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A scenario-based approach for urban water management in the context of the COVID-19 pandemic and a case study for the Tabriz metropolitan area, Iran

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HIGHLIGHTS
• The COVID-19 pandemic has affected water consumption patterns.
• The pandemic has increased the pressure on the already strained water resources in Tabriz, Iran.
• An integrated approach for assessing the impact of COVID-19 on water consumption is proposed.
• Future water demand patterns were forecasted and validated with the proposed approach.
• Authorities can use the results for sustainable water resource management.

ABSTRACT
The world’s poorest countries were hit hardest by COVID-19 due to their limited capacities to combat the pandemic. The urban water supply and water consumption are affected by the pandemic because it intensified the existing deficits in the urban water supply and sanitation services. In this study, we develop an integrated spatial analysis approach to investigate the impacts of COVID-19 on multi-dimensional Urban Water Consumption Patterns (UWCPs) with the aim of forecasting the water demand. We selected the Tabriz metropolitan area as a case study area and applied an integrated approach of GIS spatial analysis and regression-based autocorrelation assessment to develop the UWCPs for 2018, 2019 and 2020. We then employed GIS-based multi-criteria decision analysis and a CA-Markov model to analyze the water demand under the impacts of COVID-19 and to forecast the UWCPs for 2021, 2022 and 2023. In addition, we tested the spatial uncertainty of the prediction maps using the Dempster Shafer Theory. The results show that the domestic water consumption increased by 17.57% during the year 2020 as a result of the COVID-19 pandemic. The maximum increase in water consumption was observed in spring 2020 (April–June) when strict quarantine regulations were in place. Based on our results, the annual water deficit in Tabriz has increased from ~18% to about 30% in 2020. In addition, our projections show that this may further increase to about 40–45% in 2021. Relevant stakeholders can use the findings to develop evidence-informed strategies for sustainable water resource management in the post-COVID era. This research also
1. Introduction

Freshwater resources are of critical importance for sustaining human life. In addition to domestic use, water has an important role in agriculture, industry, and many other sectors. Deficiency in freshwater resources is evident in various regions worldwide and can cause risks to all aspects of human life (WHO-World Health Organization, 2015). In many parts of the world, water-intensive economic and industrial activities, combined with population growth and lack of sustainable water resource management plans and policies, have increased pressure on the already strained water resources and contributed to water scarcity. Consequently, water scarcity is now recognized as a critical issue (Shaban and Sharma, 2007). In fact, water crises were listed as one of the eight major global threats by the World Economic Forum (WEF, 2020). The quality and supply of this valuable resource have been impacted by environmental and anthropogenic stressors such as climate change, drought, pollution, and the continuous growth of industrial/agricultural activities (Feizizadeh et al., 2021).

The COVID-19 pandemic emerged amidst these challenges and swept through cities around the globe. It created unprecedented challenges to the global economy and health (Chen et al., 2021). In response, governments have implemented various measures (e.g., home quarantining, wearing a face mask, social distancing) that have caused economic and psychosocial effects ((Montemurro, 2020; Satici et al., 2020; Sılalahlı et al., 2020)). While the pandemic has affected almost all countries, middle- and low-income countries have been particularly hit hard due to their limited coping capacities. In fact, the pandemic exerted additional strains on various urban sectors in such countries, which made it more challenging to combat the spread of the virus (Sharifi and Khavarian-Garmsir, 2020). The water sector was no exception, as measures designed to combat the pandemic have further intensified water supply and sanitation service deficits in some regions (WEF, 2020).

There was a two-pronged approach to measures taken in response to the pandemic: social isolation through partial/blanket lockdowns, and the promotion of sanitation and hygiene behavior, such as wearing masks and frequent hand washing. Mixed evidence has been reported in the literature on the environmental effects of these measures. While there is ample evidence showing that lockdowns and reductions in transportation and economic activities have contributed to air and water quality improvements in some contexts (Bao and Zhang, 2020; Collivignarelli et al., 2020; Nakada and Urban, 2020; Zambrano-Monserrate et al., 2020), some studies have shown that the pandemic has caused problems such as increased hospital water waste and increased pressure on scarce water resources due to additional domestic water demand for sanitation and hygiene purposes (Cotterill et al., 2020; La Rosa et al., 2020; Sharifi and Khavarian-Garmsir, 2020). Such strains on the already scarce freshwater resources may cause a water scarcity crisis, particularly in cities located in arid/semi-arid climates such as Iran. However, there is a lack of research on how the pandemic has affected water scarcity issues in such climates.

Iran is a developing country and has been dealing with freshwater scarcity issues for decades. Iran’s water scarcity is caused by a combination of various factors, including population growth, increased urbanization, climatic changes, unregulated expansion of water-intensive industrial and agricultural activities, and ineffective water resource management (Kumar et al., 2013). In addition to the above-mentioned pre-existing factors that have contributed to water stress in Iranian cities, we have determined that the COVID-19 pandemic has further increased water demand since its emergence in late 2019. In the context of urban water consumption, various strategies, such as policy intervention, education, pricing, water-saving devices, and engineering methods have already been proposed to reduce the water consumption (e.g., (Adam et al., 2016; Davies et al., 2014; Di Mauro et al., 2021; Duarte et al., 2013; Feizizadeh et al., 2021; Jørgensen et al., 2009; Slaviková et al., 2013)). However, under unexpected and uncertain circumstances (e.g., impacts of COVID-19), there are doubts about the universal efficiency of these policies as contextual factors may lead to differential effects.

From the environmental perspective, cities are widely recognized as major consumers of water resources. In fact, large amounts of surface and groundwater resources are needed to meet the increasing water demand in cities. In some parts of the world, this increasing water demand has altered natural hydrological regimes and has led to adverse environmental impacts on freshwater ecosystems and resources (e.g., rivers, lakes and groundwater resources) (European Environmental Agency, 2020). According to previous studies (Feizizadeh et al., 2021; McDonald et al., 2011; McDonald et al., 2014), as cities increase in size, the total amount of water needed for sufficient municipal supply increases as well. This rise in the overall municipal water demand is due not only to an increase in the urban population, but also to the lack of efficient water transmission and distribution infrastructure and limited capacities for sustainable urban water planning and management (McDonald et al., 2014). The compounding effects of urbanization and global climate change are likely to further increase pressure on the already strained water resources in the coming decades. It is, therefore, critical to develop strategies and tools for efficient water resource management.

