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A GIS assisted system for monitoring illicit drug use in wastewater

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ABSTRACT

This study proposes an approach integrating current methodology, which determines the amount of drug consumed per month/day per 1,000 inhabitants by measuring concentrations of illicit drugs and their metabolites in untreated wastewater, with geographic information system (GIS) designed for this specific purpose. The proposed approach contributes to existing studies by the use of multi-criteria decision-making (MCDM) technique which enables the user to make spatial decisions based on analyzing the effecting parameters of illicit drug use. Usability of GIS technology for monitoring illicit drug consumption was showed in this study by applying the proposed methodology in a pilot study area. MCDM of the model established in the case study included four parameters: building use-cases, age, gender and population living in the study area. Weights of the stated parameters have been estimated using the analytic hierarchy process technique. As a result of the study, the proposed methodology produced a thematic map that classifies the monitoring area according to the potential for illicit drug use. Initial results of the proposed system produced by using sample data of a district in Istanbul were presented in this paper. Also, the challenges that may be encountered in the comprehensive applications of the proposed system was discussed in this study.

Keywords: Illicit drugs; Wastewater; GIS; MCDM; AHP

1. Introduction

An estimated 5% of the global adult population or quarter of a billion people, used drugs at least once in 2015. Even more troubling is the reality that 0.6 percent of the global adult population, or about 29.5 million of those who used drugs, suffer from drug use trouble where their drug use is harmful to the level that they may need treatment for their drug dependence [1]. It has been found that 17 million daily life years attributed to drug use disorders, 10 million years of life lost as a result of disability caused by drug use, and about 18 million years of life lost as a result of premature death caused by drug use [1].

Economic and social costs underlying drug dependence and use take a main part in the current hot debate on drug policy in many countries. For decades, economists and policymakers have been tracking the drug use and researching the inclusive response to this use but the solution is far

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from being workable [2]. Awareness is limited relating to sources, distribution, environmental attitude, and destiny of illicit drugs [3]. Evaluation of the range of the production, distribution, and consumption of illicit drugs differ extremely and are mainly conditional to the methodology trend of the viewer.

The target of a local illicit drug consumption analysis primarily shows local decision-makers and actors the current situation of drug addiction in the municipality. This lights the extent and implicit reasons for the drug-related issues and reveals what precautionary procedures the municipality is already taking. The analysis sets a foundation not only for decision-makers but also for planning, evaluating and monitoring prevention. In this context, monitoring and analysis go together by systematic analysis; the prevention being implemented can monitor and can see how problems, causes, and measures improve the connection to one another. Monitoring gives a base for decisions regarding the layout of related activities and keeps the issue at the primacy in the municipality. Analyses and monitoring data can then be used in the evaluation, which consecutively provides invaluable information for future monitoring activities [4].

The use of illicit drugs cannot be ignored in Turkey as well. Since a remarkable increase in illicit drug consumption was reported in the last decade, it is necessary to define the patterns of these usages. Additionally, evidence-based determination of consumption is also important to protect consumers by increasing the awareness of the people for minimizing the use of illicit drugs [5,6]. However, it is difficult to make even indirect evaluations for the consumption of illicit drugs because the use of these illicit drugs is hidden and stigmatized. Nonetheless, efforts must be made to estimate the contribution that illicit drug use makes to the global load of diseases and mortality because it is a pattern of behavior that has an essential reverse effect on the health of those who take a part in it [7].

There is always a serious attempt all over the World to monitor and evaluate the consumption of illicit drugs. The primitive methods are generally used mortality rates, population surveys, and seizure data regarding the drug to evaluate the consumption and substance dependence [8]. These methods have been tested in the American Continent particularly in the United States of America, where the data from poison centers, drug-diversion investigators and substance-abuse treatment centers are gathered to analyze the abuse of six prescription opioid analgesics: oxycodone, hydrocodone, hydromorphone, fentanyl, morphine, and tramadol [8]. In Europe, this method has also been used in different countries depending on the population surveys, police and custom's seizures, drug-overdose deaths, hospital admissions or treatment programs to track the use of different types of illicit drugs. However, there are some main limitations of these time consuming indirect methods such as the shortage of investigation systems and inaccurate results. These methods cause a delay in public authorities' reaction since the outcomes are commonly published a year after data collection [9].

