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Using GIS for the allowable soil bearing capacity estimation according to the Terzaghi (1943) equation in Eskişehir city center, Türkiye

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Abstract

In foundation engineering, it is necessary to calculate the bearing capacity of soils. The allowable soil bearing capacity required for foundation design is calculated through various empirical methods using geotechnical parameters such as specific gravity and angle of internal friction. Standard Penetration Test (SPT) values of the soil are used in these calculations. Therefore, soil tests which engineers need, are costly and time-consuming. This study aims to determine the soil bearing capacity of Eskişehir city according to the Terzaghi (1943) equation and present soil bearing capacity maps for shallow foundations. The geotechnical parameters of the soil were obtained from 40 borehole data made in the field. Within the scope of the study, according to the Terzaghi (1943) equation bearing capacity maps were created for 0-5 m depth to provide an overview of the bearing capacity of Eskişehir soil. These maps were made in the Geographic Information System (GIS), which has a database that stores and analyses regular data. In addition, these maps can assist engineers working on shallow foundation design on the site.

1. Introduction

Soil is the main material used in the construction of building foundations. The foundation should be designed according to the parameters obtained after determination of the soil properties in the area of construction. The most important of these soil parameters is the bearing capacity of the soil [1]. Soft soil layers often cannot carry the load from the superstructure causing problems such as settlement and loss of bearing capacity. Therefore, extensive soil survey studies are required to be conducted to construct a building. These studies are expensive, time-consuming and labour-intensive. Many researchers have suggested empirical equations for calculating the bearing capacity of the soil to this date [2-7]. Different engineering parameters of the soil are utilized in these empirical equations. Some researchers suggest these equations utilizing the physical and mechanical properties of the soil, while others suggest these equations according to the dynamic properties of the soil.

In the last thirty years, with the advances in computer technologies, Geographic Information Systems (GIS) are a frequently used tool for storing, processing and analysing spatial data [8]. In the last thirty years, with the advances in computer technologies, GIS is frequently used for civil engineering applications and contributes to studies such as spatial data management, the creation of smart city models and risk analysis [9,10].

It has become very important to predict the engineering properties of the soil using Geographic Information Systems (GIS) technologies in terms of geotechnical engineering. Today, there are many studies that calculate the allowable soil bearing capacity using empirical equations and present site-specific maps in GIS from the calculated data [11-13].

Allowable soil bearing capacity is the geotechnical parameter of the soil used to decide the most suitable foundation in the design of constructions. The bearing capacity should be calculated in order to determine the type and depth of foundations, as well as to prevent damage caused by building loads and earthquakes [12].

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Geotechnical properties such as relative density, cohesion and internal friction angle are used to calculate the allowable soil bearing capacity. These geotechnical properties are obtained from studies on the field such as Standard Penetration Test (SPT) and Cone Penetration Test (CPT). These studies are comprehensive survey studies conducted in field conditions and time-consuming. It costs very high to conduct such studies on the field and the engineering properties of the soil should be determined in the construction of the building foundation. A database of soil geotechnical properties may help to save from a large portion of the total project cost. Inverse distance weighting method is an interpolation method used to estimate non-spatial points from existing data [14]. Therefore, using interpolation methods by creating a database of geotechnical data for a particular site allows to obtain economical and effective results for construction design. Dungca [15] created soil bearing capacity maps from the surface to a depth of 5 meters using GIS technologies for the city of Quezon, Philippines. Al Mamoori et al. [16] determined that Inverse distance weighting (IDW is the best GIS interpolation method for the estimation of the bearing capacity of the soil in Najaf, Iraq. Al Maliki et al. [12] used IDW interpolation method in GIS to generate soil bearing capacity maps of Najaf and Kufa cities of Iraq. In this study, the geotechnical parameters of the soil obtained from the boring works carried out in the field in a certain part of Eskişehir city center were used. The allowable soil bearing capacity calculations were made using the Terzaghi (1943) equation, among these geotechnical parameters, for shallow foundations. All geotechnical parameters were stored in the Geographical Information Systems (GIS) database and maps containing the soil bearing capacity of the study area were produced by use of the Inverse of Distance (IDW) method.

2. Method

2.1. Study area

The study area, Eskişehir, is located in the Central Anatolia Region in the northwest of Turkey. The study area covers a significant part of Eskişehir city center and is located in an area of approximately 53 km^2 between 280.000-290.200 E and 4.404.000-4.410.000 N (UTM Zone 36, ED50) (Figure 1). The most important stream of the region is the Porsuk River.