Spatiotemporal analysis of urban water resources and their consumption could help us understand the distinct and context-sensitive water consumption patterns. Such methods will also help the authorities in their efforts to craft evidence-based measures towards improved water management and to raise stakeholder awareness. By highlighting the challenges of water scarcity and the subsequent problems, authorities will be able to develop strategies for improving consumer behavior and attitudes (Delju et al., 2012). The study of urban water consumption patterns (UWCPs) depends on various factors such as the type of consumption, urban land use patterns, population characteristics, water waste incidents, as well as the state of the urban water transmission system. Spatiotemporal modeling of the UWCP may be useful for understanding patterns related to these factors as it can highlight differences in freshwater systems across various spatiotemporal scales of a city (Jaramillo and Nazemi, 2018).

Accordingly, a better understanding of the impacts of COVID-19 on UWCPs requires adopting interdisciplinary analytical approaches such as geographical spatial analysis (Franch-Pardo et al., 2020). In this regard, the integrated approach of Geographic Information Systems (GIS) techniques and statistical analysis can be efficiently applied to address complex water scarcity issues ((Ghorbanzadeh et al., 2018; Naboureh et al., 2019; Satti and Jacobs, 2004; Shokati and Feizizadeh, 2019); (Ahasan and Hossain, 2020; Mohamadzadeh et al., 2020; Omarzadeh et al., 2021)). Considering the importance of water to human life, as well as its significant role in the industry and the economy, extensive research is required to monitor the UWCPs, particularly in urban environments that deal with water scarcity issues. Against this background, the main objective of this study is to apply an integrated
GIS-based spatiotemporal analysis to investigate the impacts of COVID-19 on multi-dimensional UWCPs and to forecast the future water demand in the Iranian city of Tabriz, which is located in a semi-arid climate zone and has always been suffering water scarcity issues.

2. Study area and dataset

Located in northwest Iran, the study area of Tabriz is the political and economic center of the East Azerbaijan Province (Fig. 1). Tabriz is the 4th largest city in Iran, is home to about 2 million people, and covers an area of about 245 km². Tabriz is of critical importance for the country’s economy due to its large number of industrial plants and its rich cultural heritage, which makes it a popular tourist destination. With an average elevation of 1321 m above sea level, the city has a semi-arid climate (Behboudi et al., 2018; Feizizadeh and Blaschke, 2013; Saemian et al., 2020). Extensive agricultural and industrial activities, population growth, and the recent drought induced by climate change have caused a water scarcity crisis in the city. According to the Water & Wastewater Company of East Azerbaijan Province (WWC-EAP), there are three main freshwater supply sources in Tabriz, namely the Zarieneh Rood dam, the Nahand Dam, and 86 wells and 13 Qantas around the city (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021). According to the WWC-EAP, the water consumption in Tabriz has increased significantly since early 2020. The WWC-EAP reported that all freshwater resources are continually depleted, which puts extensive pressure on the freshwater supply system.

Similar to other Iranian’s metropolitan areas, Tabriz was significantly affected by the COVID-19 pandemic. The city has experienced several waves of the pandemic since early 2020, with major social and economic impacts. According to the Iranian Ministry of Health and Medical Education (MOHME. Ministry of Health and Medical Education, 2021), since the early days of the pandemic, Tabriz has always been a major high-risk city. Since COVID-19 broke out in late 2019, home quarantine began in Tabriz, as in other cities in Iran and the world. A significant increase in domestic water consumption can be observed when comparing the domestic water consumption data of 2018 (before COVID-19) with that of 2019 and 2020. This increase is associated with the additional demand for hygiene and sanitation purposes (e.g., hand washing). As a result of this increase in demand, a water rationing policy has been in place in Tabriz since July 2020 (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021). The increased demand for freshwater puts further pressure on this diminishing natural resource, particularly in cities with arid and semi-arid climates, such as Tabriz. Considering the population growth and resource distribution patterns in developing countries, large and densely populated cities like Tabriz are expected to be more exposed to additional strains due to COVID-19, such as a water shortage crisis. We thus believe that the results of this research provide useful inputs for authorities and decision makers to use for better management of water resources during the pandemic and in the post-COVID era.

2.1. Data collection

To monitor the spatiotemporal UWCPs in Tabriz, the water consumption data for 650,000 households were obtained from WWC-EAP. These data were collected eight times per year (every 45 days). Based on technical discussions with WWC-EAP experts, we determined that to conduct an effective spatially-explicit analysis of the impact of COVID-19 in the UWCPs, the water consumption data of the three years (2018 to 2020) were required. The selection of this three years was based on the data availability and also considering the timeline of COVID-19 pandemic (for before and during the pandemic). The UWCPs evolve based on the population density, the social and cultural background of the consumers, and the land use characteristics in urban environments. Thus, the spatial correlation of water consumption patterns with respective indicators can be evaluated based on the various factors affecting the UWCPs. For this research, we obtained the demographic and land use data for the Municipality of Tabriz at a scale of

![Fig. 1. Location of Tabriz city in EAP and Iran.](image-url)
1:2000. We also obtained the monthly water leakage data of the water distribution networks for consideration in the water leakage analysis. GIS-based data gathering and precreation techniques (e.g., editing, topology creating, spatial joint and interpolation implementation) were applied to prepare data related to all indicators in raster format with spatial resolution of 10 m. The raster data were then stored in a GIS Geodatabase for further spatial analysis.