Estimating the consumption of illicit drugs in the sewage network medium is an alternative method observed in Europe, America, and Asia. Hypothesized by Daughton [10], a new approach to estimate mass drug consumption, established on measuring concentrations of illicit drugs and their metabolites in untreated wastewater. Later, the methodological approach, named sewage epidemiology, was designed and implemented by Zuccato et al. [11]. Thus, advanced analytical methods for the simultaneous measurement of illicit drugs have been constituted. In this method, human metabolic excretion products resulting from drug consumption are rapidly pooled and collected through the sewage systems, giving a useful indicator of the type and amount of drug consumed by a population [12]. This method has three main stages; sampling is the first one where wastewater samples are collected and the next step is the laboratory analysis for these samples to find the concentrations of illicit drugs [13]. The back-calculation is the final stage; it carries out by multiplying the measured concentration of each compound by the average monthly/daily flow rate to gain the daily mass loads. Mass loads are then divided by the population related to the catchment area to get the amount of the drug consumed per month/day per 1,000 inhabitants [14].

This method has been used widely in different parts around the World to reveal regional variations in illicit drug consumption. In America, the wastewater approach was used to estimate the effect of urbanization on the use of illicit drugs, revealing that the use of illicit drugs was lower in rural areas compared to the urban regions [15]. In Europe, this method has been used to evaluate the consumption of five compounds for one week in 19 European cities [16]. This technique has also been applied in Asia, wastewater analysis used to monitor influence to 9 sewage treatment plants to estimate the use of illicit drugs in four Chinese megacities. The obtained results showed in a quantitative style that the drug use patterns of Chinese are different from their European counterparts [17]. Even though this approach has been used in many studies, the analysis of these studies is restricted to one-week sampling, after all, to reduce the uncertainty, more intense random sampling schemes will be needed. Thus far, this method ignores the important influence of the age, gender, economic and social rates on the consumption of illicit drugs, since its data is considering the consumption of all sections of the population and doesn't consider the other factors [14].

In this study, we are proposing an efficient indirect method to track the illicit drug consumption sources after the consumed amount was determined by applying methodologies presented in the above-stated studies. Geographic information system (GIS)-based multi-criteria decision making analysis (MCDA) is used to consider all the parameters that are potentially related to the consumption of illicit drugs (population, age, gender, and building use cases) is combined, the weight of each parameter is calculated using analytical hierarchical process (AHP) method. Finally, within the GIS environment, a model was built to combine each parameter with its corresponding weight and then overlap all the parameters together to end up with a map showing the potential point sources of illicit drug consumption in the sewage network. While existing methodologies identify the illicit drug use for the whole population using analysis results of samples collected periodically from sewerage and processed in a competent laboratory, differently from those methodologies, the proposed study has the power of characterizing the study area based on related parameters depending on the potential illicit drug use.

2. Background

2.1. Multi-criteria decision analysis

MCDA is an important tool for solving problems that are described as a choice among alternatives. It has all the characteristics of a valuable decision support tool: it helps to concentrate on what is important, consistent, logical, and simple to use. At its essence, MCDA is valuable for making decisions because it divides the problems into more understandable parts, analyzes each part, and integrates the parts to make useful solutions contributing to the final decision to be made. GIS is often known 'as a decision support system involving the integration of spatially referenced data in a problem-solving environment'. GIS procedures and techniques have a significant role to play in analyzing decision problems. Furthermore, MCDA extends a collection of procedures and techniques for designing decision problems, structuring, prioritizing and evaluating alternative decisions. The research on integrating MCDA and GIS is an example of how connecting methods and concepts from two different fields to make spatial decisions on especially environmental problems [18,19]. These two important extents of research, GIS and MCDA can get an advantage from each other. At the most primitive level, GIS-MCDA can be described as a process that combines and transforms geographical data and value judgments to gain information for decision-making [20,21].

