OPTIMAL LOCATION OF WASTEWATER TREATMENT PLANTS CONSIDERING MULTIPLE FACTORS: A CASE STUDY OF PHNOM PENH

Yangyang Zhou[1], Yan Song[1,2,3,4] *, Wenjun Qin[1], Jie Sun[1,4]

[1] School of Geography and Information Engineering, China University of Geosciences
[2] School of Public Administration, China University of Geosciences
[3] Key Laboratory of Geological Exploration and Evaluation, Ministry of Education, China University of Geosciences
[4] National Engineering Research Center for Geographic Information System, China University of Geosciences

430074,Wuhan, China

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ABSTRACT:

Urban wastewater treatment plants (WWTPs) as an important engineering facility for urban water pollution prevention and control, the appropriate location selection for the WWTPs is the most important stage in the process of wastewater treatment. Improper site selection can lead to degradation of the water environment. Phnom Penh is located in the delta between the Mekong River and Tonle Sap River, with dense population, and most residents are religious. There are no sufficient and proper WWTPs available in many areas resulting in the environmental degradation and human health issues, so it is used as the study area. In the article, we proposed a new indicator system to select the location for WWTPs. The indicator system is established from RS/GIS data, which integrates social-cultural and multiple others factors, and more comprehensively analyzes the spatial distribution of suitable and demand areas for WWTPs. Finally, the minimize facilities and maximize coverage model are further used for spatial location selection of WWTPs, which can supply scientific plan and technological support for location selection of the WWTPs.

1. INTRODUCTION

With population increase and economy development, there is a progressively crucial need for wastewater treatment in many nations. It is calculated that 90% of wastewater in developing countries is discharged straight into streams, ponds or seas (Central et al., 2014). It may fetch about human health problems, destruct water ecosystems, and ultimately result in water shortage (Hodgson, 2008). In order to minimize these adverse effects, the construction of urban WWTPs should be enhanced to meet the growing challenges, and the rational location of wastewater treatment plants (WWTPs) is particularly significant (Zhao et al., 2009).

The predecessors in the planning and construction of WWTPs and other aspects of beneficial exploration and practice, at the same time, for the WWTPs location selection, spatial layout and functional positioning of the study is also increasingly attention. Because geographic information system (GIS) have the ability to manage multiple sources and large amounts of spatial data (Kao and Lin, 1996), WWTPs location selection can be accomplished using GIS by analyzing various indicators such as topography, prevailing wind direction, hydrology, land use type and spatial distribution of surface water, etc (Hongbo, 2019; Nigusse et al., 2020). For the location selection methods of WWTPs, various models have been investigated thoroughly, such as the multi-objective optimization model (Rezaei et al., 2019) for twofold optimization of price and energy consumption; the method amalgamated GIS, analytic hierarchy process (AHP), and remote sensing (RS) techniques (Liu et al., 2022); the model based on frizzy logic and multi criteria decision creation (Makropoulos et al., 2007); the model combined artificial neural networks (Wang and Jamieson, 2002) with genetic algorithms, and the manner by using GIS software integrated with the AHP (Hama et al., 2019) to optimization model (Jose Olivarez-Areyan et al., 2022; Alfaisal, 2022).

However, the current location selection models have mostly focused on algorithm principle design, and there are few algorithms that integrate location selection models with local social-cultural factors. In order to properly plan the location of WWTPs with restricted resources, and improve the facility service coverage of WWTPs, an empirical study is conducted in Phnom Penh, Cambodia. Firstly, for social-culture, WWTPs should be located far away from religious sites and include them in the suitability indicators. Finally, the layout of WWTPs is planned by combining the model of minimize facilities and the model of maximize coverage.

Cambodia is located in the southwest of Indochina Peninsula. Due to its unique geographical advantages, Cambodia plays an extremely important role. Phnom Penh is the capital of the Kingdom of Cambodia and the largest city of Cambodia. It is the political, economic, cultural, transportation, trade and religious center of Cambodia (Figure 2). Phnom Penh has an area of 678.46 km2 with population of 2.1 million (Siampos, 2019). Phnom Penh has a tropical climate, which is divided into two seasons: "rainy season" (from March to October) in high temperature and humidity; "dry season" (from November to April) with the low temperature about 22℃. The average annual temperature is between 28-34℃ (Kakuya, 2021).