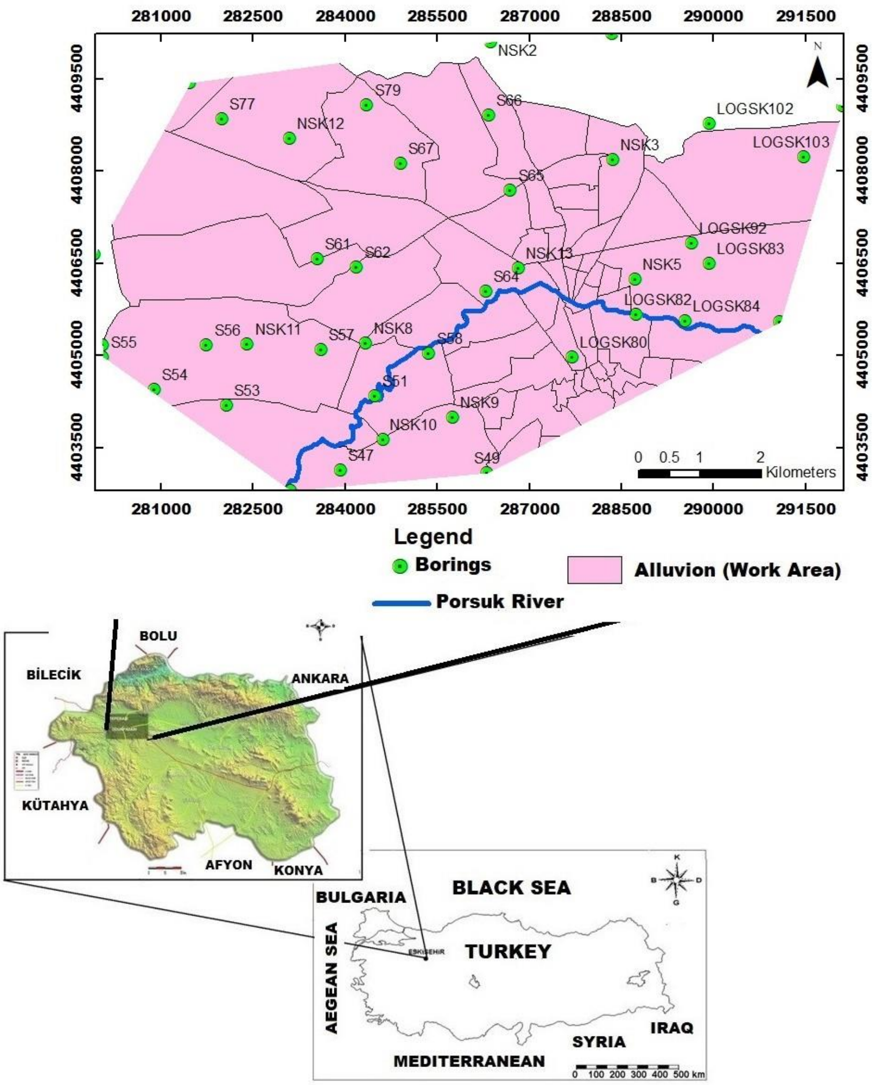

Figure 1. Boring location map of the study area

2.2. Geotechnical properties of the study area

Alluvial soil extends in most of Eskişehir city center. Geological map of the study area is presented in Figure 2. This alluvial soil is divided into two as old alluvium and new alluvium by some researchers [17]. Some parts of the study area are located on the soil, which is geologically defined as new alluvium consisting of younger and loose material. In the north-west of the study area, the soil defined as old alluvium, which was formed relatively earlier than the new alluvium, and where more compact soil layers are located. When the soil properties of the alluvial soil are examined for 30 meters, there are clay, silt, sand and gravel levels. Generally, high plasticity clay-silt levels are found up to 5-6 m from the surface, while at lower levels, it alternates from low plasticity stratified strata to sand and gravel levels [18]. In addition, there are poorly graded sand and silty sand-clay sand layers at the middle levels of some soundings at 30 m depth. In the southern part of the Porsuk River, sandstone-conglomerate units also extend as bedrock within the boundaries of the study area.

We made the local soil class map of the study area according to the Turkish Building Earthquake Code (2018) in our previous study [20] (Figure 3). We created this local soil class map by use of the Inverse Distance Weighting interpolation approach in ArcGIS program. It is understood, according to this map, that the local soil class of the site is mostly ZD, ZE and ZF.