2.2. Analytical hierarchical process

The AHP converts the evaluations of the decision-makers to a numerical form that can be compared and processed over the full extent of the problem. In the final step of the operation, numerical weights are calculated for each of the decision alternatives. These numbers show the alternatives' relative ability to achieve the decision goal, so they allow a straight accounting of the different courses of action [22]. AHP is one of the most widely used MCDA methods, which enables to the model of the problem hierarchically concerning the goal, criteria, sub-criteria, and alternatives [23–25]. Whereas the goal, criteria, and alternatives are the fundamental elements of the hierarchy building process; the alternatives in AHP can be thought of as layers in terms of spatial data [26]. Fig. 1 below shows the process flow chart of AHP including selecting the variables to be considered as a parameter affecting the complex decision to be made, setting pairwise comparison matrices and calculating consistency ratio value to determine the weights of each parameter on the final decision.

The scale for pairwise comparison is shown in Table 1. The scaling approach is applied for indicating the impact of the elements in decision-making [22].

Based on the scale definitions presented in Table 1, pairwise comparison matrices are constructed. For instance, if an element *B* has 'a_{12}' as the intensity of importance over an element *A*, *A* automatically takes '$1/a_{12}$' (Table 2). Based on the matrix, the priorities are calculated by adding each row of the matrix and dividing it by their total [22].

The most important aspect of this method is the determination of the consistency of pairwise evaluation. For this purpose, consistency index (CI) is calculated as a measure of inconsistency using Eq. (1). CI is zero when all judgments are perfectly consistent [22].

$$\text{CI} = \frac{(\lambda - n)}{(n-1)} \quad (1)$$

Table 1
Fundamental scale for pairwise comparison

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values
Reciprocals	Values for inverse comparison

Table 2
Pairwise comparison matrix

	A	*B*	*C*	*D*
A	$a_{11} = 1$	a_{12}	a_{13}	a_{1n}
B	$a_{21} = 1/a_{12}$	$a_{22} = 1$	a_{23}	a_{2n}
C	$a_{31} = 1/a_{13}$	$a_{32} = 1/a_{23}$	$a_{33} = 1$	a_{3n}
D	$a_{n1} = 1/a_{1n}$	$a_{n2} = 1/a_{2n}$	$a_{n3} = 1/a_{3n}$	$a_{nn} = 1$

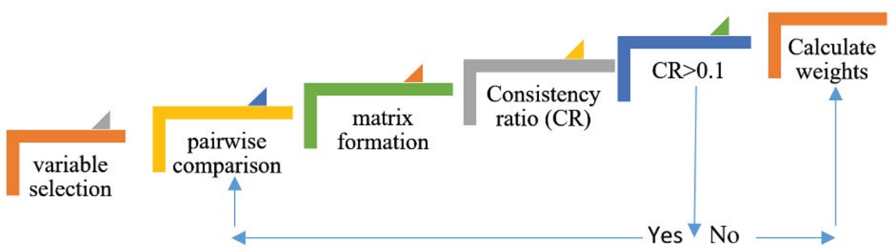

Fig. 1. AHP process flowchart.

where λ is simply the average value of the consistency vector and n is the number of criteria.

The consistency of the process is accepted when the consistency ratio (CR) is smaller than 0.10. CR is calculated using Eq. (2) where RI indicates a random index and is determined based on the number of criteria to be evaluated as presented in Table 3 [27,28].

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

The AHP also allows decision alternatives to be prioritized using pairwise comparison. However, it is not easy for the decision-maker to give certain and consistent estimation even for the comparison matrix and it may impossible to perform a pairwise comparison of the alternatives for problems involving a large number of alternatives represented by means of the raster data. The decision rule for each alternative is given by Eq. (3):

$$A_{\mathrm{AHP}} = \sum_{j}^{n} a_{ij} w_j,\ i = 1,2,3,\ldots,m \tag{3}$$

where a_{ij} is the score of the ith alternative with respect to jth criterion and w_j is the normalized weight of the jth criterion using the pairwise comparison method [27].

In this study, the AHP technique has been used to determine the weights to be applied to each of the four reclassified criteria map layers to generate the final map.