In Phnom Penh, there are lack of wastewater collection and treatment infrastructures. So it has resulted in the direct discharge of wastewater into rivers and lakes, causing significant pollution of rivers and lakes in southern and northern Phnom Penh. Furthermore, the discharges are probably pollute the underground water and surface water bodies through seepage, thus doing harm to problems for the surrounding environment and human health further (Singh et al., 2018; Tang et al., 2021; Takashi et al., 2018; Xu, 2020).

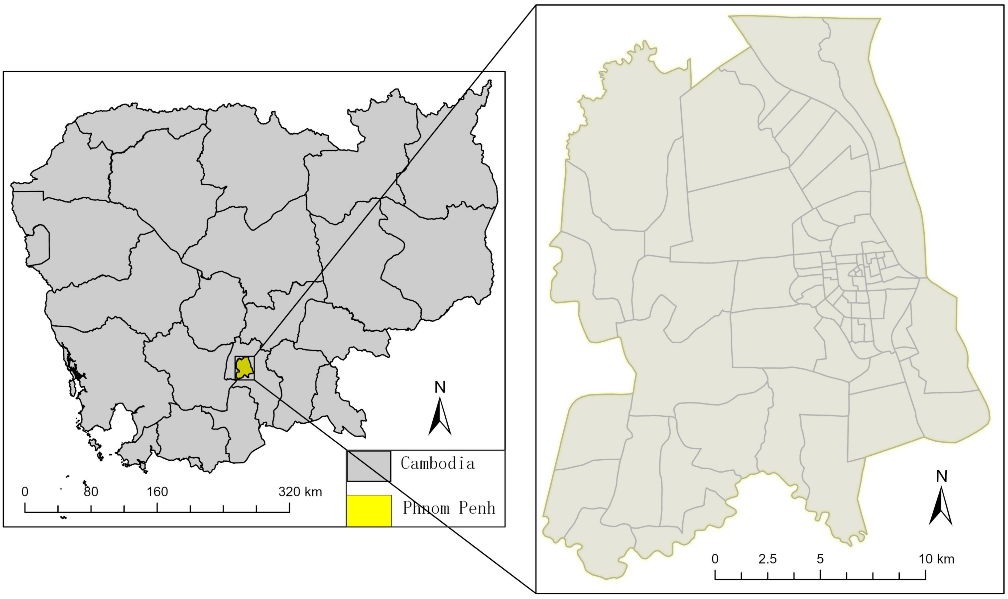

Figure 2. Study area location.

2. METHOD

The proposed WWTPs location method includes three steps: firstly, the indicator system is established and quantified separately. Then, the indicators are classified; and due to the different degrees of influence of each indicator, AHP is used to identify the heaviness of each indicator; and the weighted overlay analysis is used to obtain the suitable area and demand distribution of WWTPs; and then the candidate points and demand points. Finally, the most suitable location is determined by using the spatial location selection model. The flow chart shows the main steps of the process.

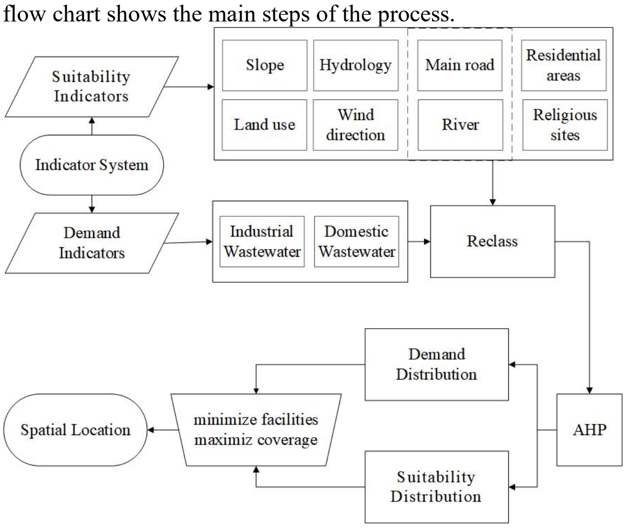

Figure1. The main process.

2.1 The Indicator System

In this study, the indicator system includes suitability and demand indicators. Suitability indicators, which are determined by laws, regulations and experience, used to get the area where WWTP is suitable for construction that required to perform the function of the facility thoroughly. Demand indicators, reflects the regions demand for WWTPs.

