

GIS based Groundwater Vulnerability Assessment of Lahore a Metropolitan using Modified DRASTIC Model

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Abstract

The metropolitans of the developing countries are experiencing the hazard of low quality drinking water. Lahore, the heart of Pakistan, has over 12 million population and is going to face the shortage of clean drinking water. The study was designed to create a groundwater vulnerability map of Lahore using modified DRASTIC model. The water table, land use/cover, hydraulic conductivity, vadose zone, soil and aquifer media layers of Lahore aquifer were analyzed using 'geostatistical analyst' and 'spatial analyst' extensions of ArcGIS software to compute the groundwater vulnerability. The Vulnerability index of modified DRASTIC model ranged from 64 – 144. The spatial variability of modified DRASTIC index were divided into 4 categories, namely, Low, Moderate, High and Very High groundwater vulnerable zones. The modified DRASTIC model revealed that 51.38% areas have low vulnerability, 36.77% areas have moderate vulnerability, 9.48% areas have high vulnerability and 2.37% areas have very high vulnerability to groundwater pollution. The 'high' and 'very high' vulnerability classes were found in the western parts of Lahore. The results of modified DRASTIC model were validated using the groundwater contamination data of arsenic in the study area. The groundwater arsenic concentrations map also showed higher values in the northwestern parts while in the eastern parts of the study area, the arsenic concentrations had a decreasing trend. In Ravi Town, the arsenic concentrations were positively correlated with modified DRASTIC vulnerability index and inversely correlated with water table depth ($p < 0.01$). It is recommended that the arsenic removal plants should be installed at all the tubewells with higher arsenic levels (arsenic concentration > 50 ppb) to provide safe drinking water to the citizens of Lahore. It is recommended that the modified DRASTIC model based on geospatial techniques can be applied on other metropolitans of the world for taking preventive measures against massive water pollution.

Keywords: Groundwater, DRASTIC, Vulnerability, GIS, Risk, Groundwater Quality, Lahore.

Introduction

For the sake of sustainable development, the first step is always vulnerability evaluation. The intrinsic characteristics that regulate the sensitivity of water to the adverse effects of an imposed contaminant load is determined by groundwater vulnerability [1]. The development of groundwater vulnerability assessment maps are not only useful in understanding the introductory information about an area but they also reveal areas of higher environmental health risk so that the anticipatory precautionary measures could be taken there [2].

According to [3], groundwater is consumed by 95 percent of Pakistan's population for drinking purposes. The abrupt and unscientific rampant exploitation of underlying groundwater aquifers' quantity and quality has sparked great interest over time [4] which escalates the risk and vulnerability of groundwater. High rates of urbanization, burgeoning population and unscientific rigorous anthropogenic activities have magnificently contributed to environmental deterioration, which has in turn produced aggravated and severe health hazards and intimidated threats to human livelihood worldwide. The global issue of groundwater quality management is exacerbated in underprivileged countries resulting in a major decline of existing water resource. The increase in demand has brought the aquifer under greater pressure as the groundwater is the pre-eminent source of drinking water but sometimes the pathogenic organism and

undesirable substances leach into the aquifers inflicting a huge change in the biogeochemical characteristics of groundwater. Groundwater quality assessment is consistently carried out to preserve an adequate supply of safe drinking water which would help circumventing serious harm from the ailments. The potential groundwater vulnerability assessment maps are increasingly helpful in understanding basic information about an area. These maps highlight areas that are highly vulnerable to environmental risks. Vulnerability assessment helps us to take adequate precautionary measures in highly exposed areas that prevent further degradation of the groundwater resources [5].

Groundwater contamination and vulnerability assessments have been substantially recorded in several parts of the world to detect groundwater pollution [6-10] and in Lahore [11-12]. Vulnerability evaluation is ascribed as the most essential step on the path of promoting sustainability and resilience, particularly in the accelerated overpopulated metropolitan's cities such as Nangasai, Dakar, Ghana, Dhanbad, and Ita Ogbolu [13-17].