3. Methodology

3.1. Approach and implementation

We saw the need to develop an integrated approach to investigating the spatiotemporal changes in UWCPs due to the effects of COVID-19. We also aimed to predict the future UWCPs and address the future urban water challenges in Tabriz, and analyze the spatial uncertainty of the outcomes. To achieve these goals, an integrated approach of a GIS spatial analysis, Moran’s I index regression-based autocorrelation assessment, multi-criteria decision analysis (MCDA), and CA-Markov were employed. In addition, the spatial uncertainty of predicted maps was examined based on the Dempster Shafer Theory. Fig. 2 depicts the main methodological steps of the research.

3.2. Spatiotemporal analysis of UWCPs

Spatial analysis lies at the core GIScience, which enables the assessment of the spatial relationships between geographic objects (Feizizadeh et al., 2021; Nazmfar et al., 2020a). Spatial analysis provides
a rich collection of methods and techniques for ‘spatial thinking’, which enables us to analyze and map the spatial patterns and relationships within the intended geographic environments (Goodchild, 2011). The spatial modeling of UWCPs allows us to map and quantify the water consumption of consumers. From the urban authorities’ perspective, in the critical conditions resulting from COVID-19 and the already existing water scarcity crisis, the results of the analysis of UWCPs can lead to a better understanding of the water consumption patterns and allow identifying the over-consuming stakeholders (Delju et al., 2012; Feizizadeh et al., 2021). To evaluate the impact of COVID-19 on water consumption in Tabriz, a three-year period seasonal trend evolution analysis was carried out based on domestic and non-domestic consumption data obtained from the WWC-EAP. These data were spatially linked to the urban parcel layers at the scale of 1:2000. It should be indicated that the water consumption data are based on quarterly records listed in seasonal periods. The first period is the winter of 2018 before the existence of COVID-19. The 2019 and 2020 data for each season were categorized, respectively.

Table 1 shows the water consumption for different study periods. Results indicate that water consumption has increased along with the spread of COVID-19. In the first three months of 2020, compared to the same period in 2018 and 2019, there is a significant increase in domestic water consumption. The total reported water consumption in Tabriz in January–March 2018 (winter) was 15,542,422 m³, while the corresponding consumption levels reported for 2019, and 2020 were 16,670,945 m³ and 17,681,669 m³, respectively. As we intended to identify the hotspots of the UWCPs, we determined a spatially explicit representation of UWCPs based on the water consumption data. In the spatial correlation, the increased consumption demonstrated an obvious correlation with residential land uses and areas with dense populations. Accordingly, the spatial interpolation and autocorrelation were performed for the spatially explicit mapping of UWCPs. Figs. 3 and 4 represent the spatially explicit representation of seasonal domestic and non-domestic UWCPs for different seasons from 2018 to 2020.

3.3. Spatiotemporal correlation analysis of UWCPs

To depict the spatial correlation of UWCPs hotspots, the impacting factors of urban water consumption were taken into account, and their spatial correlation with water consumption hotspots were evaluated. The data included three main groups of water consumption data and water incidents data received from the WWC-EAP (WWC-EAP: water and waste water company of East Azerbaijan Province, 2020), as well as demographic information and land use maps that were obtained from the Municipality of Tabriz. Since residential density, land use type, and incidents that occur in the urban water transmission network can affect the water consumption volume, the data associated with these factors were also examined. Since many businesses were temporarily closed due to the outbreak of COVID-19, the initial expectation was to observe a significant increase in the domestic water consumption and a decrease in the non-domestic water consumption. Seasonal variations might occur in the water consumption data. Thus, the annual UWCPs were computed as basic maps for the spatial correlation analysis with the indicators affecting water consumption levels (Fig. 5).

The regression method was applied to examine the spatial correlation of the UWCPs with the indicators affecting water consumption levels. Technically speaking, the regression technique is a computational technique for the quantitative explanation of the statistical associations between given values (i.e., UWCPs and the indicators affecting consumption levels). The regression method can provide the computation algorithms for the analysis and evaluation with which we can derive the exact dependence of the explained variables (dependent variables) on the independent variable (Chen et al., 2020). A spatial autocorrelation analysis can be a global or a local spatial auto-correlation. The key index of the global spatial autocorrelation analysis is Moran’s I index (Nazmfar et al., 2020b; Tian et al., 2016). The equation and mathematical background of the Moran’s I index is as follows.

$$I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} Z_i Z_j}{S_0}$$

where $Z_i$ is the deviation of an attribute for feature $i$ from its mean ($X_i - \bar{X}$), $w_{ij}$ is the spatial weight between feature $i$ and $j$, $n$ is equal to the total number of features, and $S_0$ is the aggregate of all the spatial weights:

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}$$

The $Z$-score for the statistic is computed as:

$$Z_i = \frac{I - E[I]}{\sqrt{V[I]}}$$

where:

$$E[I] = -\frac{1}{n-1}$$

$$V[I] = E[I^2] - E[I]^2$$

The value of Moran’s I ranges from $-1$ to $1$, whereby $I > 0$ indicates that a given area shows a positive correlation with its surrounding areas and tends to feature spatial agglomeration, while values below 0 indicate that the areas tend to have spatial dispersion. When $I = 0$, there is no spatial correlation between the given area and its surrounding areas. The spatial autocorrelation analysis is used to construct the geographically weighted regression model. When the spatial correlation of observation points is not important, it means that the distance between the points has only a slight effect on their correlation, rendering geographically weighted regression unnecessary (Chen et al., 2020). We assessed the spatial correlation of the UWCPs with population density and water network density using the Moran’s I index.