2.1.1 Indicator of suitability: For rational location selection, taking advantage of the natural flow of wastewater, the WWTPs should be constructed on the slight to moderate slope. Also, considering the flow direction of water, WWTPs should be arranged as far as possible in the downstream of the river. To save the cost of transporting surplus sludge and constructing new pipeline networks (Voronin et al., 2018), WWTPs should be located close to roads and rivers. However, WWTPs close to roads can affect the landscape and public health, and those close to water bodies can contaminate water and fish. Considering that WWTPs will produce harmful gases when treating wastewater, the location of the WWTPs should be selected in the downwind area of the city, so as to further the diffusion of damaging gases in wastewater treatment and lessen the injure to the environment and mortal body.

Indicator	Suitable area	Indicator quantification
Slope	The slope is small	Slope change (s_1)
Hydrology	Downstream	Flow direction (s_2)
Main road	Near main road	Distance from the road (s_3)
River	Close to the river	Distance from the river (s_4)
Wind direction	Downwind direction	Wind direction (s_5)
Land Use	Unused land	Land type
Restrictions	Outside the protected areas of residential areas	____
	Outside the protected area of religious sites	____
	Outside the main road protection zone	____
	Outside the river protection zone	____

Table 1. Suitability indicators.

In addition, the WWTPs is suitable for construction on bare land and other unused land, which is favourable to reducing land rent and reducing the fees of construction (Wang et al., 2012). So in the feature, Land cover data is used to help comprehend the current land use situation, especially when carrying out the suitability analysis of WWTPs. We can analyze the land cost of facility construction and the impact on community land cover and civic environment after completion, taking into account local policies and land use situation. When the religious countries or regions are faced with, in order to respect local cultural habits, WWTPs should not be built near religious sites to avoid pollution of these areas by sludge, exhaust gas, etc.

2.1.2 Indicators of demand: The sources of civic wastewater contain residential domestic wastewater, industrial wastewater, and other wastewater, with a little part of wastewater discharged from other sources (Yao et al., 2022). In this article, population density is used to quantify the demand for urban domestic wastewater treatment, and areas with greater population density have higher demand degree for WWTPs. Compared with domestic wastewater in ordinary residential areas, the wastewater discharge from industrial region is much greater, so industrial regions should be paid more attention, and the distance to industrial zone is used to quantify the demand for industrial wastewater treatment.

Demand Indicators	Indicator Quantification
Industrial wastewater	Industrial zone distance (q_1)
Domestic wastewater	Population density (q_2)

Table 2. Demand Indicators.

2.2 Data Preprocessing

For the suitability indicator, the area within the protection zone is considered as no-build zone. And for the quasi-build zone, we rank the suitability level of the WWTP in five aspects (suitability indicators s_1, s_2, s_3, s_4 and s_5) in terms of slope, flow direction, distance from major roads, distance from rivers and wind direction respectively. Then, combining them into a unified indicator S according to equation (1), which represents the location selection suitability of WWTPs in the whole area, and the larger of the indicator, the more it meets the decision expectation. The weights determine how much importance planners evaluate to these five aspects. Here, the APH is applied to determine the weights.

$$S = \sum_{\mathrm{i}=1}^{5} \omega_i \bullet s_i \ , \tag{1}$$

For the demand indicators (q_1 and q_2), We consider the level of demand for WWTPs in terms of both industrial and domestic wastewater. Then combining them into a unified indicator Q according to equation (2), which represents the demand degree of WWTPs in the whole area, and the higher the value of the indicator, the higher the degree of demand.

$$Q = \sum_{\mathrm{j}=1}^{2} \omega_j \bullet q_j \ , \tag{2}$$

where S is the location selection suitability of WWTPs in the study area; i denotes the i-th suitability indicator; ω_j is the weight of the i-th indicator; s_i is the suitability of the i-th indicator. For the equation (2), Q is the demand degree for the WWTPs in the study area; j denotes the j-th demand indicator; ω_j is the weight of the j-th indicator, taken as 0.5; q_j is the demand degree of the j-th indicator.

Using the idea of multi-source spatial data fusion, the suitability analysis map and the demand analysis map covering the above indicator layers are obtained. For the convenience of calculation, the original continuous indicator layer is resampled into the unified grid. The grid center points are used to represent the of the initial whole grid , and the following location model is used for the location selection of WWTPs.