Vulnerability zonation has garnered significant attention in the development, utilization, and improvement of water resources [18]. In order to determine the mitigation strategies, comprehensive prior knowledge is needed about the vulnerable areas, their population, and the reasons behind their vulnerability [19]. For the estimation of potential groundwater pollution, a number



of overlay and index methods are now available [20]; nevertheless, the DRASTIC model espoused the simplest, effective and comprehensive. and accessibility of parameters among each of these approaches [21-23]. The most frequently used models are SEEPAGE, GOD, EPIK, DRASTIC and SINTACS. DRASTIC is particularly the most documented and differentiated model among them [24-25]. This model has been implemented by several regions for groundwater vulnerability evaluation due to its unpretentious nature, notably Africa, Europe, Iraq, India, Indonesia, Iran, Jordan, and the United States [22]. NWWA (National Water Well Association) and USEPA (United States Environmental Protection Agency) established this method for the systematical evaluation of potential groundwater pollution in any area of the United States [26].

Since then the method was adopted worldwide because the input factors required for its computation are usually easily available from public agencies [27]. On the other hand, as the weights and ratings described for particular features in the original DRASTIC model do not always cope up with the exactitudes of the areas under observation, the final results of the index for those areas are considered as uncertain. A number of scientists and researchers have also modified or improved the method based on climatic, geological, hydrogeological settings and other particular conditions prevalent in their study area [28-30]. The DRASTIC model assumes that the groundwater vulnerability is controlled by few major known factors which can be weighted [31]. The advantage of using DRASTIC model is that it involves high number of parameters which ultimately reduces the influence of errors arising from an individual data layer on the final map [32]. In order to save time and get reliable results, nowadays, the scientists use GIS to evaluate DRASTIC model. The geodatabase generation, spatial analysis and modelling along with data integration facilities in GIS software allows the researchers to efficiently incorporate, analyze and manipulate geomorphological and hydrogeological data. The result of DRASTIC model is a map showing areas of different vulnerability index. The areas comprising of similar index values can be classified from high to low vulnerability zones. The higher vulnerability areas once demarcated need to be targeted for serious groundwater monitoring and suitable land use [33].

Previously, the DRASTIC vulnerability model has been applied to plateau [34-35], watershed [36-37], large basin [38-39], vast plain [40-41], valley [42-43], doab [44-45], etc. but to our knowledge no study regarding DRASTIC model has yet been conducted especially focusing on the pollution potential of urban areas of the mega cities. As groundwater pollution, in fact, is a matter of concern for public health and the mega cities

are crowded by the people so this study focuses on the urban area to analyze the vulnerability of groundwater which is a source of drinking water to over twelve million residents of Lahore. Furthermore, the groundwater arsenic contamination data was used to validate the results of modified DRASTIC model. The evaluation of groundwater quality on continual basis is imperative for such a metropolitan.

Materials and methods

Study area

Lahore is the second largest metropolitan of Pakistan and also the capital of Punjab province having a total population of 11.12 million [46] According to population census of 2023, the population density of Lahore metropolitan is 7,339/km². Due to availability of modern facilities of life, like multiple universities, hospitals, employment opportunities in large companies, better security and updated infrastructure, it is a center of attraction for the nearby rural population. Lahore is bounded by Sheikhpura district in the Northwest and Kasur district in the South. River Ravi, a main source of groundwater recharge to the Lahore aquifer, flows in the northwest of the city, but it continues to be dried up for a major part of the year after 2000 [47]. [48] cited that aquifers located in the current study area are considered to be recharged by precipitation (most prevalent in the monsoon season), the River Ravi, and irrigational canals. River Ravi receives untreated wastewater which contains municipal, industrial and animal waste. In Lahore, groundwater quality is under pressure due to anthropogenic activities. There are more than two thousand industrial units in Lahore. Water and Sanitation agency (WASA) provides drinking water from more than 500 tubewells having maximum depth range of about 120–245 m [49]. The underlying Lahore aquifer is the only source of drinking water [50]. This study is covering those areas of Lahore which comes under the WASA authority and approximately covers 245km². In context of climatic conditions, Lahore is considered as semi-arid region with an average rainfall of 715mm. Figure 1 is showing the study area of District Lahore and the geographical locations of WASA tubewells whereas the location of major roads is provided in Figure 2.

Modified DRASTIC model

DRASTIC vulnerability model comprises of seven factors. Groundwater vulnerability is assessed by employing the DRASTIC model, which allocates ratings (R), weights (W), and media ranges to each DRASTIC parameter, as reported by [31 and 51]. Every hydro geological factor is given a 1 – 10 rating value and a 1 – 5 weighting value (Table I). The parameter with the greatest impact is assigned a weight of 5, whereas the least influential factor is provided a weight of 1 [52].

