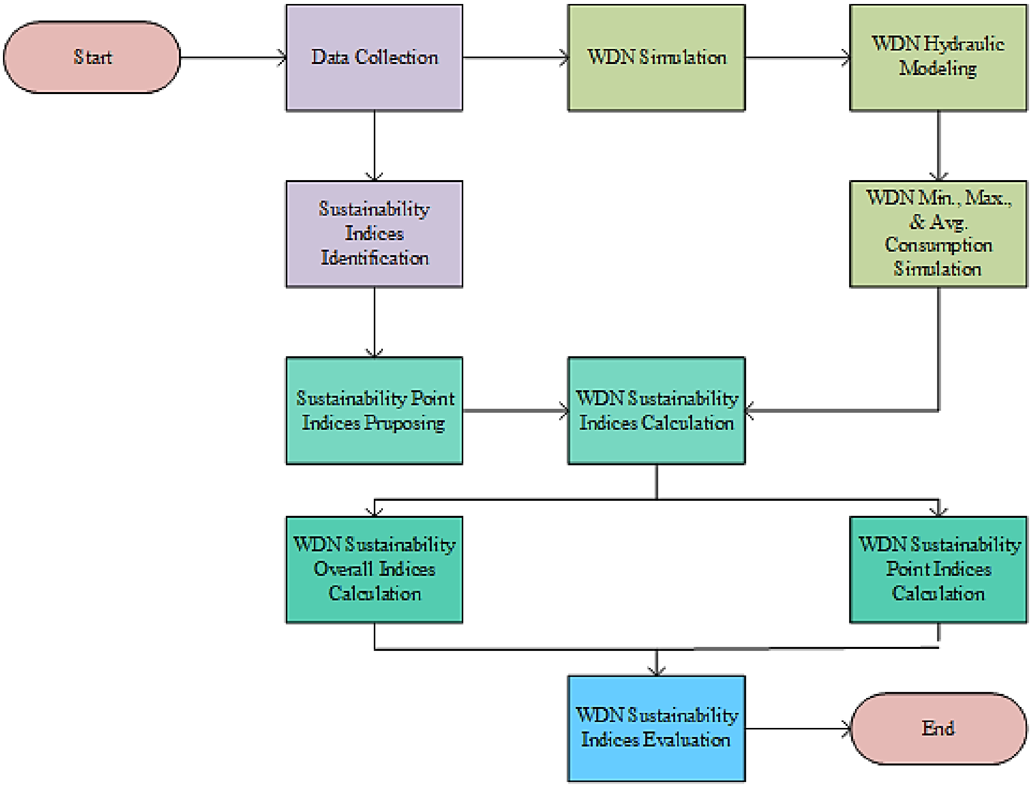


Figure 3: Research process.

the network is considered between 26 and 60 meters of water pressure.

Pi <pmin, pi> pmax: disutility at point I

Pi> = pmin, pi <= pmax: utility at point I

The network sustainability index is a combination of reliability, flexibility and vulnerability that can be variable over time. Network reliability is the probability of network satisfaction status using the following relation:

Duration of Network Utility Status/Total Network Analysis Time = REL

The flexibility shows the network's return speed to the desired position after an event.

General status of the network/the uncertainty of the network status = RES

The amount of vulnerability or time of unacceptable network status is defined as the amount of network vulnerability at the specified time interval:

Sums of undesirable values / Total values =VUL

In the present study, the network sustainability index was defined by the following relation (Bakhtiari et al., 2016):

$$Sl_i = \left[\mathrm{Re}\, l_{time}^{i} \times Erl_{C}^{i} \times \mathrm{Re}\, s^{i} \times \left(1 - Vul^{i}\right) \right]^{1/43} \qquad 5$$

The domain of the network sustainability index changes (SI) from zero, which means disutility water supply, to one, which means utility water supply to all network points in the defined domain. The network status evaluation is determined by the sustainability index based on Table 1.

Table 1: Evaluation of the network condition based on resilience index.

SI index value	Network status
0-0.25	Unacceptable
0.25-0.5	Medium
0.5-0.75	Acceptable
0.75-1.00	Excellent

DISCUSSION AND FINDINGS

Simulation

The hydraulic conditions of WDNs are generally evaluated by using demand-driven modeling (DDM) models as a demand function in normal operational conditions and additional pressure-driven modeling (PDM) implementations that have better responded to WDNs (WDN) analysis in operating conditions. Water distribution calculations were investigated by an under-pressure model, as it provided a better description of the system's conditions than the classical model formulas in the event of a pipe failure.

The assumption of fixed node use (DDM approaches) is valid only in normal conditions when the pressures are sufficient to meet the determined demand. The system's performance was also simulated in critical pressure conditions (due to some critical events such as mechanical and hydraulic or surplus demand failure), and the relation between pressure and output was considered. The performance of the WDN was simulated using hydraulic computer models.