3. Materials and methods

3.1. Study area and data

Istanbul is composed of 14 main wastewater treatment plants and a few wastewater elevation centers due to its large surface area and population. Çatalca, which is a rural district in Istanbul, was selected as the pilot study area for this modeling. The district is located in the north-western part of Istanbul City by the Black Sea. It has a relatively large area of 1,715 km^2 and a low population of 69,000 in 2017 differently from most of the other districts in Istanbul. The wastewater elevation center covers 15,000 inhabitants (22% of the total population) of Çatalca district and it has a quite new sewage system [29].

Population, age, gender, and building use cases as settlement, industrial or café/bar/restaurant, are the main criteria that have been used to generate a map showing the potential consumption sources of illicit drugs. Vector data of the study including sewerage networks and the building with their use cases were provided by Istanbul Water and Sewerage Administration. Census data and demographics were provided by the Turkish Statistical Institute. Additionally, the sampling processes were conducted during seven consecutive days in November 2017 as 24 h composite influent samples with a time-proportional mode. The sampling unit was set to collect 250 mL in each hour. Flow rate data of each collection day and the weather conditions (rainy/sunny) were also recorded [29]. The collected samples in the high-density polyethylene bottles were transferred to the laboratory, where they were stored at −20°C until analysis [30].

Table 3
Random index

n	RI
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

3.2. Methodology

As presented in Fig. 2, this study proposed an integrated system composed of two basic units for sample collection and GIS. The dissemination unit is optional and available for disseminating the results to policy or decision-makers using various services through web-based on the requirements of the installed system. Sample collection and analysis unit processes based on the common methodology applied for monitoring illicit drug consumption in wastewater. The 24 h composite samples collected during 7 d from the treatment plant serving in Çatalca were first analyzed for obtaining concentrations of the target residues. Using flow rate (m^3/d) of the sewerage network, the number of target residues entering the treatment plant (g/d) was calculated and then the amount of a substance consumed by the population living in the area where the treatment plant serves was determined to apply the human metabolism correction factors. Finally, the amount of the substance to a defined population and the amount of the substance as doses/day per 1,000 inhabitants was determined considering population estimates and mean dose information. The detailed information on the processing principles of this unit is available in the previous publications of the authors [29].

The second unit of the system was a GIS application using MCDA and AHP for determining the potential sources of drug consumption obtained as a result of laboratory analysis performed in the first part of the system. The first and one of the most important steps of MCDA was to determine the criteria which have the potential effects on illicit drug use. In this study basically 4 criteria were used for determining the potential sources of the illicit drug consumption based on the opinions of experts working in Istanbul University Cerrahpasa Institute of Forensic Sciences: gender as male (F1) and female (F2), population living in the