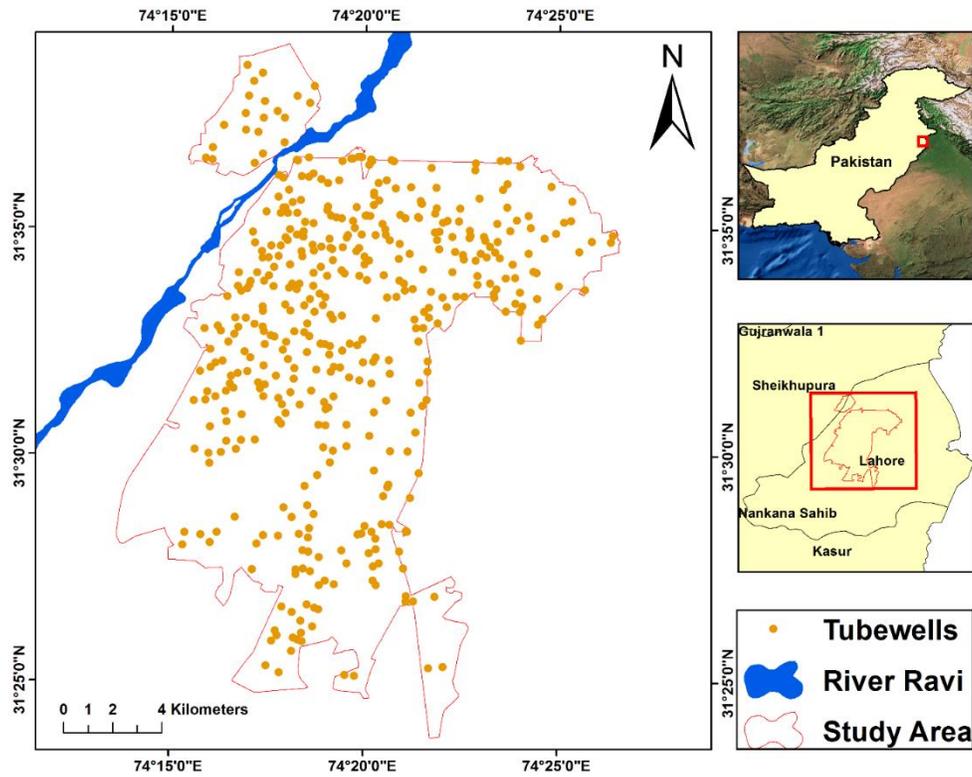


Figure 1. Study area and geographical locations of tubewells in Lahore district.

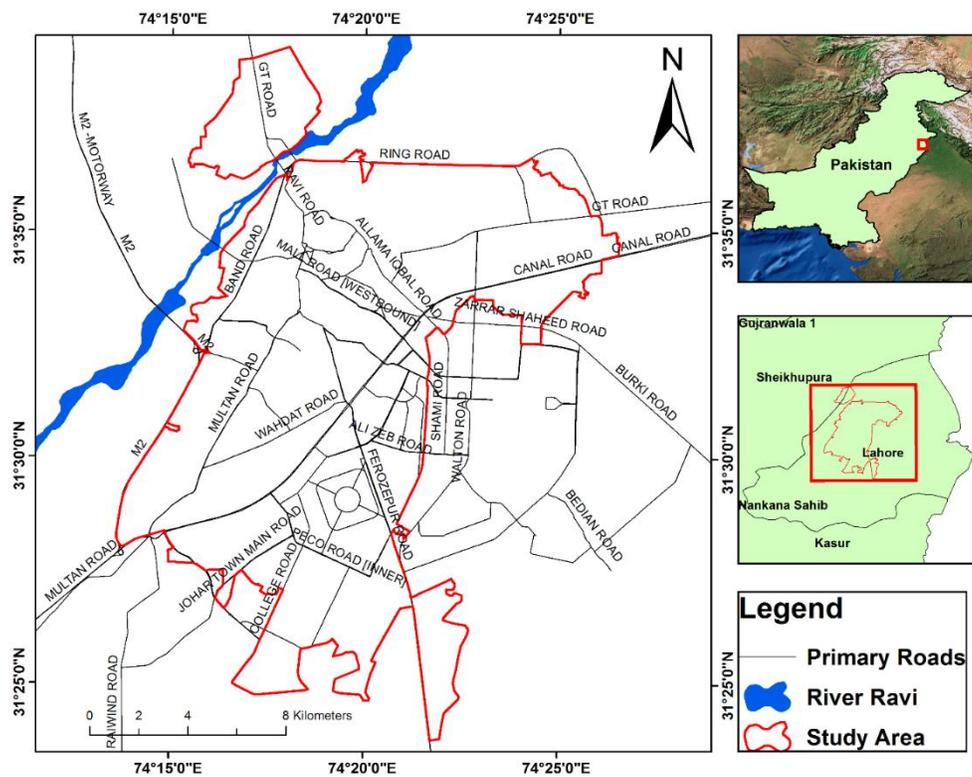


Figure 2. Study area boundary and the location of major roads of Lahore.