2.3 Location Model

The section introduces the theoretical method of establishing dynamic spatial location model of WWTP based on GIS. The model of minimize facilities and maximize coverage is used to locate the WWTP. Specifically, the model of minimize facilities is used to select the minimum number of facilities required when the effective service radius of the WWTP covers all the demand points, which is taken as the construction quantity of the WWTP. The maximize coverage model solves the optimal location under the given number of WWTPs so that the wastewater treatment demand points within the effective service radius of the given number of WWTP are the most. They are represented by the following symbols:
The i represents the ith geometric demand center, the m is the total number of demand points, and the demand point $\mathrm{i} \in I = \{1,2,3 \cdots m\}$,
The j represents the jth candidate grid, the n represents the number of candidate grid, and the candidate point $\mathrm{j} \in J = \{1,2,3 \cdots n\}$,
The r represents the service radius of WWTP, assuming that the service radius of each WWTP is the same.
The p is the number of WWTPs to be built,
The $\mathrm{d_{ij}}$ is the distance from $\mathrm{i}(a_i, b_i)$ to $\mathrm{j}(a_j, b_j)$, $\mathrm{d}_{ij} = \sqrt{(a_i - a_j)^2 + (b_i - b_j)^2}$,
Decision variables:

$$\mathrm{x}_{ij} = \begin{cases} 1, & \text{the i}^{\text{th}} \text{ demand location is served by the j}^{\text{th}} \text{ WWTP} \\ 0, & \text{no selection} \end{cases}$$

$$y_{\mathrm{i}} = \begin{cases} 1, \text{The i}^{\text{th}} \text{ candidate grid was selected} \\ 0, \text{not selected} \end{cases}$$

The mathematical model of minimizing facilities is as follows:
Objective function -- select as few points P as possible among the candidate points

$$\min \sum_{j \in M(I)} y_j$$

The specific constraints are as follows;
a. The following equation indicates that each WWTP serves at least one demand point:

$$\mathrm{s.}t \sum_{j = M(i)} x_{ij} \geq 1$$

b. The demand point is within the effective service radius r of the cansidate point

$$M(\mathrm{i}) = \{j | d_{ij} \leq r\}$$

The mathematical model of maximizing coverage is as follows:
Objective function - To maximize the total demand covered by the WWTPs

$$Max \sum_{i \in I, j \in J} x_{ij}$$

Specific constraints are as follows:
a.Determine whether the demand point is covered by the treatment plant:

$$x_{ij} \le \sum_{j=1}^{n} y_j$$

b.Select p facilities:

$$\sum_{j=1}^{n} y_j = p$$

c.need to be binary value variable:

$$x_{ij} \in \{0,1\} \forall I, J$$

$$y_j \in \{0,1\} \forall J$$

3. DATA AND ANALYSIS

3.1 Data Sources

This study used the multi-source data, including: (1) the OpenStreetMap data (OSM: http://www.openstreetmap.org); (2) land use cover data: 2020 FROM- GLC10 global 10m land cover map (http://data.ess.tsinghua.edu.cn); (3) Population density data: WorldPop Population density dataset 2020 (http://www.worldpop.org); (4) Elevation data: ASTER GDEM 30 m resolution data in the study area (http://www.gdem.aster.ersdac.or.jp).

3.2 Suitability analysis

In fact, the restriction constraints are converted into the distance constraint of the WWTPs forbidden construction zone in order to select the best location for the WWTPs. In Figure 3, there are 32.82% of the religions sites are located in residential areas. Referring to the Water Supply and Drainage Manual (Beijing Municipal Engineering Design and Research Institute, 2004), the buffer distance of 300m is set for residential and religious areas. Similarly, we set a buffer zone of 300 m for religious sites, and the no-build zone was expanded by 20.45 square kilometers (Figure 4). And, the buffer distance of 50m is set for roads and water bodies. Finally, the areas within the buffer distances are excluded from the suitable construction zones.

The DEM Slope analysis in Phnom Penh municipality is conducted in Figure 6， which demonstrates that the slope of the entire Phnom Penh city area is gentle and the terrain is almost flat in the vast majority of the city. Furthermore, the hydrological analysis of the DEM data is conducted to obtain flow direction raster.

We simulate and map the wind field in Phnom Penh based on the average wind direction from March to October 2020. The southwest wind is the dominant wind direction in Phnom Penh in rainy season, hence, the WWTPs should be built in the northeast area of the city.