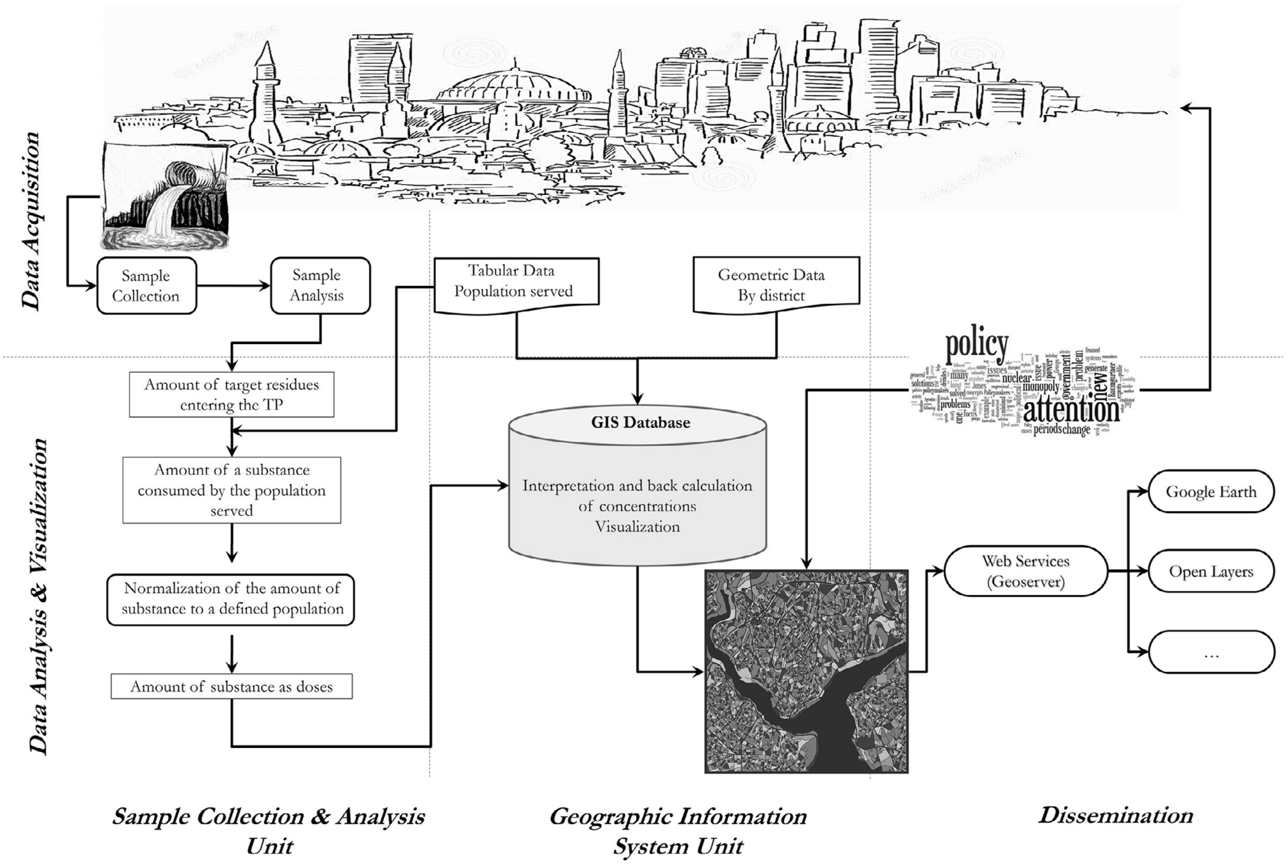

Fig. 2. Study framework.

study area (F3) and building use cases (cafe/bars/restaurants, industrial and settlements) (F4). Gender criterion was also improved by defining a specific age range between 15 and 34 since the highest rates of illicit drug use were reported especially among young males and females aged 15–34 years in Turkey [1]. Building use cases were classified as settlement, industry/business and cafe/bar/restaurant to indicate the effect of the drug use in bars and cafes. After determining the criteria, the methodology presented in Section 2 was applied. In this context, determined criteria were standardized, and weights of each criterion were determined to run the model by considering the individual effect of each criterion on illicit drug consumptions. For this purpose, the AHP model was used. Since the AHP model is a computational model, expert's opinions were also considered to make the proposed model more realistic based on the fundamental characteristics of the phenomenon, geographical, socioeconomic and cultural structure of the study area. Stated methodologies were applied in a GIS environment and as a result, a map highlighting the potential point sources of illicit drug consumption was produced as an output. The success of the model was based on the precise determination of the criteria and exact weighting of the criteria as well as the accuracy of the input data.

The third unit proposed was optionally use final maps to support policy-makers or the results may be disseminated to the end users such as related professionals, policy-makers or public by the use of web services through internet.

4. Results and discussion

Pairwise comparison of four criteria used in the study was performed by identifying them as extreme favors, very strong favors, strongly favors, and equal using intensity importance chart presented by Saaty [23] as presented in Table 1. The comparison matrix was obtained as presented in Table 4 based on the following basic rules:

- If the judgment value is on the left side of one, the actual judgment value was used.
- If the judgment value is on the right side of one, the reciprocal value was used based on the theory presented in Table 2.

After structuring the comparison matrix, each cell value was divided by its column total to normalize the values. To calculate the priority vector or weight, the mean value of the rows was determined, and the normalized values and the calculated weights were presented in Table 5. CI and CR values were calculated as 0.065 and 0.07 respectively as explained in Eq. (1) and Eq. (2). Since the consistency ratio value is less than 0.10 the proposed model parameters were considered as consistent, and they were assigned as acceptable.