To find out the DRASTIC index, all factors were unified by overlay index analysis method and the sum of these factors at all locations is calculated on ArcGIS. The higher the DRASTIC vulnerability index at a location, the higher the groundwater vulnerability [41]. The results of groundwater vulnerability mapping can be graded into several classifications representing comparable contamination possibility of groundwater. The formula for the index calculation is given below:

$$DVI = TrTw + RrRw + ArAw + IrIw + CrCw + SrSw + DrDw$$

Here;

w = Thematic layer's weights (range 1 – 5)

r = Each class is given the rating of thematic layer (range 1 – 10)

R = Recharge of water

D = Depth of water table

S = Soil media

A = Aquifer media

I = Impact of vadose zone

T = Topography

C = Hydraulic conductivity

DVI = DRASTIC model vulnerability index

Table I

Actual weights for DRASTIC Parameters [53]

| Parameters | Weights |
|------------------------|---------|
| Depth to water table | 5 |
| Recharge | 4 |
| Aquifer media | 3 |
| Soil media | 2 |
| Topography | 1 |
| Impact of vadose zone | 5 |
| Hydraulic Conductivity | 3 |

Depth to water table

The depth to water refers to the distance in meters from ground surface to water table. The contaminant percolates through this depth to reach the aquifer. The deeper water table has relatively fewer chances of getting contaminated than the shallower water table. The depth to water table data of 343 tubewells was available. The data was added in the attribute table of tubewell shapefile containing corresponding geographic coordinates of WASA tubewells. The water table values were interpolated to get the water table depth for the whole study area. The raster containing water table pixels was classified while keeping in view the 'original' DRASTIC ratings for water depth (Table II) [53].

Table II

Ranges (m) and ratings for depth to water table

| Ranges | Ratings |
|----------------|---------|
| 9.1m to 15.2m | 5 |
| 15.2m to 22.9m | 3 |
| 22.9m to 30.5m | 2 |

| | |
|-----------------|---|
| More than 30.5m | 1 |
|-----------------|---|

Recharge

The groundwater recharge refers to the total quantity of water that seeps into the ground surface and reaches the water table on an annual basis. It can be considered as means of transportation for the pollutants to reach the aquifer. The reliable data of net recharge from the urban area was unavailable. So, instead of using recharge values for the study area, a modification in the DRASTIC model was done by using the land use/cover data of Lahore city to provide the recharge values. The interrelated land use/cover classes were merged and reclassified to be used in the modified DRASTIC model for assigning the ratings of recharge to different land use/cover classes [54]. Though Lahore city receives a reasonable and regular rainfall in terms of quantity to recharge the aquifer from rainwater harvesting [55], but most of the study area comprises of built-up area. The roofs, roads and pavements does not allow the rainfall to directly infiltrate into the ground. As a result, the recharge from this portion is very low. Hence, it was assigned the lowest rating of 1. According to WASA personnel (personnel communication), the tertiary drains designed to accumulate storm water during monsoon season carry loads of water to secondary and primary drains. A lot of seepage from unlined drains also occurs during the process. The unlined Lahore canal that passes through the urban center along with several primary drains also contribute to the recharge significantly. The seepage from River Ravi undoubtedly is still the principal source of recharge to the aquifer. So, the water bodies were assigned a maximum rating of 10 for the recharge parameter. The agricultural and open lands also exist in few parts of Lahore city. The infiltration from agricultural areas and the low lying open lands having stagnant rainwater act as ponds for recharge, so the rating for bare lands was assigned to 6. There are more than 850 large and small parks in Lahore that are under the jurisdiction of Parks and Horticulture Authority and they are regularly irrigated with freshwater [56]. The parks were assigned a rating of 5. The sparsely built-up areas mostly have grassy or open area so they were assigned a rating of 4 (Table III).