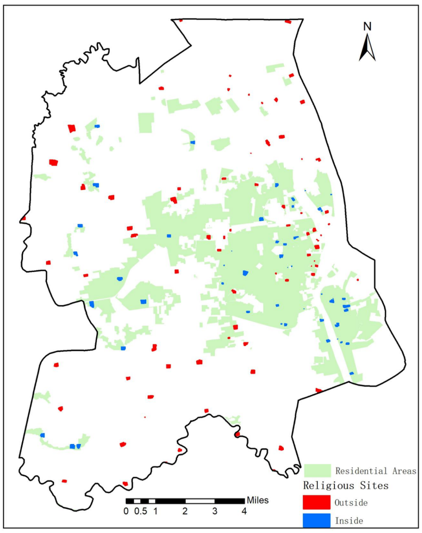

Figure 3. Residents and religious places.

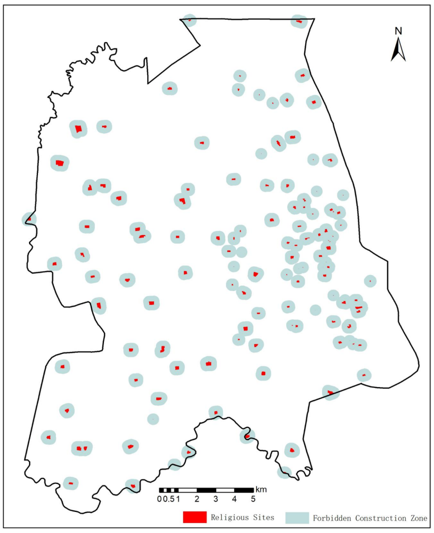

Figure. 4. Religious site buffer.

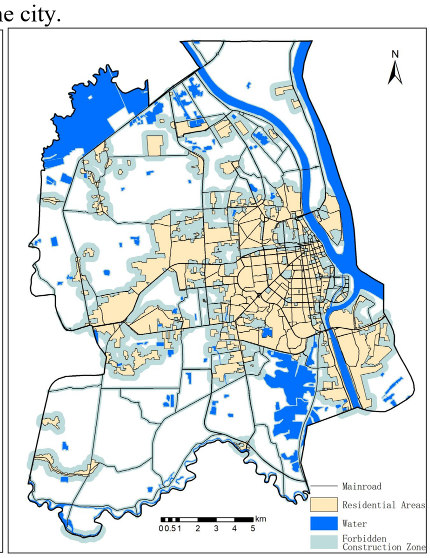

Figure 5. Forbidden construction zone.

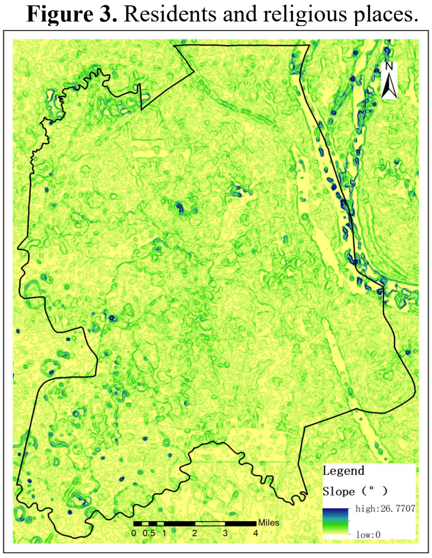

Figure 6. Slope analysis.

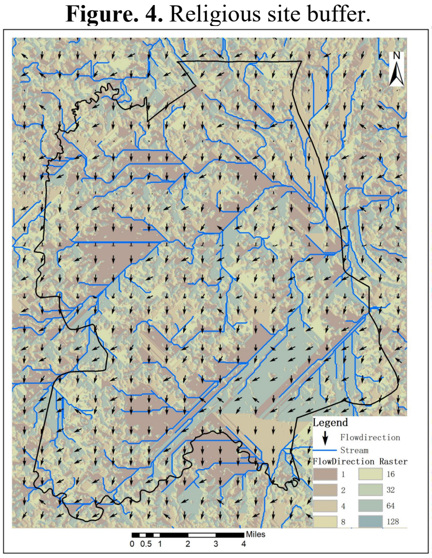

Figure 7. Flow grid.

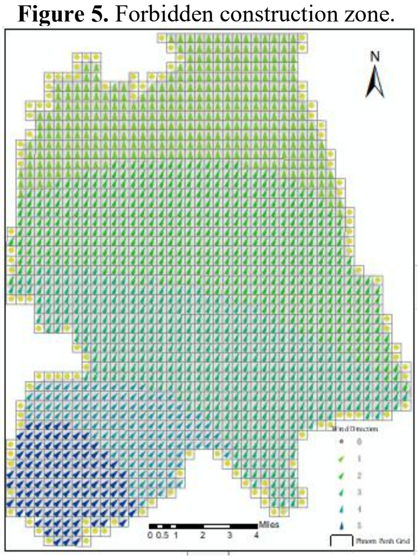

Figure 8. Wind direction map.