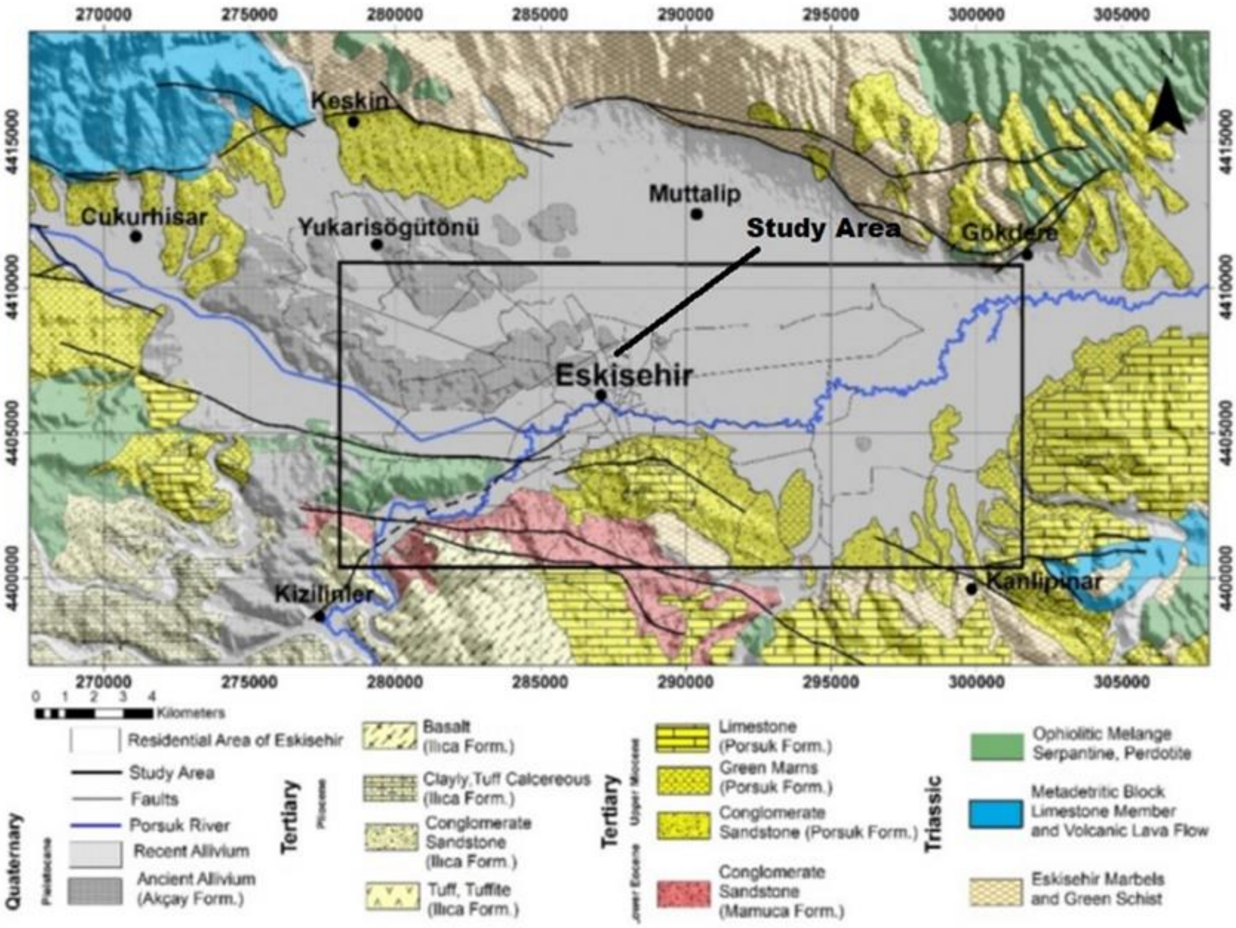

Figure 2. Geological map of the study area [19]

3. Methodology

Shallow foundations transmit the applied constructional loads to the soil close to the surface. Meanwhile, they generate shear stresses in the soil. Bearing strength failures occur when shear stresses exceed the shear strength of soil or rock. The relationship between foundation dimensions, load and soil properties should be known in order to prevent failure of bearing capacity of shallow foundations [1].