ModelBuilder application of ArcGIS 10.x has been used to generate the spatial model for the AHP analysis to calculate, classify, manage and run all the related procedures for the

Table 4
Comparison matrix

	F1	F2	F3	F4
F1	1	3	5	7
F2	1/3	1	3	5
F3	1/5	1/3	1	3
F4	1/7	1/5	1/3	1
Σ	1.7	4.5	9.3	16

Table 5
Normalized matrix and weights

	F1	F2	F3	F4	Weight
F1	0.596	0.661	0.535	0.437	0.56
F2	0.198	0.220	0.321	0.312	0.26
F3	0.119	0.735	0.107	0.187	0.12
F4	0.085	0.044	0.035	0.062	0.06

map layers up to the producing of the final map representing the potential illicit drugs consumption as shown in Fig. 3.

In the built model, each input parameter was defined as spatial data. In this context, the parameters F1 and F2 were vector layers that show the concentration of the male and female population between the ages of 15 and 34 within the study area. These vector layers were converted to raster format and then were reclassified into four classes (1–4) based on the age field. Population vector layer (Parameter F3), which shows the concentration of the total population within the study area was also used as another input and a similar process was also applied to this layer for obtaining the raster data to be used in multi-criteria decision-making model. Finally, land use/building use cases vector layer (parameter F4), which shows the distribution of the land use (whether it is a cafe, restaurant, bar, settlement, industrial, or others) within the study area were processed and reclassified in to four classes (1–4) according to the category field. Raster data obtained as a result of reclassification were presented in Fig. 4 for each input layer.

Reclassified raster fields were used as the input data of weighted overlay analysis and final map data indicating the potential illicit drug uses in the study area were obtained as raster data set. To make this raster output more understandable, it was converted into vector data in point geometry. The final map characterizing the potential consumption sources obtained from the overall evaluation is presented in Fig. 5. In the final map, sources of the drug consumption were presented by their potential as no potential or low, moderate, and high potential. The result was obtained by applying the Jenks Natural Break classification with 4 classes to the resulted map of the model.

The main objective of this study was to demonstrate how GIS-based MCDA can be used for contributing the existing studies on monitoring illicit drug consumption in wastewater. As presented in the study, GIS is useful for characterizing the study area depending on the multiple criteria with various effects on this characterization. This study proves that this function of GIS can be used for the characterization of the study area to determine potential illicit drug consumption sources. However, the final result of this study presented anonymously (without borders of the study are and street or neighborhood names), because the proposed model can only be considered as successful after validation works. As it is stated in the study, the success of the produced model is not only based on the accuracy of the input data but also directly related to the precise determination of the model parameters and their weights. In this study, a sample data set were used for indicating the usability of the model for this specific case. Parameters were determined considering expert opinions working in Forensic Sciences Institute and the published reports. However, opinions of the experts from various related disciplines were not taken into account since the improvement of the model is considered as the future work. Another requirement for ensuring the success of the proposed model is to increase the number of sampling points