3.4. Water consumption sensitivity mapping

As part of the research methodology, the sensitivity and water demand map were produced based on the GIS multi-criteria decision-making model.
analysis (MCDA). The MCDA is an approach as well as a set of techniques that can provide an overall ordering of alternatives from the most preferred option to the least preferred one (Abedi Gheslaghi et al., 2020; Chowdhury and Rahman, 2008). An integrated GIS-based MCDA is a powerful methodology for spatial modeling (Abedi Gheslaghi and Feizizadeh, 2021; Feizizadeh and Blaschke, 2013; Yusianto and Hardjomidjojo, 2020). GIS-MCDA is the most popular technique used by experts in the context of spatial decision-making in environmental planning, including for water resource management and sustainable planning and development (Chen et al., 2007). In recent years, several MCDA studies have been carried out to provide answers to decision-making problems in the field of water consumption management with the aim of moving towards sustainable development (Lan et al., 2020; Javed and Sajid, 2020).

In this research, GIS-MCDA was employed to develop a water consumption sensitivity and demand map. Therefore, water consumption indicators were identified based on previous research (Abu-Bakar et al., 2021; Feizizadeh et al., 2020, 2021; Ghorbanzadeh et al., 2019; Lan et al., 2020). In this context, the residential density and different categories of urban land use (e.g., the residential area, trade center, official, hospitals and health centers, other service centers, educational, military, and industrial) were selected as the casual urban water consumption indicators. The initial data related to these indicators were collected from the associated organizations and developed as a GIS dataset after applying the required geometric and editing corrections. The standardization technique was also employed to prepare all data at the same scale suitable for criteria weighting and aggregation. Since several criteria were used to achieve the study objective, an integrated fuzzy
A system and analytical network process (FANP) approach was applied to derive the criteria weights. The weightings of the selected indicators were obtained based on the integrated approach of fuzzy and ANP, which is the most efficient criteria weighting approach approved by previous research (Abedi Gheshlaghi et al., 2021; Ebrahimy et al., 2020; Ghorbanzadeh et al., 2018; Mohamadzadeh et al., 2020; Omarzadeh et al., 2021; Pourmoradian et al., 2021). The integrated approach of FANP allows evaluating the internal weight of each indicator. Aside from the fuzzification of the layer, the FANP contributes to the overlay of data with various characteristics. In the FANP approach, the pairwise comparison technique can be employed for criteria ranking and computing the respective criteria weights. Table 2 shows the mathematical background and computation of the ANP method. This approach is performed using the initial criteria ranking by experts using a scale of 1–9, whereby 1 represents an equal importance, 2–4 indicate a weak significance, 5–6 express moderate significance, and 7–9 indicate a high and extreme significance of the indicators. In our research, the selected water consumption indicators were ranked by 30 experts from the WWC-EAP, the Municipality of Tabriz, the Department of Water Resources and Urban Planning, and researchers from the Department of Remote Sensing and GIS (TGIS) at the University of Tabriz. Table 3 shows the FANP's super matrix for the criteria weighting computed using the Super Decision software. The ANP’s developer suggests using the consistency ratio (CR) to evaluate the reliability of the computed weights (Saaty, 2008). According to the rules of the ANP method, in the pairwise comparison stage, the comparisons must be logical and consistent with the nature of the criteria (Malczewski and Rinner, 2015). The optimum CR value, which expresses the reliability

![Fig. 4. Non-domestic water consumption in Tabriz; a) winter 2018, b) winter 2019, c) winter 2020, d) spring 2018, e) spring 2019, f) spring 2020, g) summer 2018, h) summer 2019, i) summer 2020, j) autumn 2018, k) autumn 2019 and l) autumn 2020.](image-url)
of the computed weights through ANP’s super matrix, is supposed to be less than 0.01. Table 3 shows the equations and their components used to compute the ANP method and the CR value. In this research, the obtained CR value was 0.078, which indicates a good reliability of outcomes and criteria weights. The weights obtained by this method were exported to ArcGIS to apply the GIS-based aggregation functions. All indicators were compiled in a GIS spatial dataset (see Fig. 6) and aggregated in the GIS environment based on the computed FANP’s weights (see Table 3). The Water Consumption Sensitivity Map (WCSM) was produced through the GIS aggression capability using equation number 6 as follows:

$$WCSM = \sum_{j=1}^{n} W_j x_{ij}$$

(6)

Table 2
The analytical network process equations.

| Raw Equation | Description | Components |
|--------------|-------------|------------|
| 1 \[ CI = \frac{\lambda_{\text{max}} - 1}{\frac{1}{n} - 1} \] | coefficient Index | CI: compatibility index, \[\lambda_{\text{max}}\]: maximum eigenvalue of the judgment matrix |
| 2 \[ CR = \frac{CI}{RI} \] | compatibility rate | CR: consistency ratio, CI: compatibility index, RI: random index |
| 3 \[ AW = \frac{A}{\lambda_{\text{max}} W} \] | eigenvector matrix | A: pairwise comparison matrix, W: eigenvector, \[\lambda_{\text{max}}\]: maximum eigenvalue of the judgment matrix |
| 4 \[ W_j^{\text{lim}} = \left( \frac{1}{K} \right)^{-1} \] | limit super matrix | W: weighted super matrix, K: exponent determined by iteration |

Fig. 5. Spatial relationship between water consumption and the used indicators, a) residential areas, b) population density, c) non-domestic water consumption, d) domestic water consumption and e) incidents in water network.
### Table 3
The FANP matrix for criteria ranking and computed weights.