In the design of shallow foundations, the ultimate bearing capacity calculation is made by using the geotechnical properties of the soil. According to Terzaghi (1943), soil bearing capacity is calculated using the corrected SPT-N values of the drilling logs. This calculation is given in Equation 1.

$$N_{60} = \frac{E_m C_B C_S C_R C_N N}{0.6} \qquad (1)$$

In Equation 1, N_{60} is the corrected SPT-N value (pulses/ft) determined by considering the number of blows. The corrected SPT-N_{60} values are used to determine the geotechnical properties of the soil such as relative density, undrained shear strength and internal friction angle. The E_m ram efficiency is the C_B borehole diameter correction. C_S is the sampler correction. C_R is rod length correction. C_N is the cover pressure correction and N is the SPT-N value recorded in the field.

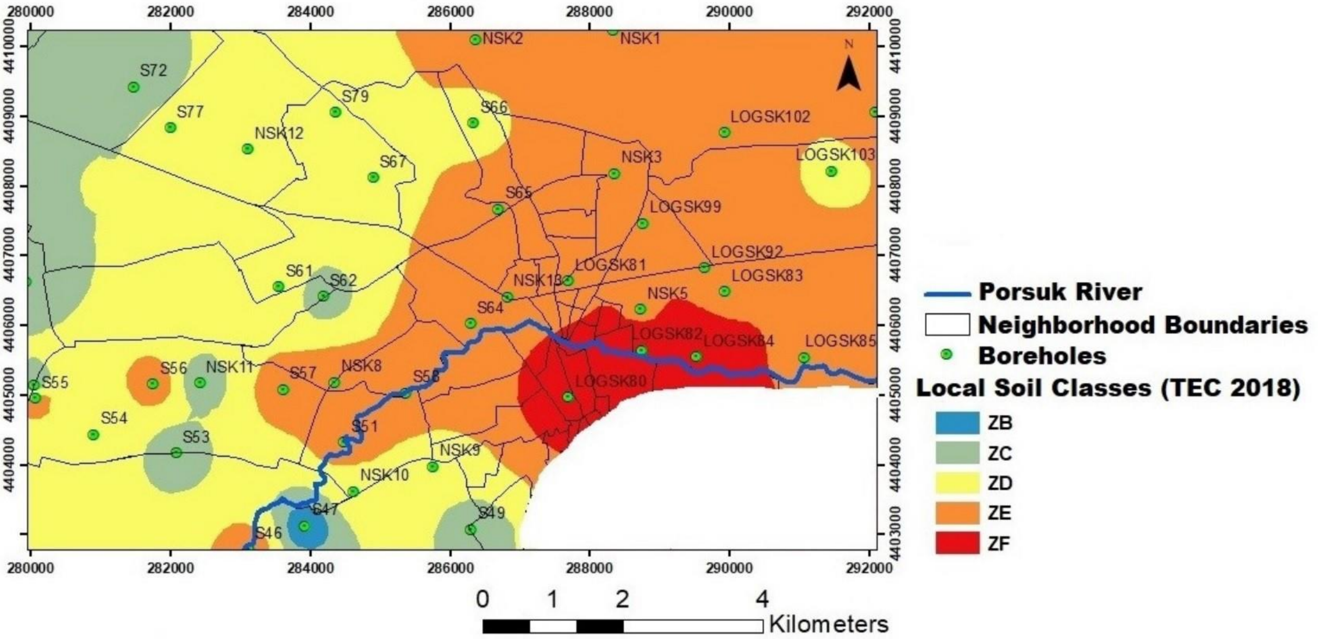

Figure 3. Local soil classes of investigated area according to Turkish Earthquake Code 2018

Soil has two mechanical properties, namely shear strength and bearing capacity. Soil bearing capacity, which is one of the most important features in foundation design, represents the contact pressure between the foundation and the soil. Various boundary balance methods used to calculate soil bearing capacity were developed in the first half of the twentieth century. However, it is the method of Terzaghi (1943) that is widely accepted. Terzaghi (1943) considers three zones in soil as wedge zone, radial slip zone and linear slip zone. He assumes that the sliding surface stops at this depth and that the overlying soil is displaced by the surcharge pressure because the soils between soil surface and foundation depth neglect the shear strength. This approach is conservative and limits the method to relatively shallow foundations (D≤ B) [1].