Using the information collected from the relevant references, first the physics of the distribution network in the hydraulic model was first built. At this stage, the information of pipes diameter and type, the location of the pressure-reducing valves, their regulatory output, the limit valve between the tanks and between the compressive zones, the location of the tanks, etc. were entered into the model, and after resolving the model problems, such as the lack of connection of some points to the supply resource of hydraulic model physics, they were completed. Then the height digits were allocated to the nodes in the hydraulic model, using the digital maps prepared by the mapping organization, and then the amount of consumption for each node was assigned using subscriber consumption meters information (received from the water and sewage area in question). The customer use pattern was calculated according to the output pattern of the tank and the maximum daily and hour coefficient based on the output discharge analysis and assigned to the nodes of each tank.

Available data in Qazvin Province Water and Wastewater Company is used to determine and evaluate the efficiency of the network. Also, the data noted during the last 5 years of operation (2017-2021) in the relevant infrastructure was studied. For this purpose, the hydraulic model of the water distribution system was first established using WaterGems software. The water consumption process was investigated, and the 24-hour consumption chart was extracted for minimal, medium and maximum consumption days. Simulation of network hydraulic behavior (pressure, speed, and point bode) for all three states of consumption was performed. Then the relationships between effective components in the network sustainability index were extracted in the assimilation process of studies with research backgrounds, vulnerability, compatibility and reliability for the existing network in three modes of committee: medium and maximum consumption. Besides, a database of network failures and refurbishments was reviewed and processed. In order to achieve the purpose of the research and the innovation, the network sustainability indicators were calculated and components classified for all points (nodes) of the open network. In the final stage, point indicators, along with network indices, were evaluated and analyzed.