Table III

Classes of LULC and their ratings for recharge parameters

| LULC Classes | Ratings |
|----------------------------------|---------|
| Water bodies | 10 |
| Agricultural and low lying areas | 6 |
| Gardens | 5 |
| Sparsely built-up areas | 4 |
| Completely built-up areas | 1 |

Aquifer Media

The aquifer media layer illustrates the properties of saturated zone material that controls the contaminant attenuation processes. The speed of contaminant movement is also dependent on the aquifer media. The aquifer containing high void ratio has higher permeability and vulnerability towards pollution. The aquifer information layer from WAPDA was integrated into the model. The sand and kankar mixture contains larger pores than the coarse sand and fine to medium sand so it was assigned the highest rating than the others. The aquifer media ratings for the layer are provided in Table IV.

Table IV
Aquifer media layers and their ratings

| Aquifer media layer | Ratings |
|--------------------------|---------|
| Coarse type sand | 7 |
| Kankar and sand mixture | 8 |
| Fine sand to medium sand | 6 |

Soil media

Soil media parameter represents the uppermost weathered portion of the unsaturated zone where the biological activities are higher. It controls the amount of recharge that can infiltrate into the sub-surface. The fine grained soils like clay or even silt indicate lower soil permeability and decreases the transportation of toxins, whereas, the loamy soils are well known for their infiltration capacity. The soil texture data from WAPDA was used to identify the spatial variability of soil in the study area. The rating values for different soil texture classes is listed in Table V.

Table V
Classes of soil texture and their ratings

| Classes of soil texture | Ratings |
|-------------------------|---------|
| Loam | 5 |
| Sandy Loam | 6 |
| Clay loam | 3 |
| Silty Loam | 4 |

Topography

Topography refers to slope of the surface as percentage in the DRASTIC model. Not only it has an effect on the soil type of the surface but it also determines whether the surface runoff will allow contaminants to percolate into the saturated zone. Gentle slopes reduce the flow rate of surface runoff and provide more residence time for rainwater to infiltrate. Therefore, the seepage will be higher and the area is more vulnerable to groundwater pollution. Lahore has a very gentle slope and keeping in view the slope of Lahore, a 'constant raster' was created in ArcGIS software to assign a constant rating of 10 for the plain study area.

Impact of Vadose Zone

Impact of vadose zone refers to the portion of sub-surface that is above groundwater and is either

unsaturated or discontinuously saturated. The contaminant travels from this zone before reaching the groundwater. It is a complex factor and different physicochemical processes also occur here. Depending on the lithology and travel distance, it acts as a natural filter and minimizes the pollution effects. The ranges and rating assigned to the vadose zone media are shown in Table VI.

Table VI
Vadose zone media ranges and their ratings

| Ranges | Ratings |
|---------------------------|---------|
| Sandy clay | 5 |
| Fine sand to medium sand | 7 |
| Kankar clay/ surface clay | 3 |
| Hard clay | 2 |

Hydraulic Conductivity

Hydraulic conductivity indicates the ability of aquifer to transmit water through the soil profile. It regulates the flow rate of a contaminant within the groundwater system which depends upon the viscosity, density, permeability and saturation. The porous material has high hydraulic transmission so it is more vulnerable to pollution. Due to non-availability of the specific hydraulic conductivity values for the study area, the typical values of the prevailing hydrogeological conditions can be incorporated in the DRASTIC model [57]. So considering the available data about aquifer media, the typical values for hydraulic conductivity were assigned [58]. The ratings for different classes is available in Table VII.

Table VII
Hydraulic conductivity ranges and ratings

| Ranges | Ratings |
|------------------------|---------|
| Greater than 12.2m/day | 4 |
| 3.7 to 12.2m/day | 2 |

The shapefiles for land use/cover, aquifer media, soil media, impact of vadose zone and hydraulic conductivity were converted to raster format. These rasters along with the interpolated depth to water table and the constant slope rasters were reclassified to bring them in accordance with the DRASTIC model requirements. After the assignment of weights and ratings, the modified DRASTIC vulnerability index, Eq. (1), was calculated using spatial analyst extension of ArcGIS software.