The reclassification result are divided into five levels. Further the AHP is utilized to confirm the right, and the results of the AHP hierarchical analysis are shown in the following table:

Item	Eigenvector	Weight
Slope	0.867	17.333%
Hydrological	1.362	27.232%
Road	1.050	21.009%
River	1.350	27.009%
Wind direction	0.371	7.416%
Maximum eigenvalue value	5.060	
CI value	0.015	
RI valve	1.120	
CR value	0.013	
Consistency test result	Pass	

Table 3. AHP hierarchy analysis results.

The AHP hierarchy study was conducted for slope, hydrology, road, river, and wind direction by constructing judgment matrix, and the feature vectors were obtained as (0.867, 1.362, 1.050, 1.350, 0.371), and the corresponding weight values were 17.33%, 27.23%, 21.01% , 27.01%, and 7.42%. In addition, the maximum eigenroot (5.060) can be calculated by combining the eigenvectors, and then the CI value (0.015) is calculated ,which is used for the consistency test. The CR value calculated is 0.013<0.1, which means that the judgment matrix of this study satisfies the consistency test and the calculated weights are consistent (The SPSSAU project , 2022).

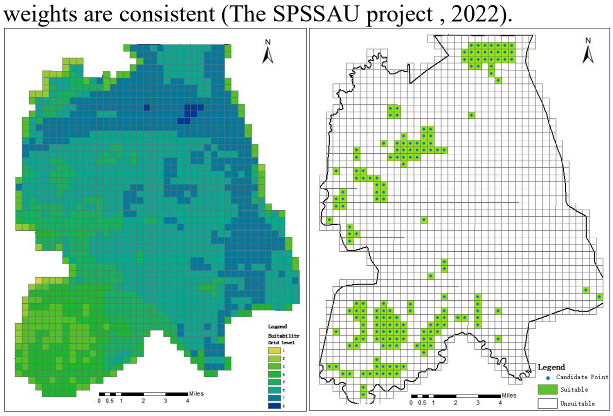

Figure 9. Distribution of suitable locations and candidate points.

According to the weight, the reclassified suitability feature maps are overlaid, and the whole study area are divided into suitable area and unsuitable area. The distribution of suitable locations for WWTPs land are shown in Figure 9, and its proportion is shown in Table 4, which shows that the grid suitable for WWTP locations in the study area accounts for 10.74%, and a total of 175 candidate locations for WWTPs are created using the center of grid.

Evaluation of suitability	Number	Proportion/%
Suitable	175	10.74%
Unsuitable	1455	89.26%

Table 4. Number and proportion of grid in suitable area.

3.3 Demand Analysis

In Figure 10, the industrial zones in Phnom Penh city are mainly distributed in the edge of the city and the suburban areas away from the city center. The industrial zones are all under 100 hectares, and the industrial waste water treatment demand are divided into 5 levels zones according to distance to industrial zone: 0-300m, 300-600m, 600-900m, 900-1200m and 1200-1500m.

In Figure 11, the population is mainly distributed in the dense urban areas in the central-eastern part of Phnom Penh city, while the population in the urban fringe and rural areas is relatively small. And the natural break (Jenks) is used to reclassify the population density into 5 levels.

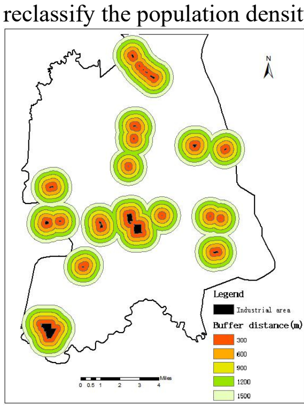

Figure 10. Industrial area.

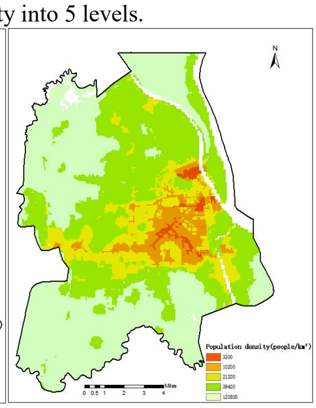

Figure 11. Population density.