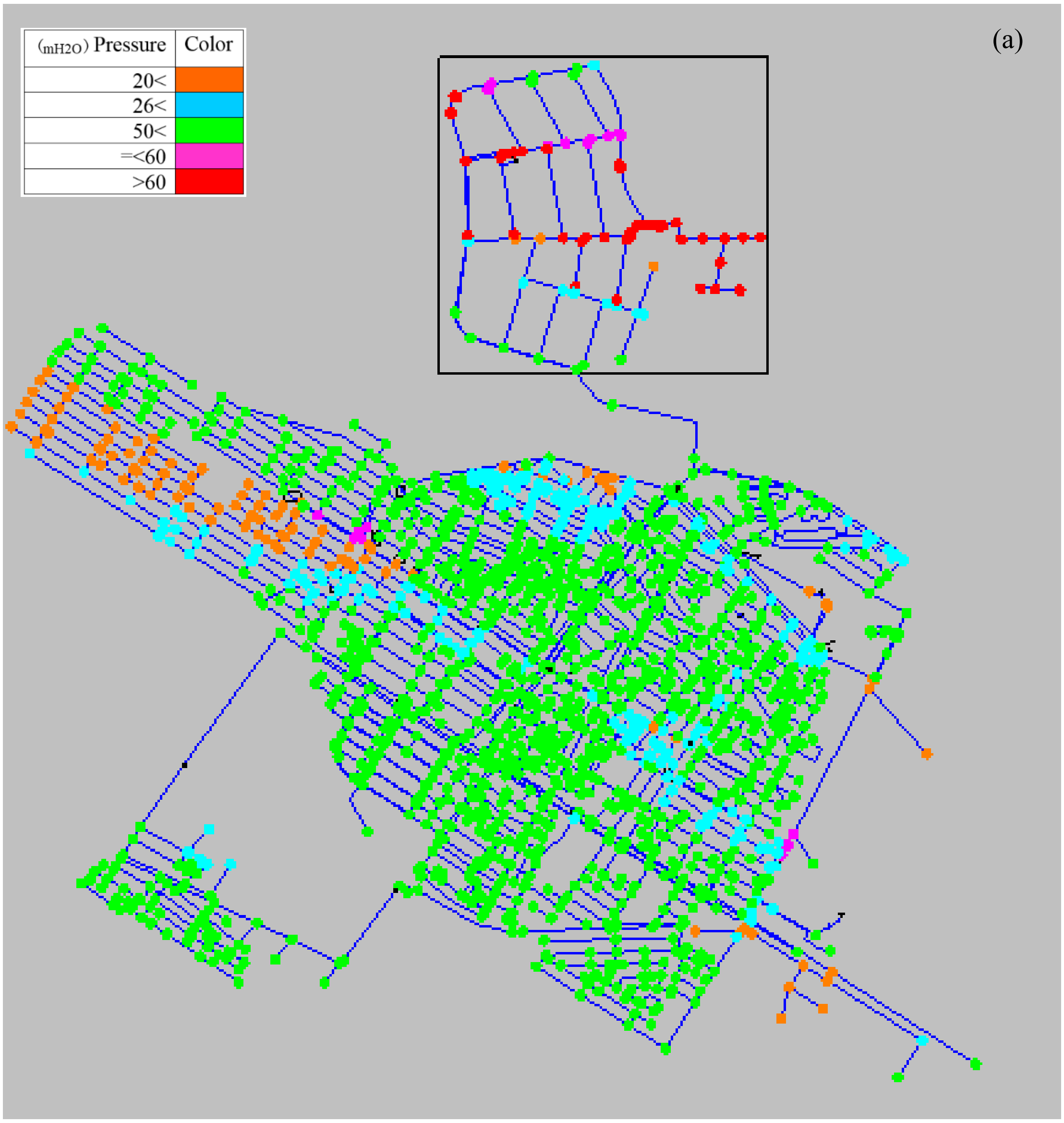
Pressure zoning of Distribution Network

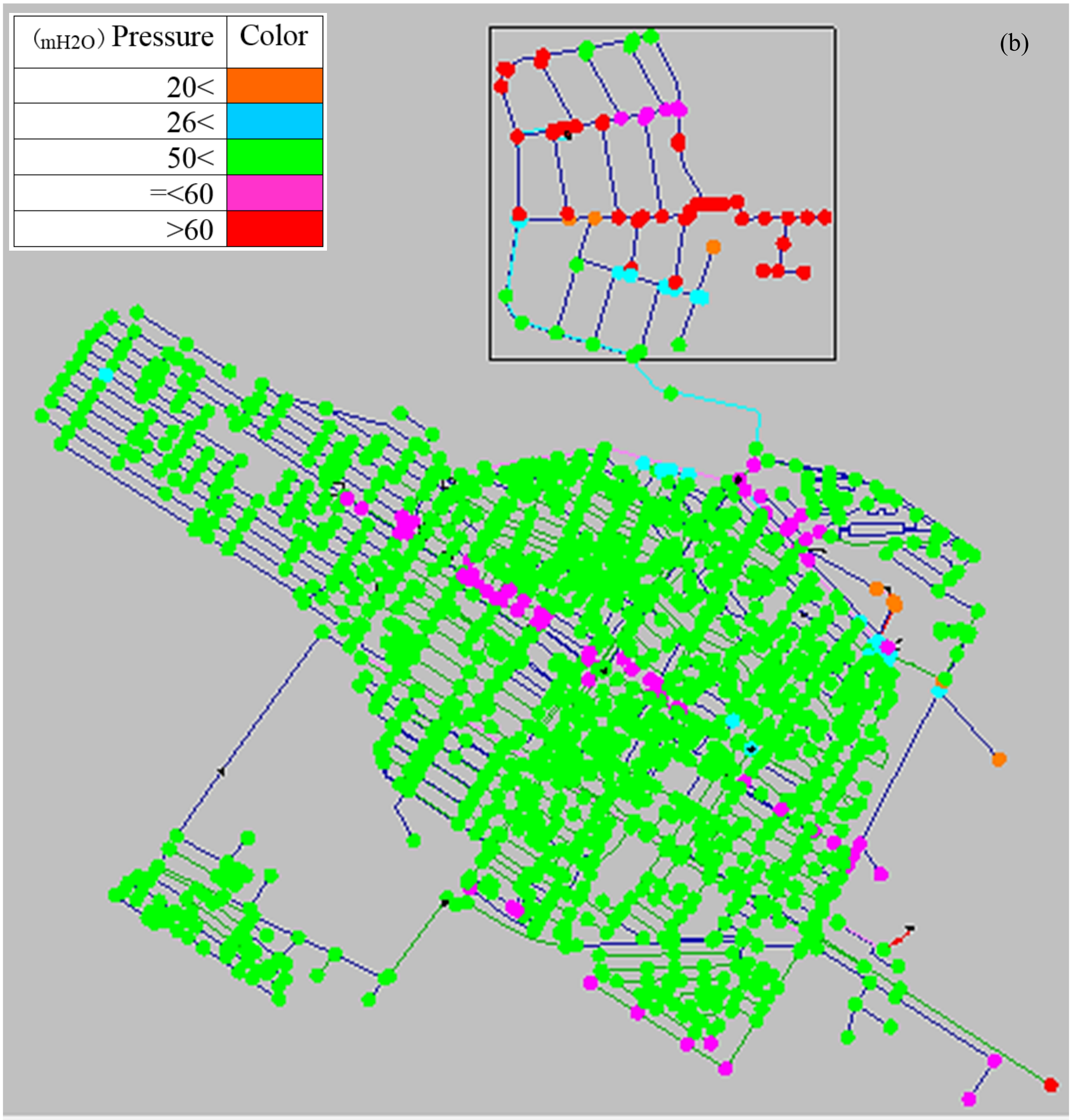
At this stage, the hydraulic behavior of scope drinking WDN nodes in the modeling and their compliance with the corresponding hydraulic behavior in different areas were investigated. The hydraulic model of the network was simulated in dynamic form for maximum, medium, and minimal consumption days, and then the hydraulic components were processed alongside the physical properties of the network. Figure 4 shows the hydraulic model of the WDN in terms of maximum and minimum hourly consumption. The model pressure was calibrated using the pressure recorded in the area's barometer along with the gauges. For the possibility of separating the pressure zone of the simulated distribution network in maximum, medium and minimal consumption hours, the output of the pressure distribution is displayed by the following ranges:

- Low pressure range in the grid for points less than 26 m of water column with orange color
- Normal network pressure range for points with pressure between 26 and 40 m of water column with blue color
- Range on the threshold of high pressure for points with pressure between 40 and 50 m of water column with green color
- Network high pressure range for points with pressure greater than 50 m of water column with purple color.