| Causal indicators                      | Official center | Industrial area | Hospitals and health centers | Trade center | Service area (incidents) | Population density | Educational centers | Military sites | Residential area | Service based centers | FANP weights |
|----------------------------------------|----------------|----------------|-----------------------------|--------------|--------------------------|--------------------|---------------------|----------------|------------------|----------------------|--------------|
| Official centers                       | 0.006          | 0.006          | 0.006                       | 0.006        | 0.006                    | 0.006              | 0.006              | 0.006         | 0.006            | 0.006                | 0.068        |
| Industrial area                        | 0.053          | 0.053          | 0.053                       | 0.053        | 0.053                    | 0.053              | 0.053              | 0.053         | 0.053            | 0.053                | 0.148        |
| Hospitals and health centers           | 0.043          | 0.043          | 0.043                       | 0.043        | 0.043                    | 0.043              | 0.043              | 0.043         | 0.043            | 0.043                | 0.109        |
| Trade center                           | 0.032          | 0.032          | 0.032                       | 0.032        | 0.032                    | 0.032              | 0.032              | 0.032         | 0.032            | 0.032                | 0.069        |
| Service area (incidents)               | 0.0435         | 0.0435         | 0.0435                      | 0.0435       | 0.0435                   | 0.0435             | 0.0435             | 0.0435        | 0.0435           | 0.0435               | 0.068        |
| Population density                     | 0.045          | 0.045          | 0.045                       | 0.045        | 0.045                    | 0.045              | 0.045              | 0.045         | 0.045            | 0.045                | 0.135        |
| Educational center                     | 0.04           | 0.04           | 0.04                        | 0.04         | 0.04                     | 0.04               | 0.04               | 0.04          | 0.04             | 0.04                 | 0.085        |
| Military sites                          | 0.021          | 0.021          | 0.021                       | 0.021        | 0.021                    | 0.021              | 0.021              | 0.021         | 0.021            | 0.021                | 0.05         |
| Residential area                       | 0.072          | 0.072          | 0.072                       | 0.072        | 0.072                    | 0.072              | 0.072              | 0.072         | 0.072            | 0.072                | 0.159        |
| Service based centers                  | 0.037          | 0.037          | 0.037                       | 0.037        | 0.037                    | 0.037              | 0.037              | 0.037         | 0.037            | 0.037                | 0.067        |

**Fig. 6.** Causal indicators for water sensitivity mapping, namely: a) industrial area, b) trade center, c) official centers, d) hospitals and health centers, e) educational, f) service-based centers, g) military, h) residential areas, i) population density, j) handling service area.

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where, for cell i, \( w_i \) is the relative importance weight of criteria j, \( x_{ij} \) is the standardized score of cells i for criteria j, and n is the total number of criteria (Malczewski, 2000; Tercan et al., 2021).

3.5. Spatiotemporal mapping of urban water leakage

The urban water losses due to water leakages might exert significant pressure on the freshwater distribution networks. Water leakages are a serious issue for the functionality of water utilities. In most cases, leakages cause an additional burden on the operation of water utilities and contribute to other issues, such as service disruption and the loss of energy and other natural resources (Adedeji et al., 2017). According to some estimates, about 7% of the original volume of water is wasted in some regions due to water leakages in the network. This is, however, the estimate for water network systems that are relatively well-designed and well-maintained. According to some estimates, in developing countries, where there is limited maintenance, water leakages in the water pipeline network can result in water loss of up to 50%, which has significant implications for sustainable water resource management and may also have implications for energy resources considering the water-energy nexus (Adedeji et al., 2017; González-Gómez et al., 2012). The cause of leakage from pipes in the water distribution networks can be attributed to one of two major types, namely the burst type and the context type leakages. The former is marked by a sudden decrease in pressure and can be easily identified by computing instruments (e.g., pressure sensors) that can be stationed along the water pipelines in specific locations (Adedeji et al., 2017). Generally, high volumes of water leakage increase the supply costs for water utility companies, primarily due to the additional resources required for water extraction and treatment. The risk of pollutant infiltration into the water network can also be increased through leaks if the pressure in the distribution network is low, as contaminants can infiltrate through the fractures. Additionally, water loss in the distribution network may result in supply cuts or water pressure change that will affect service provision efficiency and efficacy. Thus, reducing the water leakages is one of the main objectives of urban water resource management (González-Gómez et al., 2011).

In this research, the annual report of water losses and leakages for the years 2018 to 2020 were obtained from the WWC-EAP. Since the exact locations of the leakages were recorded by GPS, the GIS-based point pattern analysis was applied to determine the geographical density of water losses and leakages in the water distribution networks of the city. The main objective for analyzing the spatiotemporal pattern of water leakages in this research was to highlight and indicate the large scale of water leakage in Tabriz and communicate its significance to decision makers and authorities. Due to the considerable amount of water leakages in Tabriz over the past years, it is recognized that optimized management of urban water infrastructure can be an efficient solution for water sacristy risk management.

3.6. CA-Markov model

The CA-Markov model is an integrated approach of the Markov and the Cellular Automata methods and an efficient technique for prediction and forecasting tasks in GIScience (Naboureh et al., 2017). The Markov technique is used to produce a matrix of transition probability from two basic maps obtained for different timelines (e.g., annual UWCPS). The matrix of transition probability is used to compute a probability degree in each pixel in a map’s class that will accordingly be converted to another class or preserve the same class (Feizizadeh, 2018). The Markov chain, as a separate random method, uses the transition probability to predict the next state and all subsequent states based on the current state (Naboureh et al., 2017). Technically speaking, it is an efficient technique for forecasting environmental and geographical characteristics, except for some of the after-effect events. In this research, the annual water consumption maps of 2018, 2019 and 2020 are equivalent to a state of the Markov process for predicting the water consumption maps for 2021, 2022 and 2023 using the ratio of the state transition probability. The following equation represents the Markov implementation (Naboureh et al., 2017):

\[
Z_{(i+1)} = Z_{(j)} \times Q
\]

where \( Z(1) \) = water consumption map in year 1, \( Z(1 + 1) \) = water consumption map in year 1 + 1, \( Q \) = state transition matrix, and \( Z \) can be described as the following matrix:

\[
Z = [Z1, Z2, Z3]
\]

According to the cellular automata model, discrete cellular, finite state, neighbor, and rules are the four aspects of a typical CA model. The next state cell is determined by the current state and its surroundings, according to a transformation function (Naboureh et al., 2017). The annual water consumption maps for 2021, 2022 and 2023 were developed based on the CA-Markov using the water consumption maps of the years 2018, 2019 and 2020.