Terzaghi developed his theory for continuous foundations (that is, foundations with a very large L/B ratio), which is one of the shallow foundation types. However, in the ongoing process, he suggested similar approaches for square and rectangular foundations, using his experimental results. Accordingly, in this study, the bearing capacity equation developed by Terzaghi for continuous foundations was used to determine the soil bearing capacity and this is presented in Equation 2 [2].

$$q_n = c'N_C + \sigma_Z' N_q + 0.5\gamma' B N_\gamma \qquad (2)$$

Here, q_n indicates the Ultimate bearing capacity of the soil, c' indicates the Effective cohesion of the soil under the foundation, σ'_z indicates the Effective vertical stress at foundation depth, γ' indicates the Effective unit weight of the soil, B indicates the Foundation width, N_c, N_q and N_γ: Terzaghi indicates the bearing power factors. Although bearing capacity calculation of Terzahgi was developed for effective stresses, this calculation can also be used in total stress analysis [2].

In calculating the allowable bearing capacity (q_a): the ultimate bearing capacity (q_u) is divided by a factor of safety (Equation 3). The foundation is then designed so that the contact pressure (q) does not exceed the allowable bearing capacity (q_a).

$$q_a = \frac{q_u}{F} \qquad (3)$$

Safety factors are not stated clearly in most of the building codes. However, constructional engineers determine the safety factor by taking into account the design loads depending on the soil type, terrain structure, soil variability and construction type. The factor of safety varies between 2.5-4.5. The one commonly used in foundation engineering is 3 [1].

In this study, the allowable soil bearing capacity values of 40 boreholes were calculated using the corrected SPT-N values and soil parameters. The factor of safety was taken as 3, divided by the ultimate bearing capacity in order to determine the allowable bearing capacity of the soil. Allowable soil bearing capacities at different locations are calculated for depths of 1.5 meters, 3 meters and 4.5 meters. Allowable bearing capacity maps of the soil were produced using GIS technologies for a certain part of Eskişehir city center,

4. Estimation of soil bearing capacity

Theoretically, the ultimate bearing capacity of the soil is the acceptable load bearing capacity of the soil layers without any collapse [21,22]. The issue of ultimate bearing capacity can be expressed in terms of the contact pressure between the soil and the construction and the pressure allowing optimization of the superstructures interacting with the soil. In this study, the ultimate bearing capacity of the soil was calculated by considering the soil properties obtained from area studies for 1.5, 3.0 and 4.5 depths from the surface. In the study, the physical and mechanical properties obtained from 40 boreholes representing the land made in different locations were used (Table 1).

Table 1. Soil parameters used in the study

Study Type	Unit	Value
Boreholes	amount	40
Total Borehole Length	meters	1200
SPT	amount	800
Definition Test (such as cohesion, internal friction angle, unit weight of the soil	amount	689

Inverse distance weighting (IDW) is a popular interpolation method that estimates values at unknown points using the value and distance of a nearby known point. In this method, connection and resemblance rate is proportional to the distance between the points (that is, those that are closest to the known point have more weight than those that are far away) [23].

In the IDW method, the unknown points value is estimated using the following equation (Equation 3) [23].

$$z(x_0) = \left(\frac{\sum_{i=1}^{n} \frac{x_i}{h_{ij}^{\beta}}}{\sum_{i=1}^{n} \frac{1}{h_{ij}^{\beta}}} \right) \quad (4)$$

Calculations were made according to the empirical approach of Terzaghi (1943) for shallow foundations. Maps were produced by creating a database in GIS from the calculated soil bearing capacity data. These maps were created using the IDW interpolation method from the Geostatistical Analyst Wizard (GAW) methods in ArcGIS 10.7 software. Geotechnical maps representing the bearing capacity at these 3 depths were produced for the settlement area within the scope of the study. Figure 4, among these maps, shows the permissible soil bearing capacity of the study area at a depth of 1.5 meters from the ground surface. Here, the carrying capacity values are as low as 289 kPa in some places, while maximum values of 539 kPa have been obtained in some places.

The allowable soil bearing capacity map of the study area at a depth of 3.0 meters was created based on the calculated data within the scope of the study (Figure 5). As can be seen from Figure 5, allowable soil bearing capacity values for the 3.0 meters depth of the study area range between 369 kPa and 773 kPa.

The allowable soil bearing capacity map of the study area at a depth of 4.5 meters was created based on the calculated data within the scope of the study (Figure 6). According to the map presented in Figure 6, the carrying capacity values have been seen to vary between 849 and 1.533 kPa. It is observed that the bearing capacity values increase as the depth increases.

Also, a groundwater level map of the study area was created taking into account the studied geotechnical field data (Figure 7). The groundwater level of the city center varies between 2-13.40 m according to this map (shallow depths).