Results and Discussions

Modified DRASTIC model

Water table Depth

The water table map (Figure 2a) showed that the north western part of the study area is more prone to contamination as it has lowest depth to water table, i.e., across River Ravi. The water table decreases moving away from the river in the east. This could be due to recharging of the aquifer from river which eventually

raises the water table in nearby areas. The maximum rating 5 was assigned to the areas showing water table less than 15.2 m and the minimum rating 1 was assigned to the areas showing water table depth more than 30.5 m [53]. Generally, the central and eastern parts of the study area had quite deep water table because of over-exploitation of groundwater due to horticultural requirements, rapid urbanization and increased domestic use. The maximum depth to water table was observed as 46.9 m in the study area.

Groundwater recharge

The land use/cover map (Figure 2b) incorporated to assign recharge ratings revealed that the major recharge areas are the active flood plain area of River Ravi and the adjacent agricultural or open land belt. The presence of agricultural lands and open areas in the bordering parts of the study area are expected to enhance deep percolation. These areas were also associated with adjoining cottage industries and the water from urban and industrial waste might be used for irrigating [59]. [60] also reported that the spinach crop irrigated from wastewater near Saggian had higher levels of toxic metals. The irrigation of hundreds of parks in the study area requires a lot of water and in case of heavy rainfall the water percolates through the sub-surface. The large and small sparsely built-up features also exist in the area. Here the rooftop rainwater accumulated in the pipelines is often drained out on the ground surface and it joins the water already flowing there. The water soaks into the surface from nearby grassy area and open land. Most of the study area is built-up and is landscaped in such a way that there is hardly any direct infiltration of the rainfall, so most of the rainwater reaches the tertiary drains of WASA.

Aquifer media

The aquifer media map (Figure 2c) showed that the fine to medium sand is prevalent in the western parts along River Ravi while eastern parts have coarse sand dominant in the aquifer. However, there are areas of sand and kankar in few portions of the study area. The kankars are rolled, often nodular residuals of calcium carbonate formed in the soils of semi-arid regions. Although their size, shape and smoothness depends on the soil texture yet these granules mixed with sand or the substantial dominance of sand in the entire area indicates larger spaces between the particle which makes this rich and extensive aquifer more prone to pollution.

Soil media

The soil map (Figure 2d) showed sandy loam on both sides of the River Ravi. A belt of loam, which contains almost an equal share of sand, silt and clay, is found next to the sandy loam. The central part of the study area is covered with silty clay loam. The presence of clay loam is dominant in the southern and north eastern parts. It is evident from the soil map that the sandy areas in the

western part of the study area are more prone to water pollution than the clay lenses in the north and south.

Topography

According to the DRASTIC classification [53], the flat land topography or very gentle slopes having percentage slope 0-2% are assigned the highest rating of 10. In general, Lahore has a flat topography with a very low average gradient, i.e., 1:3000 in the south and south-west [61]. So the slope of Lahore is conducive for water percolation.

Impact of vadose zone

The impact of vadose zone map (Figure 2e) showed that the unsaturated zone lithology mainly consists of fine to medium sand and hard clay. The fine to medium sand is spread on both sides of River Ravi and covers the western to central part of the study area, while the hard clay covers the eastern part of the study area which is far away from the river. There are few deposits of sandy clay and clay kankar in all parts of the study area.

Hydraulic conductivity

The map (Figure 2f) showed that the sand with kankars and the coarse sand that covers the eastern part of Lahore have hydraulic conductivity values above 12.2 m/day. It means that these areas favour the fast movement of a contaminant in the aquifer and are more prone to vulnerability. The fine to medium sandy areas spreading all over the western part have hydraulic conductivity values ranging from 3.7 to 12.2 m/day.

The results of the modified DRASTIC vulnerability index range from 64 to 144. The vulnerability to groundwater in an area is compared in terms of its response to identical contamination sources and is validated in a relative manner [62]. So, four categories having an index interval of 20 were created to describe the spatial variability of groundwater vulnerability in the study area. The modified DRASTIC index values were classified as 'low' for values 64-84, 'moderate' for values 85-104, 'high' for values 105-124 and 'very high' for values 125-144. The area covered by low, moderate, high and very high classes were 51.38%, 36.77%, 9.48% and 2.37%, respectively (Figure 4).

The two vulnerability classes 'low' and 'moderate' encompass more than two thirds of the area but it does not mean that these areas are not polluted or there is no pollution potential from toxic arsenic as a result of anthropogenic activities because the DRASTIC classes are relative [63]. However, the comparison between low, moderate, high and very high valued areas needs to be done. The distribution of 'moderate' vulnerability areas which cover more than one third of the area are mainly in the western half and northern parts of Lahore. The western part of Lahore showing 'high' and 'very high' vulnerability classes means that the potential for pollution is high there or these areas are more vulnerable to pollution.