3.7. Spatial uncertainty analysis

In GIS-based spatial modeling, different spatial data from various sources are integrated into a model based on the research objective. Due to a number of factors impacting GIS-based spatial modeling (e.g., data quality, expert knowledge, criteria weights and etc.), uncertainty becomes inevitable (Feizizadeh and Blaschke, 2013). The uncertainty may have significant impacts on the results and lead to inaccurate and undesirable consequences (Feizizadeh and Kienberger, 2017; Feizizadeh et al., 2014). Thus, applying uncertainty analysis allows us to determine the accuracy of GIS-based modeling. In the context of GIS-based spatial uncertainty analysis, the Dempster Shafer Theory (DST) is one of the most effective methods for determining the spatial accuracy of a GIS model (Feizizadeh, 2018). This technique was originally based on the work of Dempster on the generalization of the Bayesian principle and was later formalized by Shafer (Feizizadeh, 2018). The aggregation of these two methods provides a mathematical basis for explaining models based on incomplete information. In probabilistic models and hypothesis testing, the DST offers additional flexibility for the specification of uncertainty. In artificial intelligence and expert systems, the use of DST has mostly concentrated on unclear reasoning. The DST of evidence is based on rough reasoning where evidence and plausibility poses the ambiguity of the interpretation (Naboureh et al., 2017). In this research, we applied DST to examine the uncertainty of CA-Markov for the predicted water consumption maps for 2021, 2022 and 2023. Therefore, the belief function in Idrisi software was used to
examine the uncertainty of the results based on the annual water consumption of 120 customers that were selected randomly.

4. Results

The results of this research are presented below along with the research objectives. Figs. 7 and 8 depict the aggregated water consumption maps for the years 2018, 2019 and 2020 for both the domestic- (Fig. 7) and non-domestic categories (Fig. 8). Fig. 9 also shows the total water consumption pattern for both the domestic- and non-domestic categories for 2018 to 2020. Our results indicate that the domestic water consumption in Tabriz has increased significantly due to COVID-19, which implies additional pressure on the already strained freshwater resources in Tabriz. However, for the non-domestic sector, the water consumption has been decreasing due to the restriction of activities to help control the spread of COVID-19. Our results show that the total volume of water consumed by the non-domestic sector was 12,220,509 m$^3$ in 2018, 11,274,545 m$^3$ in 2019, and 10,080,029 m$^3$ in 2020. The decrease in the non-domestic water consumption is a result of the lockdown measures, which included the closure of commercial and industrial businesses. By contrast, the increase in the domestic sector’s water consumption can be attributed to the additional water use required to follow the sanitation and hygiene measures recommended to slow the spread of COVID-19. The urban water consumption patterns (UWCPs) also highlight areas of water consumption hotspots, which are closely correlated with population density and urban land use. Analyzing the detailed spatial correlation of the UWCPs with the indicators that affect water consumption was one of the main objectives of this research. Thus, we determined the spatial correlation of the UWCPs based on Moran’s I index and the results are shown in Fig. 10.

As indicated in the methodology section, we also developed a water consumption sensitivity map to represent the spatially explicit freshwater demand in Tabriz. This map was produced by weighting the relevant indicators through FANP. Fig. 11 shows the results of the water consumption sensitivity map in the form of the spatial water demand pattern in Tabriz. According to this map, the central, mostly residential areas of the city are the main water consumption hotspots in Tabriz. The central areas are highly populated and basically cantina the urban worn-out texture. Thus, as the water distribution networks in these areas have aged, the water losses have become very high. Fig. 12 depicts the spatial distribution of the annual reports of water loss in the water distribution network. As this figure shows, there is a positive correlation between water losses and UWCPs hotspots.

Fig. 13 shows the predicted water consumption maps based on CA-Markov. These maps were produced based on the annual water consumption in the years 2018, 2019 and 2020 to predict the annual water consumption for the years 2021, 2022 and 2022. A DST-based spatial uncertainty analysis was carried out to test the reliability of the predicted maps. The results are shown in Fig. 14. The results of the DST method indicated that the three computed maps have a spatial accuracy of 93%, which is quite significant.

5. Discussion

The primary objective of this research was to carry out a spatiotemporal analysis of the urban water consumption patterns (UWCPs) from 2018 to 2020 in order to evaluate the impacts of COVID-19 on the urban water consumption in Tabriz. Since water is important for cleaning and frequent washing (e.g., washing hands, clothes and surfaces), the increase in its consumption due to the prevalence of COVID-19 is not
Fig. 8. Spatial distribution of the annual water consumption for non-domestic use in a) 2018, b) 2019, and c) 2020.

Fig. 9. Spatial distribution of the annual water consumption for both domestic non-domestic use in a) 2018, b) 2019, and c) 2020.
surprising. Our results have revealed that, in addition to incidents in the urban water supply network (e.g., water leakages or other disruptions) and rapid population increase, unexpected events such as the prevalence of COVID-19 can also affect water consumption. Therefore, a dynamic technique that can identify and display how unforeseen phenomena (instance, e.g., COVID-19) may affect the operational capacity of the water supply and distribution networks could be used to improve water resource management.

In our integrated approach, we applied GIS spatial analysis, Moran’s I index, MCDA, FNAP, CA-Markov and DST methods to obtain the results, which revealed that the outbreak of COVID-19 led to an increase in the domestic water consumption. To better illustrate the results, a regression based on Moran’s I index was applied to show the spatial relationship between the criteria and the final map showing the water consumption in different areas of Tabriz. The evaluation of the spatial correlation between the water consumption and the assessed criteria indicated that the water consumption is significantly correlated with the indicators affecting water consumption (correlation values ranging between 0.6 and 0.91). The domestic water consumption in 2020, with a correlation of 0.91, has the most significant correlation with the UWCPs hotspots. This indicates a clear link between COVID-19 and associated social distancing policies and the increase in domestic urban water consumption. Other criteria applied in the research also had a relatively high spatial correlation with the water consumption in 2018, 2019, and 2020 (Fig. 11). Results also indicated a spatial relationship between water consumption and the different seasons. Based on the results, the UWCPs can be influenced by the urban water supply network, demographic characteristics, and land use type categories as well.