Reviewing the pressures corresponding to the points and comparison with the defined compressive range indicates that nearly 92% of the nodes in the distribution network under maximum hourly consumption conditions (the lowest hydraulic water pressure in the distribution network), have the appropriate pressure in the range of 26 to 60 meters of water column, and taking a look at the internal distribution of this acceptable compressive range shows that the compressive range between 26 and 50 meters of water column, which has the most positive effect on water consumption management, with a significant superiority, has more compressive distribution in consumption nodes. Figure 4a shows that most of the network includes the middle range, from the west to the east, and the south of the network has an appropriate compressive distribution, but the northwest part of the network needs to improve pressure by implementing network consumption management and reform programs.

It is also deduced from the compressive distribution zoning under average hourly consumption (Fig. 4b), which is about 89% of the nodes in the distribution network under aver-


(mH2O) Pressure
Color
20<
26<
50<
=<60
>60
(a)


(mH2O) Pressure
Color
20<
26<
50<
=<60
>60
(b)

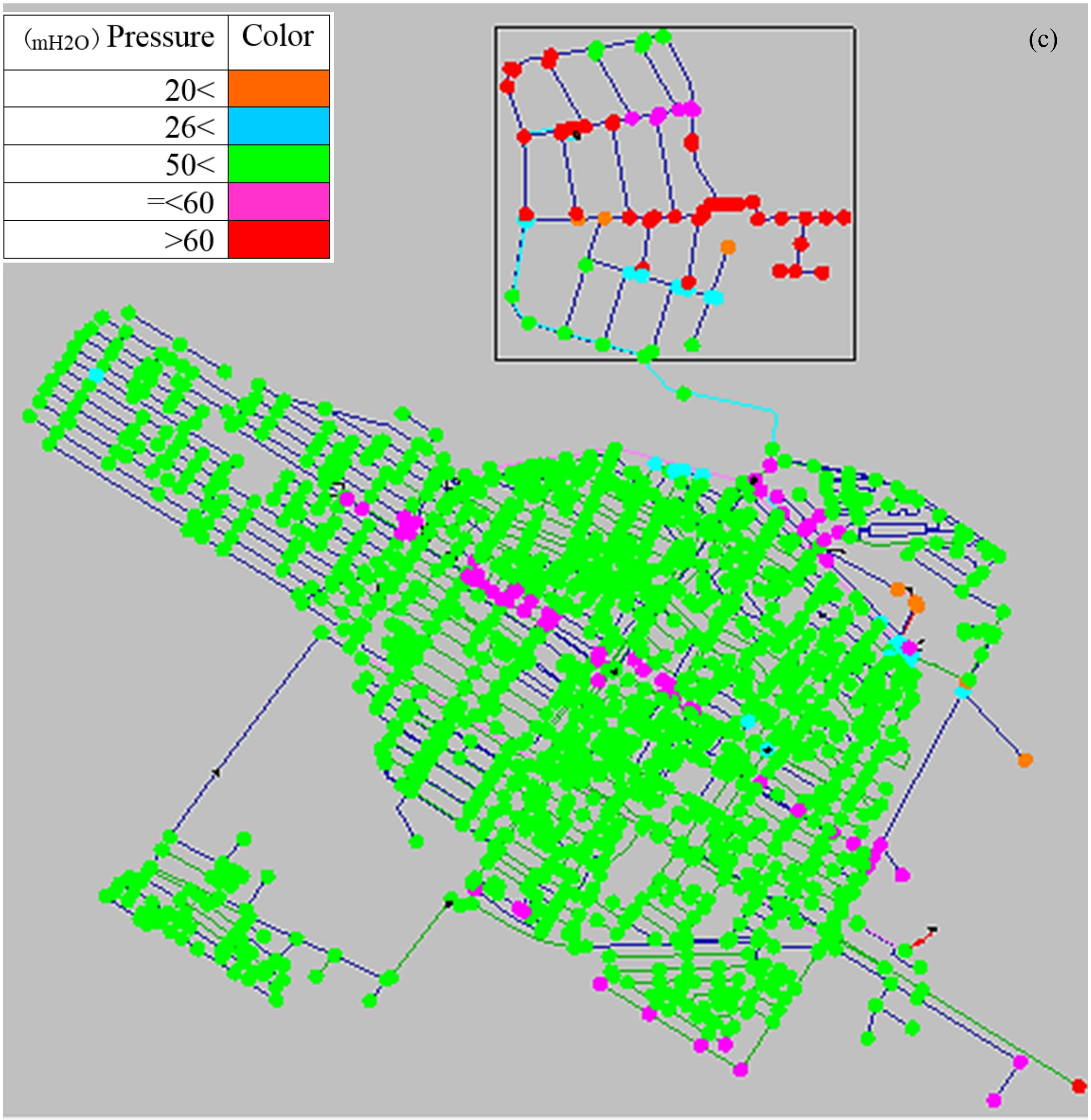


Figure 4: The coloring of the pressure situation in the network: a- maximum hourly consumption, b- average hourly consumption and c- minimum hourly consumption.