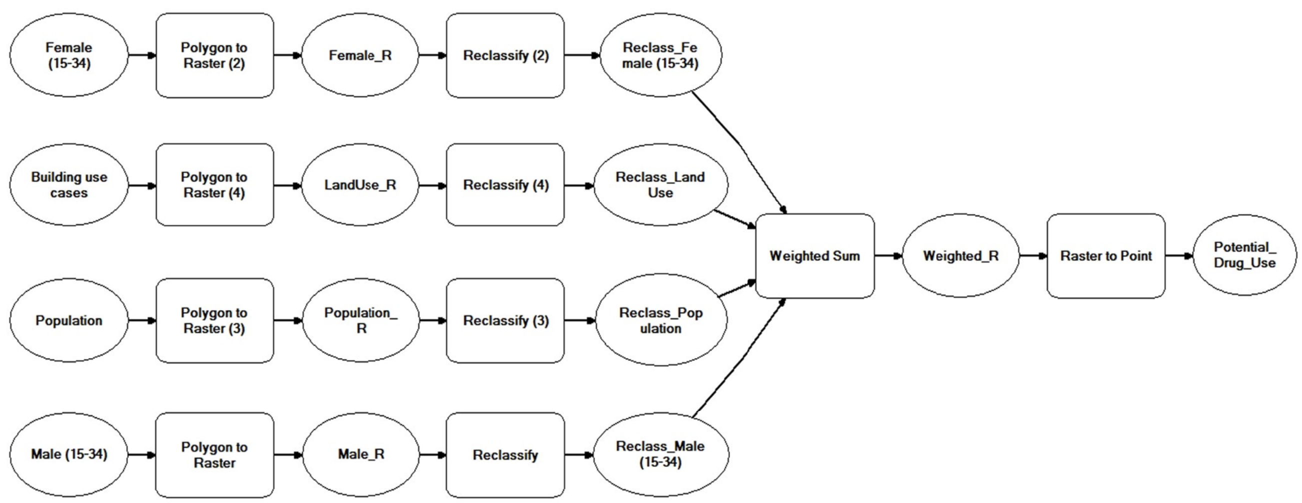

Fig. 3. A spatial model of the proposed methodology.

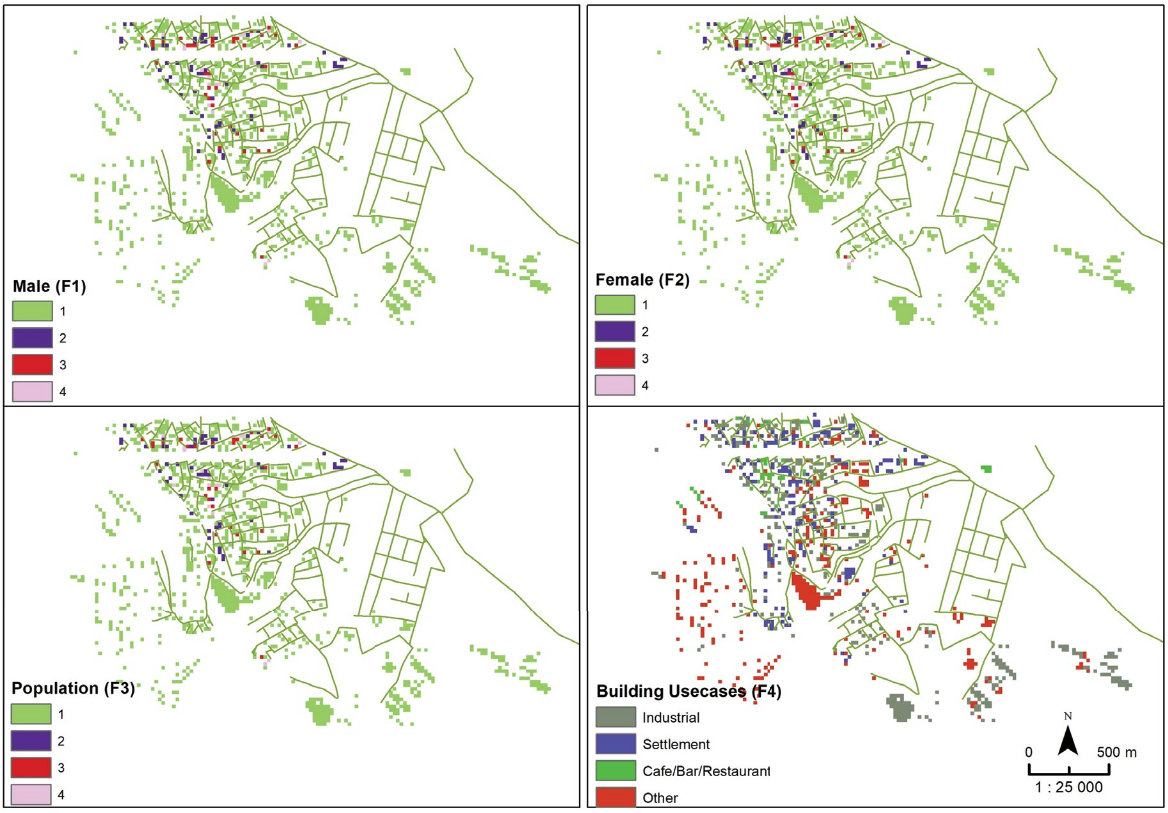

Fig. 4. Reclassified raster maps of input parameters.