The global average daily water consumption of about 150 l per person is estimated to have increased to 250 l since the outbreak of COVID-19 (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021). According to our results, the maximum increase in water consumption was observed in the spring of 2020 (April–June) when the domestic water consumption level was about 2634.265 m³ (17.57%) more than during the same period in 2019. Since the normal annual increase, for example between 2018 and 2019, is 9.21%, this stark increase between 2019 and 2020 can be attributed to the impact of COVID-19. The Iranian Ministry of Health and Medical Education (MOHME) implemented policies to help minimize the spread of COVID-19, including several lockdown policies and extensive home quarantine measures, which were applied from April to July 2020, and led to a significant increase in the urban water consumption. As a consequence of COVID-19, Tabriz experienced a serious water scarcity crisis in the summer of 2020, forcing the city authorities to implement water rationing measures during the summer. The average annual water deficit in 2018 and 2019 was about 18%, in 2020 it reached 30%, and it is expected to reach 40–45% in 2021 due to the impact of COVID-19 (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021). Despite the limited water resources, the CA-Markov simulation predicts a considerable increase in UWCPs for 2021, 2022, and 2023 (Fig. 13). Since the result of the spatial uncertainty...
analysis for these forecasts is relatively high (0.93 out of 1), it is expected that the city will experience an even more critical water crisis in the coming years.

Table 4 shows the list of the water sources and their contribution to the urban water supply. The Zarineh Rood Dam is the major water source with a contribution of 45–50% of the urban water supply of Tabriz. The water from this dam is pumped from Bokan city along a 177 km water transfer pipeline to supply 30,000,000 to 45,000,000 m$^3$ of freshwater to Tabriz each year. Zarineh Rood Dam is one of the major reservoirs feeding Urmia Lake, which has been drying up since 2010 (Mardi et al., 2018). Thus, increased water extraction from this dam may further exacerbate environmental issues in the future. About 40–55% of the freshwater in Tabriz is supplied from groundwater accessed through 86 wells and 13 Qantas around the city. However, recent climate-induced droughts have depleted the groundwater resources significantly, and various natural hazards, including land subsidence, have been observed in the western plains of Urmia Lake, such as in Tasouj, Shabster, Marand, Tabriz, Azarshard, Osku and Bonab (Ebrahimy et al., 2020; Nadiri et al., 2020). The third freshwater source is the Nahand Dam, which provides 15–20% of the required water in Tabriz. This dam has a very limited capacity of about 21,000,000 m$^3$ while its annual supply to Tabriz is about 12,000,000 to15,000,000 m$^3$. Geographically, this dam is in the upper area of the salty lands around Khajeh, and the water quality has been impacted by the formation of salt hills and slopes around the dam. Some of these salt hills and slopes are also covered by the dam lake, resulting in freshwater salinization.

Water scarcity is a tangible issue in Tabriz city and is acknowledged by authorities and decision makers, particularly by those in the WWC-EAP, which is the major organization in charge of water resource management. According to the recent annual report of the WWC-EAP (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021), the water crisis continues to be a serious challenge, and water consumption reduction policies and renewable resources (e.g., water pumping from the Aras River) should be considered due to the limitation of the current resources. Several related policies have also been proposed, which include a) stormwater management and greywater recycling, b) water-sensitive urban forestry and urban agriculture to minimize water demand for non-residential purposes, c) enhancing efficiency of water infrastructure to minimize water loss, and d) raising citizen awareness to promote water-sensitive behavior (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021).

Fig. 15 shows the enlarged hotspots of the annual urban water consumptions maps and their respective population density, land use, water demand, and predicted UWCPs using the CA-Markov model. As can be clearly seen in this figure, the central part of Tabriz is highly populated and has been the primary water consumption hotspot in 2018,
From an urban planning perspective, it is important to consider that this large hotspot overlaps with the historical center of Tabriz where buildings are often of poor structural quality, and the population mainly follows a traditional lifestyle. Due to the limited network maintenance, water loss through pipeline leakage is also common in this area. As indicated in Figs. 11 and 15, significant volumes of annual water leakage have been reported in this part of the city. However, the number of water leakage occurrences have increased significantly in 2020. According to the annual report of the WWC-EAP (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021), the amount of water loss due to leakage was 17.02% of the total water supply in 2018, 17.8% in 2019, and a record high of 18.2% in 2020. This clearly indicates the lack of efficient water resource management in Tabriz, which is significantly contributing to the serious water crisis in the city.

This research proposed a novel and efficient methodology that can be applied in future urban water studies ([Lawrence, 2013]; Li et al., 2019; (Abu-Bakar et al., 2021; Di Mauro et al., 2021; Feizizadeh et al., 2021)). Numerous studies have been conducted in the field of urban water resource management that have demonstrated the importance of efficient management of water resources and methods needed to deal with water stress. In some studies, based on spatial methods, various parameters were applied to identify water consumption patterns. For instance, in a recent study, Abu-Bakar et al. (Abu-Bakar et al., 2021) conducted an analysis using the demand-side management strategy to determine water consumption patterns. This study examined various factors affecting household water consumption such as the use of metering tools, age of people, level of education, water price, etc. They found that the most important measure was the amount of water consumed by the household. They also concluded that the advent of smart meters has revolutionized the collection of data in the domestic water sector, which can facilitate enhanced measurement of water consumption patterns to identify high-consumption areas. However, as COVID-19 contributes to the global water scarcity, it is expected that the outcome of this research will provide new insights into the water crisis management that can be employed for future related studies. Therefore, in addition to considering various factors in distinguishing water consumption patterns, this study has also determined the effect of disease outbreaks on changes in UWCPs in Tabriz.