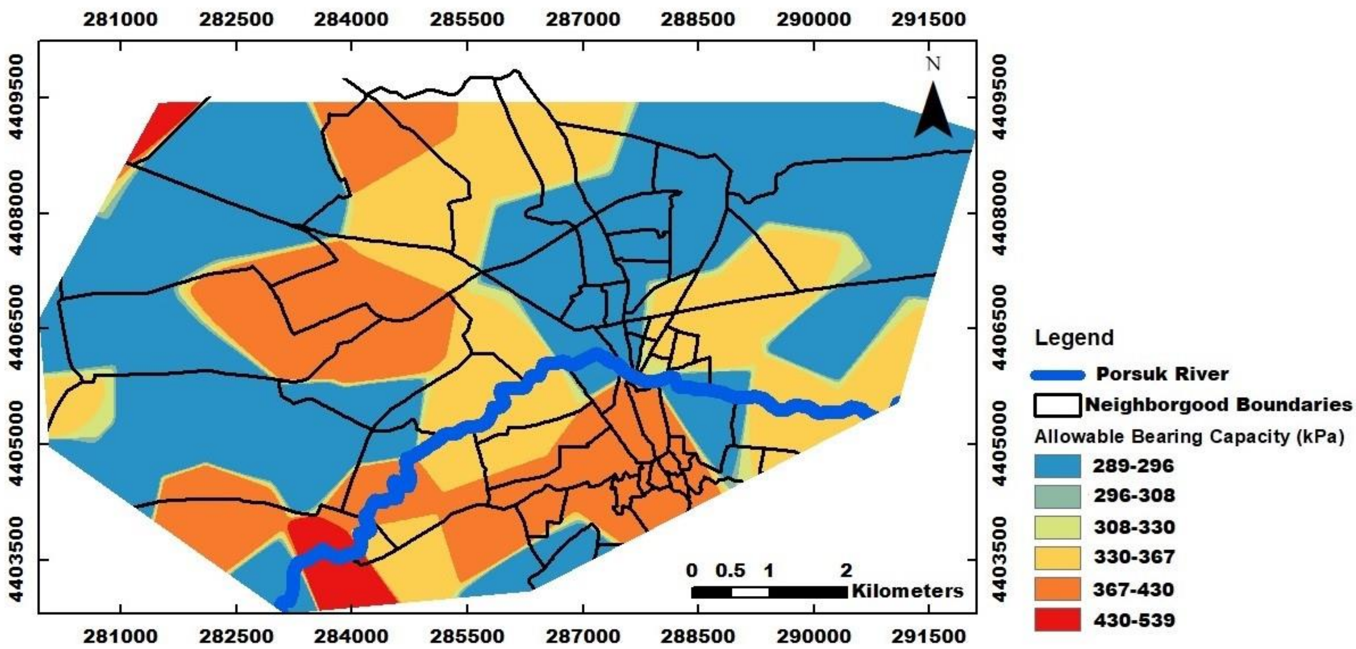

Figure 4. Allowable Bearing Capacity Map of the Study Area at 1.5 meters

5. Conclusion

It is determined that the soil bearing capacity has lower values (0-290 kPa) in some parts of the study area with younger geological units, while it has relatively higher values in some regions according to the maps created. The bearing capacity values are higher on the soil consisting of old alluvium units on the north side of the study area. Low values where the carrying capacity may pose a problem noticed in the units defined as new alluvium on the northern side of the study area. The zone consisting of rock units as soil features in the south of the study area has bearing capacity values greater than 1500 kPa. It has been determined that ZB, ZC class soils have higher soil bearing capacity when the local soil properties are taken in to account. In addition, in soils where the groundwater level is high, the allowable soil bearing capacity was obtained as lower values.

In the construction of shallow foundations, it is one of the most accurate methods to determine the bearing capacity of soils by performing loading tests that force them to collapse. However, these experiments are not economical and are rarely performed due to some uncertainties in practice. Therefore, today, the bearing capacity calculation of the soil using SPT-N and soil properties is more preferred due to its practicality in practice. In this study, site-specific allowable soil bearing capacity maps were created according to the Terzaghi (1943) approach by using the data obtained as a result of the calculations in GIS. It has been determined that especially the new alluvial ground has a risky bearing capacity according to the maps obtained as a result of this study. The estimated maps presented in this study were created using the Terzaghi (1943) method only. For this reason, it is necessary to make general bearing capacity calculations for the Turkish Building Earthquake Regulation (2018), which is used in earthquake-resistant building design today.