age hourly consumption (the lower hydraulic water pressure in the distribution network), has appropriate pressure on the 26 to 60 m of water column domain, and a look at the internal distribution of this accepted compressive range shows that the compressive range between 26 and 50 meters of water column, which has the most positive effect on water management, with a look at the internal distribution of this accepted compressive range shows that the compressive range between 26 and 50 meters of water column, which has the most positive effect on water management, with a relative superiority has more compressive distribution in consumption nodes. At the same time, most of the network includes the middle part; from the west to the east and south of the network, there is appropriate compressive distribution, but the northwest part of the network needs to improve pressure by implementing network consumption management and reform programs. Finally, the distribution of pressure in the minimum consumption conditions (Fig. 4 c) shows that about 96% of the nodes have the appropriate pressure in the range of 26 to 60 m of water column, and a look at acceptable internal distribution shows that the compressive range between 26 and 50 m of water column meter, with a significant superiority (89% of the total network), had a more appropriate compressive distribution in the nodes. These digits show very favorable conditions in terms of pressure distribution and consumption compared to the hydraulic conditions of the network at the maximum and average consumption of nodes. Domain color separation for proper distribution of pressure in the WDN in Fig. 4 c, shows that a very limited and small part of the network consisted of a small part of the mid-range of the grid that did not have appropriate compressive distribution.

Network Sustainability Index

In the studied WDN and as the second series of model outputs, the parameters needed to extract network resilience, pressure parameters per node during discharge and water supply () in meters of water column and discharge rate of each node ()in L/s, from the model output for each node, and according to the technical and executive system criteria, the minimum required pressure 26 meters of water column was determined and used in calculations In the extraction of network reliability, based on 24-hour hydraulic changes, the WDN simulation for each node, the pressures of each node at the mentioned time interval, and the number of nodes with favorable compressive conditions (more than 26 and less than 60 m of Water column) were calculated compared to the optimal compressive nodes. The ratio of the total number of nodes with optimal compressive conditions to the total number of nodes in the 24-hour variations of water flow in the network was calculated as an index of network reliability for the water ratio with optimal pressure for the subscribers. The network vulnerability index was extracted after calculating the number of low-pressure nodes (less than 26 meters of water column) at the output of the simulated network model and their ratio to the total number of nodes. In the last stage, the network sustainability index was calculated on the basis of the relationships contained in Section 3 of this article.

In Fig. 5, the network indicators that lead to the sustainability index in the three modes—minimum, average and maximum consumption—have been shown. Comparison of the network resilience index in minimum, medium and maximum consumption states shows that the network has relatively similar hydraulic behavior in minimal and average states. While entering the maximum phase of consumption, this indicates an increase in vulnerability and a significant decrease in reliability in the optimal hydraulic behavior of the network. Therefore, any corrective program can be maximized in the output of the model in maximum state, based on the attention of the network operation that, respectively, has pressure drop or over-optimal pressure changes.

Point Sustainability Index of the WDN

The relationships of extracting the indicators of reliability, flexibility and vulnerability according to the relationships listed in section 2-2, in order to extract the point sustainability in the research network, by modifying the general relationships appropriate to the point conditions in an innovative manner for this research were suggested (equations 6, 7 and 8). Explaining that these relations are presented and used for the first time in applied research to calculate and evaluate the working condition of a point in the water distribution network. In deriving the stability index of a point in the network, based on 24-hour hydraulic changes, simulating the water distribution network under research for each node, the pressures of each node in the mentioned time period, and extracting per hour the number of nodes with favorable pressure conditions (more than 26 and less than 60 meters of water) compared to nodes outside the optimal pressure limit were counted.

In the last step, the stability index of the network was calculated as a mathematical result using components of resilience, reliability and vulnerability, using equations 5.

Point Resilience Index for Network

The network resilience index was defined as the total discharge ratio in the point pressure difference from the minimum pressure required in the network to the total flow in the minimum pressure required in the network. In order to point out the calculation of resilience in each network node, it was defined as follows:

$$\begin{aligned}
&IF\left(q_i^{req}\left(h_i - h_{\min i}\right)\right) = 0\\
&\qquad , RESp = 0,\\
&IF\left(q_i^{req}\left(h_i - h_{\min i}\right) \geq q_i^{req} h_{\min i}\right)\\
&\qquad , RESp = 1,\\
&IF\left(q_i^{req}\left(h_i - h_{\min i}\right) \prec q_i^{req} h_{\min i}\right)\backslash\\
&\qquad , RESp = ABS\left(q_i^{req}\left(h_i - h_{\min i}\right) / \left(q_i^{req} h_{\min i}\right)\right),
\end{aligned} \tag{6}$$

The calculation of RESp for all network points showed that this point index with the defined conditions is in the range of 0 to 1. Index 1 indicates the complete resilience of a point to pressure and flow rate changes, and zero indicates the lower limit of this point index, which has an abstract meaning and is considered for the nodes of the network whose point moment flow rate could not be extracted. At the same time, for the points of the network where the ratio calculated for RESp was greater than 1, the maximum limit of this index, which is 1, is intended.