Our results prove that a GIS-based spatial analysis is an efficient approach to overcome issues associated with unstructured and heterogeneous spatial data such as UWCPs. In fact, in urban water supply systems, there are several complexities, such as differences in land use, number of households, morphological land characteristics that can influence water transfer processes, and time differences in water demand. These complexities can make it very difficult to manage water resources in different situations (such as during the COVID-19 pandemic, which has increased water consumption). To deal with these complexities, it is suggested to use decision-making techniques that can consider different criteria and consider temporal and spatial differences simultaneously. Thus, an integrated approach of GIS and spatial analysis (e.g., the proposed methodological scheme in the current research) shall enable the development of a spatial model of the UWCPs and allow the prediction of future water demand in urban environments (Feizizadeh et al., 2021). The methods used in this research included GIS techniques and spatial and temporal correlation analysis.
Fig. 13. Results of using CA-Markov to predict the water consumption for 2021 (a), 2022 (b), and 2023 (c).

Fig. 14. Results of using DST to analyze the spatial uncertainty of the predicted UWCPs using CA-Markov, a) 2018; b) 2019 and c) 2020.
between changes in UWCPs in different areas and times. Currently, systematic approaches for urban water consumption trend modeling are rare, and the proposed methodology may help future researchers in the domain of urban water studies to apply efficient methods and obtain more accurate results.

6. Conclusion and future research

Water scarcity has always been a serious challenge in Tabriz and has become even more severe because of the COVID-19 pandemic. In this research, we investigated the impacts of the pandemic on the urban water consumption in Tabriz. Accordingly, geolocated data related to household water consumption were collected. These data were used to prepare maps of water consumption and understand patterns of water consumption in different areas of the city. Results showed that consumption levels have increased significantly in 2020 compared to the previous two years (before the COVID-19 outbreak). We used GIS in combination with multi-criteria decision systems to analyze the water resources of a complex urban environment. The results showed that water consumption is directly related to land use, the population density, and the prevalence of leakage incidents in the water distribution network. An increase in water consumption without proper management and control of the water resources can lead to serious problems in densely populated cities. Problems could include groundwater depletion and associated risks such as land subsidence, or induced pressure on energy systems considering the water-energy nexus. It is thus essential to comprehensively monitor the status of the water resources supplying such cities and develop appropriate plans and strategies towards sustainable water resource management. In this context our future research will focus on water scarcity mapping and assessment in Tabriz city based on the UWCPs obtained from this research.

| Water resources | Number | Contribution % | Estimated capacity m³ |
|-----------------|--------|----------------|-----------------------|
| Nahand Dam      | 15-20  | 21,600,000     |                       |
| Zarineh Rood Dam| 45-50  | 800,000,000    |                       |
| Wells           | 86     | 56,000,000     |                       |
| Qantas          | 13     | 120,000,000    |                       |

Table 4: List of water sources (WWC-EAP: water and waste water company of East Azerbaijan Province, 2021).

Fig. 15. Enlarged water consumption hotspot map and its characteristics, namely: a) Population density, b) Urban land use, c) Computed water demand, d) Predicted water consumption for the 2021, e) Predicted water consumption for 2022, f) Predicted water consumption for the 2023, g) Water losses and lakes for 2018, h) Water losses and lakes for 2019, and i) Water losses and lakes for 2020.
study. A scenario-based water scarcity mapping for sustainable development will be also considered as part of our future research. This will include examining impacts of different climate- and population-change scenarios on water scarcity patterns in Tabriz.

The combined effects of water scarcity, urban population growth and the expansion of water-intensive economic activities are the main reason for the water crisis in Tabriz and similar cities. We demonstrated that disruptive events such as pandemics can further exacerbate the water crisis issue. Therefore, comprehensive and systemic approaches that consider multiple compounding effects should be used. In this regard, applying integrated approaches to identify spatial characteristics of the UWPs, especially in large cities, could provide critical information for better water resources management. In this regard, this research makes use of an integrated GIS-based spatiotemporal analysis for evaluating the trends of the UWPs as well as forecasting future patterns of water demand. Based on the results, we conclude that to improve future methods for identifying patterns of water consumption in urban environments, use of more accurate data and assessment of environmental features and unexpected events should be considered by researchers. In addition, the use of new integrated methods in combination with GIS can provide a visual representation that can aid in understanding and identifying water consumption patterns and improve resource management. We conclude that this approach is an efficient and effective GIS-based framework that can support future research in urban water consumption trend assessment and pattern analysis as well as water demand mapping and reliability assessment.

Considering the importance of water to human life and its significant role in economic growth, extensive research is required for UWPs monitoring, demand analysis, and clarifying the consequences of reducing water loss in urban environments. From the environmental perspective, the proposed approach can be applied for urban water consumption mapping and spatiotemporal analysis at any scale worldwide. We argue that the outcomes of this investigation can be utilized by planners and decision makers in their efforts towards sustainable water resource management. A major finding was that inefficient water infrastructure and consumption patterns can have regional environmental impacts and contribute to ecosystem degradation, land subsidence, and freshwater salination. In the absence of sustainable water resource management strategies, future climate changes may further intensify such impacts. In addition to highlighting potential areas of water loss, the findings can be used to identify the areas with the highest levels of water consumption and design targeted plans and policies for reducing their consumption levels. Furthermore, since COVID-19 is a global challenge with significant impacts on the economy, quality of life, and water consumption, the proposed methodology can be applied to other parts of the world to enable authorities to take more evidence-based response actions now and in the post-COVID era.

CRediT authorship contribution statement

**Bahktiar Feizizadeh:** is the main author who has developed the paper and wrote the all sections. He also developed a methodology and he will be acting as sole author.

**Davoud Omarzadeh:** he has contributed for data gathering and implementation of the research methodology.

**Zahra Ronagh:** she has essentially contributed for data gathering and validation of research results. She also wrote some sections of the study area.

**Ayyoob Sharifi:** he contributed for improving the paper’s results, justifications and also theoretical background of the paper.

**Thoms Blaschke:** he has acted as supervisor and contributed for improving the statements, methodology, results and discussions. He also improved the English of the paper.

**Tobia Lakes:** she contributed as supervisor and improved the discussion, research outcome and its collaboration as stat of art.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported entitled:

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