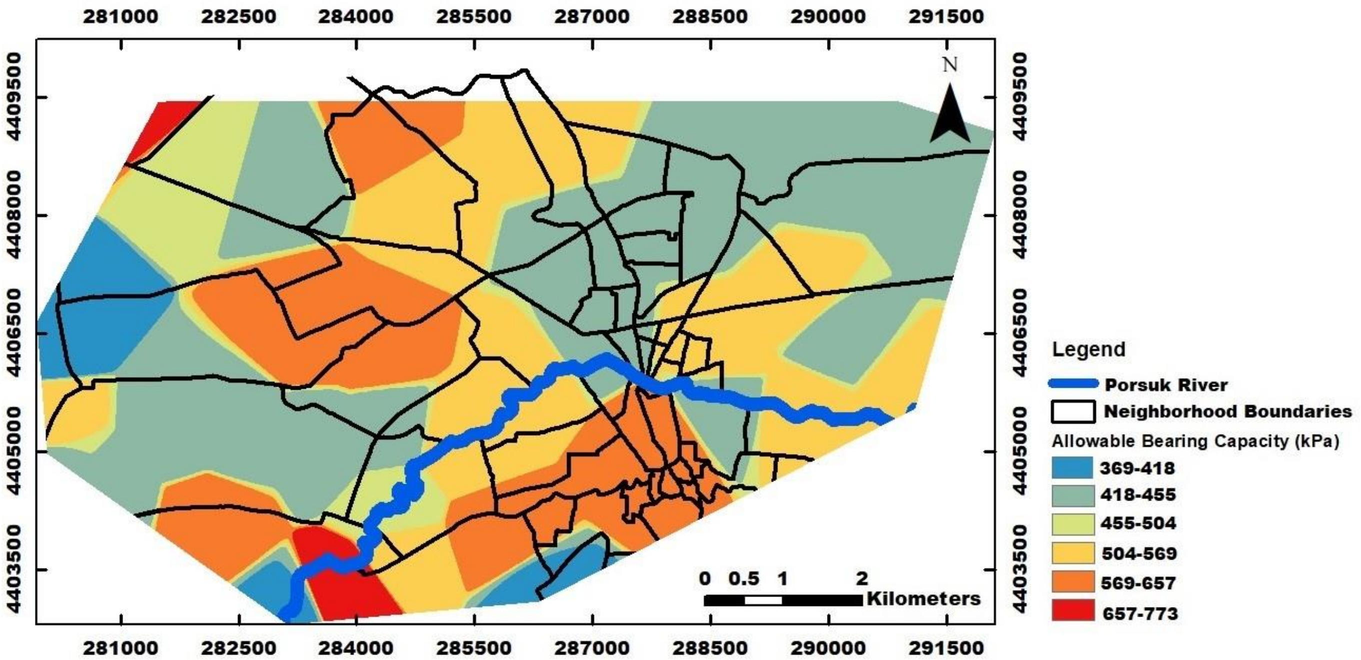

Figure 5. Allowable Bearing Capacity Map of the Study Area at 3.0 meters

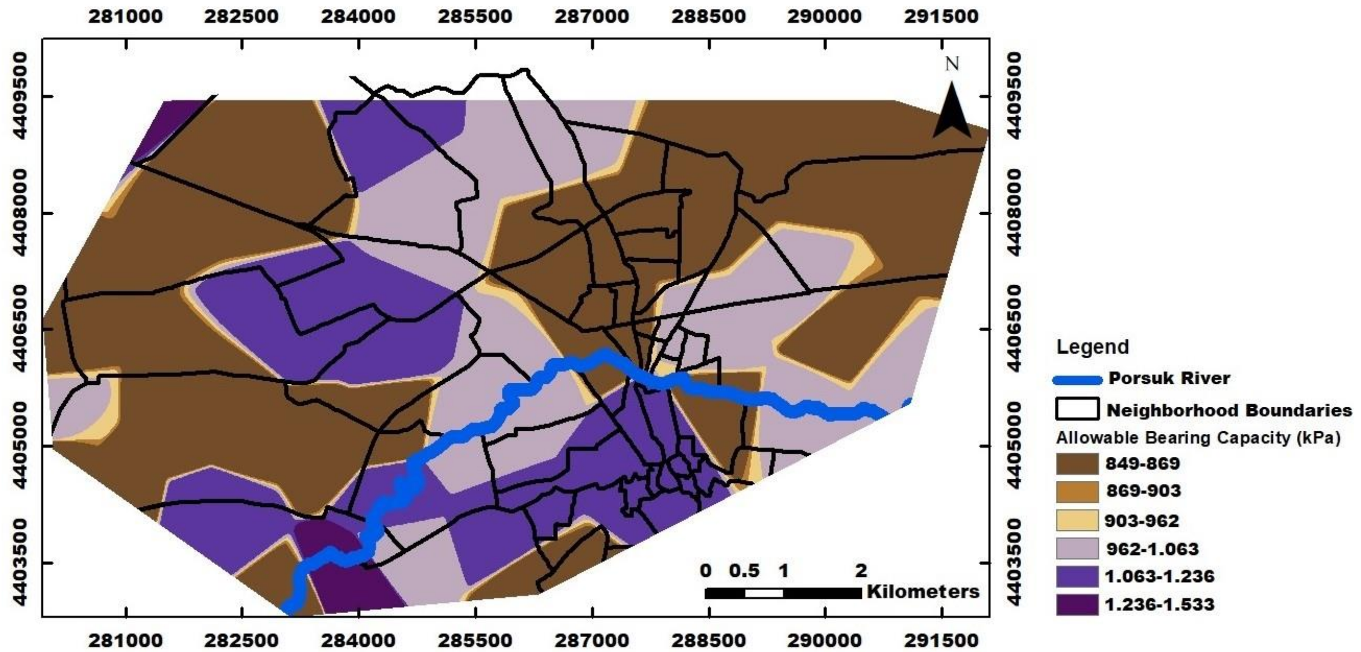

Figure 6. Allowable Bearing Capacity Map of the Study Area at 4.5 meters