The reliability point index was defined as the ratio between the total numbers of nodes with optimal pressure (range of 26 to 50 meters of water column) and the total number of nodes in the 24-hour network operation simulation in 1-hour intervals. In accordance with the mentioned index, the reliability point index, the ratio of the moment pressure of each consumption node, to the upper or lower limit of the desired pressure (26 and 50 meters of water column, respectively), was defined as follows and calculated for all consumption nodes:

$$\begin{aligned}
&IFh_i \prec 26, RELp = h_i / 26,\\
&IFh_i \succ 50, RELp = 50 / h_i,\\
&IFh_i / \left(\left(50+26\right)/26\right) \geq 1;1; RELp = \left(\left(50+26\right)/2\right) h_i,
\end{aligned} \tag{7}$$

The calculation of RELp for all network points showed that this point index is in the range of 0 to 1 with the defined conditions. Index 1: full point reliability to water supply in optimal flow and pressure and zero limit indicates the lower limit of this point index, which has an abstract meaning, and considering that this index is calculated with 2 decimal digits, therefore RELp is smaller than 0. 01 was displayed with the number zero. Also, for the points of the network where the ratio calculated for RELp was greater than 1, that is, the highest limit of reliability, the maximum limit of this index, which is 1, 0.1, was considered.

The point vulnerability index was defined as the ratio between the total numbers of nodes with low pressure (less than 26 meters of water column) and the total number of nodes. In accordance with the mentioned index, the point vulnerability index, the pressure ratio of low-pressure nodes to the lower and upper limits of the desired pressure (26 and 50 meters of water column, respectively), was defined as follows and calculated for all consumption nodes.

$$IFh_i \geq 26; IFh_i \succ 50; \left(h_i - 26\right)/26; 26 - h_i/26 \tag{8}$$

The calculation of VULp, the calculation of the point vulnerability index for all network points, showed that this point index has the range of zero to 1 with the defined conditions. Index 1 indicates full point vulnerability to water supply in optimal flow and pressure and the zero limit indicates the lower limit (complete safety) of this point index, which has an abstract meaning.

Evaluating the point sustainability index,

The point sustainability index was extracted according to the formula of the sustainability index, the result of the combination of point resilience, reliability and vulnerability indices for all points of the network. Therefore, to understand the state of the WDN of the studied area in disutility conditions, the upper, middle and lower limits of the point sustainability indices in the network were calculated for minimum, medium and maximum consumption conditions (Table 2). The extraction of the above 3 indicators for the entire network showed that the most critical state (the lowest amount of desirable indicators) occurred in the maximum consumption state. Also, in the triple consumption states, the point sustainability indexes followed the same trend, and the widest range of low and medium sustainability of points can be seen in the maximum consumption mode.

In another process and in accordance with the zoning of pressure distribution in the network, the distribution of the point sustainability index was grouped in the intervals of 0.00–0.43, 0.43-0.83, and 1.00-0.83. Total and point sustainability indicators of the network were drawn in a diagram for three modes of minimum, medium and maximum consumption (Fig. 6). The comparison of the point sustainability indicators distribution showed that more than half of the network nodes are in a relatively stable state; on the other hand, a significant part of the network nodes are in the relative sustainability range, and a small part (negligible) of the network nodes are in the unstable range.

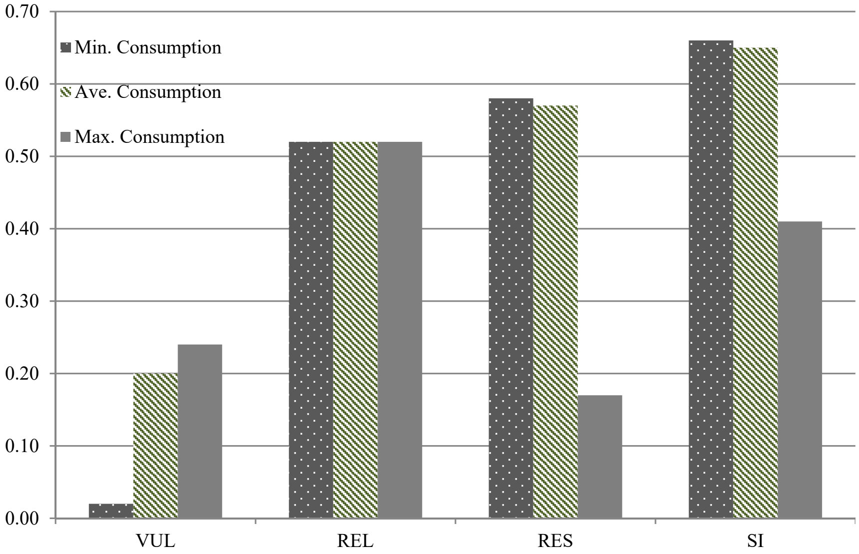


Figure 5: Chart of network indicators in different consumption situations.