The two demand indicators are superimposed to finally give the demand distribution map of Phnom Penh municipality for WWTPs. A total of 273 demand points were obtained by combining town location centroids and demand degree centroids.

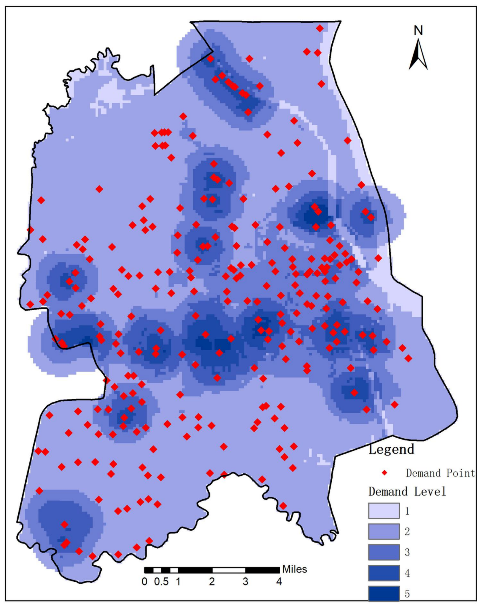

Figure 12. Demand distribution map.

4. WWTP LOCATION SELECTION

The service scale of the WWTP is mainly related to the treatment capacity of the WWTP, the water quality and quantity within the service scope, and the level of the wastewater containment. We refer to the "Urban Drainage Engineering Planning Code GB50318" (Department Ministry of Construction of the People's Republic of China., 2001) to list three kinds of scale of wastewater plants and their corresponding service radius.

Type	Processing scale (*10000m3/d)	The radius of service (km)
Large	>20	16
Medium	5-20	10
Small	<5	7

Table 5. Size of wastewater treatment plants.

4.1 Existing WWTP service area

The treatment level of the existing WWTP in Phnom Penh City is level 2, which can serve about 1.63 million people (Ehalt Macedo et al., 2022). Maximize coverage was determined for an existing WWTP with a service radius of 10 km (Figure 13). Analysis of the coverage of overall demand points: Among all 273 demand points, the existing WWTP can cover 291 demand points, with a coverage rate of 60.25%, and the coverage effect is good. Analysis from the situation of the covered area: the demand points in the northeast and west of the study area are not covered, indicating that there are still parts of the study area that need to build new plants.

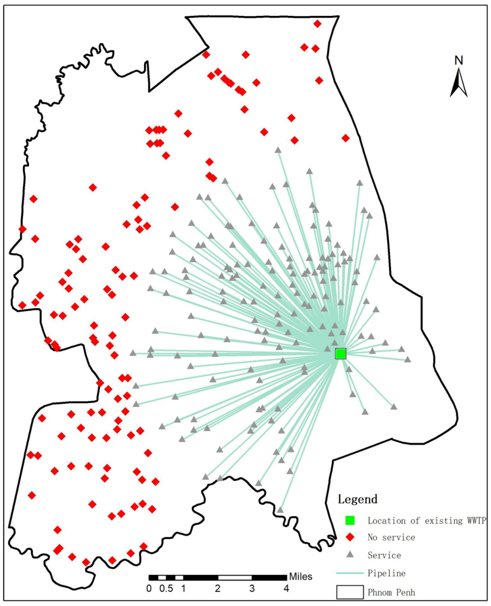

Figure 13. Service status.

4.2 New wastewater treatment plant

The combined wastewater volume per capital and the combined wastewater volume per unit area are used to predict the wastewater volume and determine the scale of the WWTP. The comprehensive domestic water consumption index is planned to be 210L/ person •d in 2022. The water consumption index of industrial enterprises is 40,-600, km3/ha. According to the development of Phnom Penh City, the release coefficient of domestic wastewater and industrial wastewater is 0.85. According to the forecast of the above indicators and considering the prospective reservation, the total wastewater volume in 2022 is 144 kt/d, and the long-term WWTP is considered as 150 kt/d. According to the needs of recent construction and development, the recent scale of the WWTP is 40, kt/d, and combined with the treatment technology and intensive land use requirements of WWTPs, the area of wastewater treatment is 7-8 ha/kt, with a total area of 12.9 ha (Irvine et al., 2015).