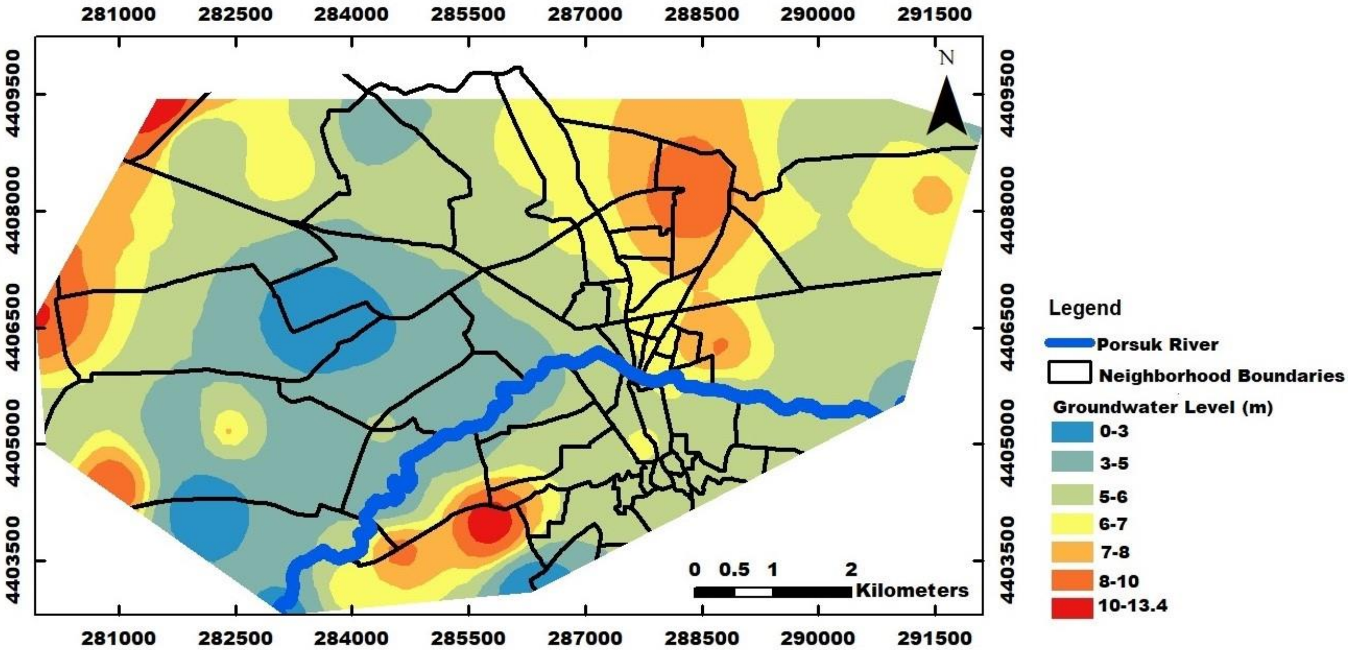

Figure 7. Groundwater level map of the study area

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Conflicts of interest

The authors declare no conflicts of interest.

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