Table 2: The maximum and minimum limits of the SIp index for network points in different consumption situations.

Consumption	Minimum	Average	Maximum
SIp			
Lower limit	0.15	0.02	0.00
Average	0.80	0.32	0.27
Upper limit	1.00	1.00	1.00

The proposed solution includes extracting the point sustainability index by combining resilience, reliability and point vulnerability indices for all points of the network with a comprehensive assessment of the stability of the water distribution network in different conditions. In a normal trend, the most critical state, which was visible with the least favorable indicators, was observed during the maximum consumption. In addition, the point sustainability indices showed a stable trend in different consumption conditions, and the highest out-of-stability ranges (low and medium ranges) were observed in the maximum consumption mode. The comparison of total and point sustainability indices revealed that a significant part is in the range of relative sustainability, and only a few points were classified as unstable. Therefore, the use of the sustainability index of the whole network, for regional improvement, reconstruction or development plans, cannot represent the conditions of improvement of stability in a specific area of the WDN, while this condition can be clearly simulated by the use of a point stability index.

RESULT AND CONCLUSION

Reviewing the past researches history showed that the network sustainability criterion is used to compare and evaluate network performance in time periods (daily, monthly, seasonally and annually) or to compare the performance of homogeneous networks in different geographical environments for use in evaluating the performance of network operators and planning improve, modification, refurbishment and development programs (in the case of functional comparison of a set of WDNs in cities and villages) for an operating company or an employer organization. Reviewing the records showed that it is necessary to design and propose an index that can correctly simulate the satisfaction status of each consumer in the network. For this purpose and by using the valid relations that are used for the 3 indicators and the relation of these indicators to calculate the sustainability index, the point resilience, reliability and vulnerability indicators were defined and for all 3 modes of

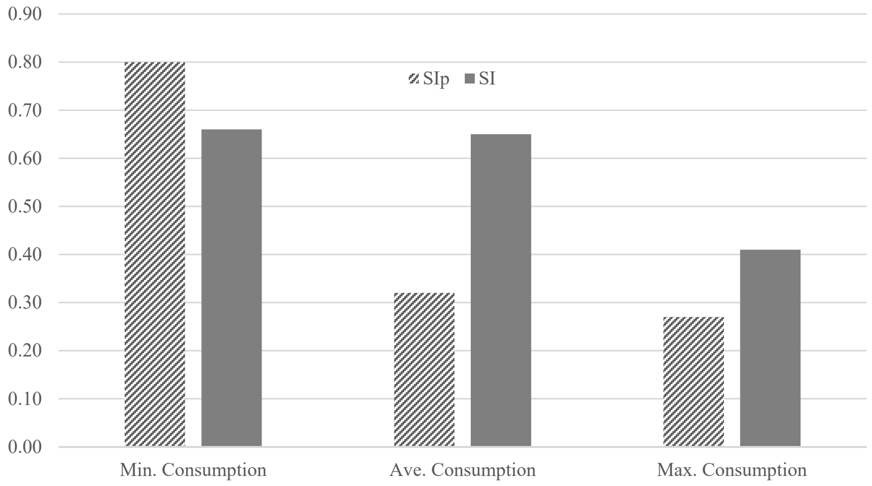


Figure 6: Comparison chart of point stability indicators and the whole network in different consumption stuations.

minimum, medium and maximum consumption, they were extracted and analyzed using the basic statistics and the output of the network hydraulic model. In a simulation process, the pressure zone and flow distribution in the network consumption nodes were simulated.

Formerly, based on the records and results of the researches, three indicators of resilience, reliability and vulnerability were extracted to determine the sustainability of the entire network and based on them, the level of network sustainability was extracted. Based on the evaluation criteria, the network sustainability index at the minimum consumption was above average (acceptable), and at the maximum consumption, the upper limit was acceptable, and in the process of changes in consumption from minimum to maximum, the consumption of the network sustainability index was reduced. The point indicators of the network were also defined, and after calculating the results, it showed that in the state of maximum consumption, the distribution of point sustainability in the network is in a lower state than other consumption states. Also, the comparison of the statistical results of this point index with the sustainability index of the entire network and their changes trend showed the similarity of decreasing sustainability index trend from the minimum consumption state to the maximum consumption state, while the distribution of the network points sustainability index acceptable limits shows the decrease in the number of sustainable points within an acceptable pressure range. As a result, compared to the sustainability index of the network representative, the point sustainability index in the state of maximum consumption can be a better indicator for the nodes of the network consumption, and applying any network improvement, modification, or refurbishment changes can be evaluated in the simulation of this operation based on its point sustainability index before implementation. At the same time, the examination and analysis of the results showed the sustainability index convergence of the whole network with the point sustainability index; therefore, the design of corrective programs based on the improvement of the points' sustainability index will also improve the sustainability index of the whole network.