Considering the range of pipeline laying, distance too far, pipeline length is too long, increase the construction difficulty, cause resource waste, and it is difficult to achieve the effective management, it needs to make overall plans, therefore,we calculate the minimum number of three-scale processing plants using the minimize facilities model, the system automatically calculates that at least one large or two medium or three small WWTPs of these three types of size can basically meet the requirements. Next, the maximize coverage model is used to calculate the location situation when the number of wastewater plants is 1-3, combined with the location distribution of existing wastewater plants. The calculation results are shown as follows.

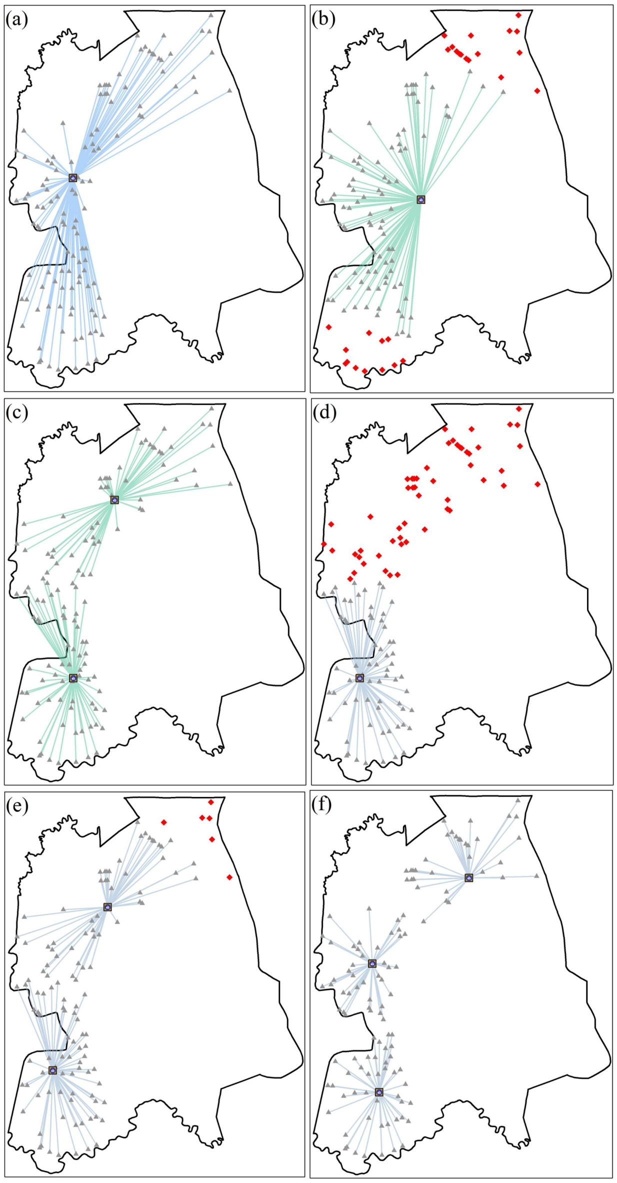

Figure 14. Distribution of wastewater treatment plants of different scales: (a)One big factories; (b)One medium factory; (c)Two medium factories; (d)One small factory; (e)Two factories; (f)Three small factories.

As mentioned above, there is only one medium or small factory, not all demand points can be covered, and two small factories can cover most of the demand points. Building one additional large or two medium or three small factories would cover all locations without missing any, with the most desirable results. This result has two main advantages. First, in the demand area, the distribution of WWTPs is reasonable, sharing the local wastewater treatment task. In addition, our plan can improve the service coverage, especially in land-use intensive areas of the city. Therefore, through our model, the effect of wastewater treatment can be significantly improved.

5. CONCLUSION

In this paper, a novel indicator system based on GIS spatial analysis location model is proposed to plan the layout of WWTPs. Considering social-cultural factors, we uses the POI data of religious sites is utilized as one of the suitability indicators, and incorporating it into the indicator system. Finally, the proposed novel indicator system of WWTP are evaluated and visualized, and the locations are selected using the facility model to give three different sized WWTP selecting location solutions.

The methodology used in this study combines minimize facilities model and maximize coverage model to make it easier for the study to get valuable facts about the study area. Therefore, the article provides the important judgment-making tool for selecting the right wastewater treatment facility at the right location. However, extra field studies are necessary to confirm the consequence obtained. In this regard, it is highly recommended that further location surveys of selected areas be carried out in the presence of professional engineers to determine the optimal location of sewerage facilities between each area. The methodology employed can be used to obtain optimal location in similar studies covering various aspects and studies.

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