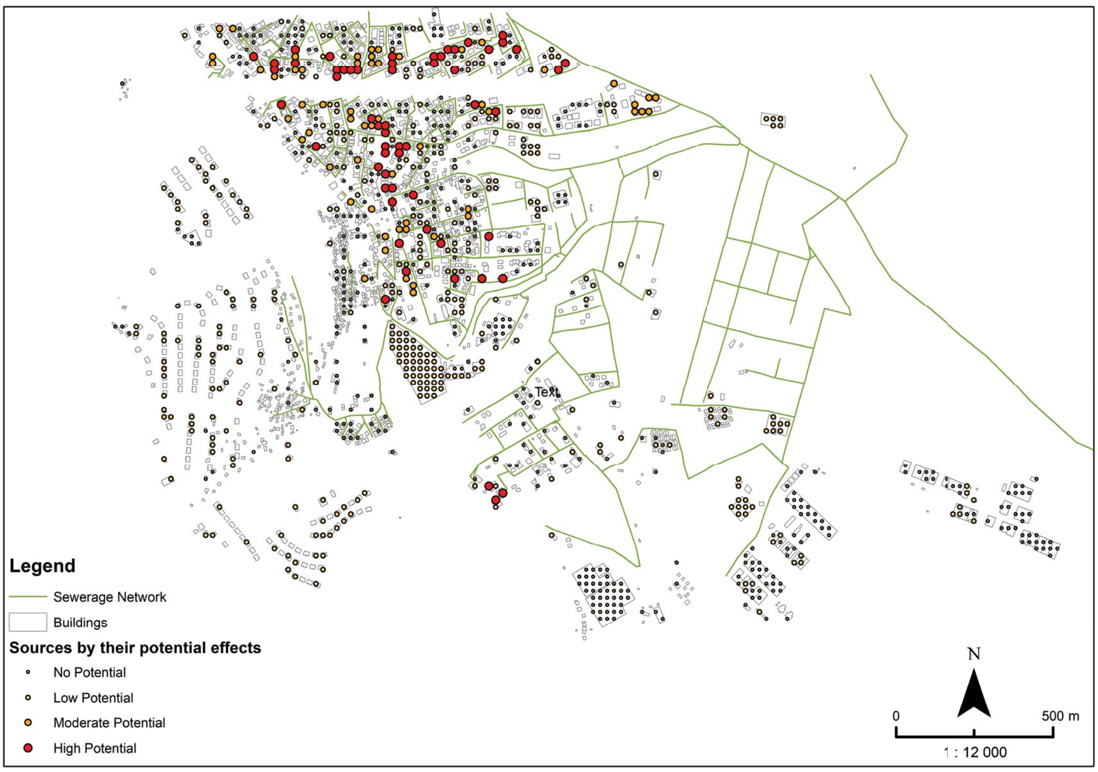

Fig. 5. Potential point sources of the used illicit drug.

within the sewerage network and their locations should be selected carefully to represent the part of sewage network discharging to these points. As a difficult part of this study, samples were only collected at the wastewater elevation center receiving the whole discharge of the study area because of the difficulties in sampling for 7 consecutive days and 24 h in Istanbul conditions even in Çatalca with a new and well-planned sewerage system. In order to increase accuracy and the precision of the proposed model sampling points should be diversified.

5. Conclusion

This study was concluded with a set of future works for developing proposed model to get more precise results by examining more parameters related to the consumption of illicit drugs, analyze their class value ranges, and assign them to our model to gain the best simulation to the point source consumption of illicit drugs with the help of the experts on the field.

Istanbul is composed of 14 main wastewater treatment plants and a few wastewater elevation centers due to its large surface area and population. To profile the whole city, it is necessary to collect samples from all of these facilities simultaneously. Some of the facilities, such as Çatalca, have the new infrastructure, but many others are quite old due to the ancient history of the city. Many of these older facilities serve more than one district due to infrastructural conditions and geological reasons, which make it difficult to integrate with GIS. For this reason, authors of this study suggest that stakeholders such as municipal corporations, water and sewerage administration, civil registry offices, etc should be in collaboration to expand data of current sewerage maps including parameters such as building use-cases, age, gender and population living in the sampling area. Furthermore, the infrastructural map of the city for sewage systems should be generated in detail thus the uncertainty in the study with GIS can be minimized.

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