REDRENCES

Ahmadi, N. A., Moradi, E., Hoseini, S. M., & Shahraki, A. S. (2022). Simulation of the dynamics of water resources in the Hirmand watershed under economic and environmental scenarios. Environment, Development and Sustainability, 1-27. doi:10.1007/s10668-022-02713-9

Azadkhani Pakzad. (2022). The impact of modern construction technology in improving the quality of the architectural environment of sustainable educational buildings. Journal of Urban Management and Energy Sustainability, 3(4), 16. doi:10.22034/jumes.2022.1986028.1109

Bakhtiari, S., Safavi, & Mohammadi, G. (2016). Analysis and evaluation of the performance of water distribution networks using performance criteria and deterministic and fuzzy stability index (In Persian). Water and Wastewater Science and Engineering, 1(1), 28-36. doi:10.22112/jwwse.2017.51051

Batten III, J. J. (2018). Realizing a More Sustainable Water Future From a "One Water" View. Journal: American Water Works Association, 110(6).

Behzadpoor E., Tabaeian A., & Khatibi M. (2020). Evaluation of the Level of Urban Social Resilience to Earthquakes Using a Good Urban Governance Approach. Journal of Urban Management and Energy Sustainability, 1(4), 8.

Beker, B. A., & Kansal, M. L. (2022). Fuzzy logic-based integrated performance evaluation of a water distribution network. AQUA—Water Infrastructure, Ecosystems and Society, 71(3), 490-506.

Borzì, I., Bonaccorso, B., & Aronica, G. T. (2018). Performance Analysis of the Water Distribution System of the City of Messina through Sustainability Indices. EPiC Series in Engineering, 3, 295-301. doi:10.29007/sr9c

Dziedzic, R., & Karney, B. W. (2016). Performance index for water distribution networks under multiple loading conditions. Journal of Water Resources Planning and Management, 142(1), 04015040. doi:10.1061/(ASCE)WR.1943-5452.0000564

Elshaboury, N., Attia, T., & Marzouk, M. (2021). Reliability assessment of water distribution networks using minimum cut set analysis. Journal of Infrastructure Systems, 27(1), 04020048.

Geleta Ebsa, D., & Fufa, F. (2021). Hydraulic performance Analysis of water supply distribution network using water GEM v8i. Drinking Water Engineering and Science Discussions, 1-18.

Kuma, T., & Abate, B. (2021). Evaluation of hydraulic performance of water distribution system for sustainable management. Water Resources Management, 35(15), 5259-5273. doi:10.1007/s11269-021-03000-4

Macías Ávila, C. A., Sánchez-Romero, F.-J., López Jiménez, P. A., & Pérez-Sánchez, M. (2021). Leakage Management and Pipe System Efficiency. Its Influence in the Improvement of the Efficiency Indexes. Water, 13(14), 1-25. doi:10.3390/w13141909

Marques, J., & Cunha, M. (2020). Upgrading water distribution networks to work under uncertain conditions. Water Supply, 20(3), 878-888. doi:10.2166/ws.2020.011

Prasad, R. K. (2021). Identification of Critical Pipes for Water Distribution Network Dziedzic Rehabilitation. Water Resources Management, 35(15), 5187-5204. doi:10.1007/s11269-021-02994-1

Tabarestani Ali, Nabi Bidhendi Gholamreza, & Baghdadi Majid. (2023). Investigating and explaining the model of urban wastewater management with a decentralization approach by presenting an optimal design model (District 4th of Tehran). Journal of Urban Management and Energy Sustainability, 4(3), 3.

Vitan, E., Hotupan, A., & Hadarean, A. (2021). Average Operating Pressure Effect on Water Supply Systems Performances. A Case Study for 12 Romanian Small Water Distribution Networks. Journal of Applied Engineering Sciences, 11(2). doi:10.2478/jaes-2021-0019

Vitan, E., Hotupan, A., Hadarean, A., & Cilibiu, C. (2022). Overview and Recommendations for Analysis of Water Distribution Systems Based on Performance Indicators. Journal of Applied Engineering Sciences, 12(2), 237-244.

Zhang, M., Zhang, J., Li, G., & Zhao, Y. (2020). A framework for identifying the critical region in water distribution network for reinforcement strategy from preparation resilience. Sustainability, 12(21), 9247.

Zischg, J., Mair, M., Rauch, W., & Sitzenfrei, R. (2017). Enabling efficient and sustainable transitions of water distribution systems under network structure uncertainty. Water, 9(9), 715. doi:10.3390/w9090715

HOW TO CITE THIS ARTICLE
Biranvandi, D., Hassanpour Darvishi, H., Ebrahimi, H., & Taherei Ghazvinei, P. (2024). Enhancing Sustainable Urban Management: A Proposal for Point Sustainability Index to Optimize Water Distribution Network Performance. International Journal of Urban Management and Energy Sustainability, ( ), -.
DOI: 10.22034/ijumes.2024.2016944.1186