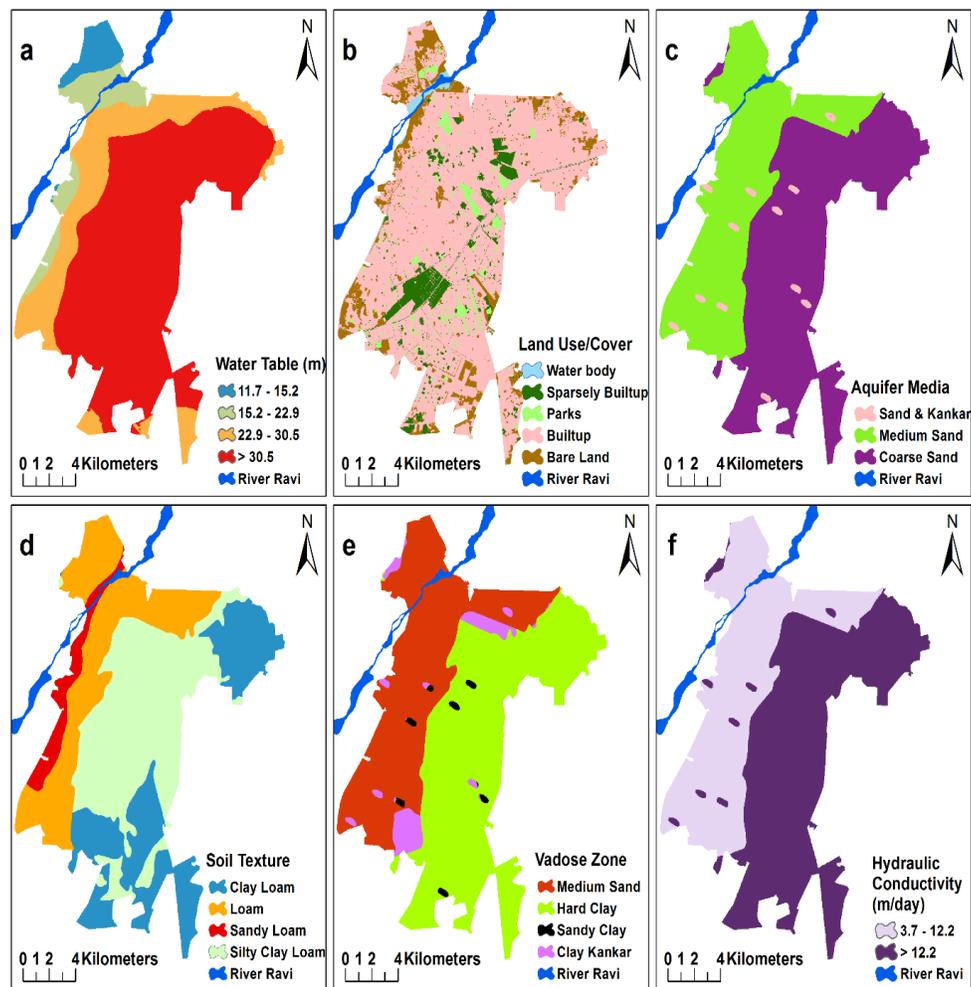


Figure 3. Layers of (a) water table depth (b) land use/cover (c) hydraulic conductivity (d) vadose zone (e) soil map and (f) aquifer media of Lahore aquifer used for computing the modified DRASTIC index

These areas are attributed to shallow water table and the dominance of sand particles in the soil, vadose zone and aquifer. On the other hand, the 'low' vulnerability class in the eastern part means that these areas are more resistant to pollution potential. The lower vulnerability observed there was due to deep water table and prevalence of clay particles in the soil and vadose zone. Comparatively, the impact of the vadose zone and the depth to the water table were determined to be the most significant criteria in the groundwater vulnerability mapping among all the factors, and as a result, both were ascribed with the greatest weightage. According to the analysis of the current study shows that groundwater is generally more prone to contamination in regions with lower groundwater depths and less susceptible in regions with greater groundwater depths which is in agreement with multiple previous researches [13 and 64-66]. The water table of Lahore is closest to the ground

in the vicinity of River Ravi [67]. The Lahore aquifer is especially susceptible to water contamination because of its low gradient, which affects outflow and groundwater discharge. The relevant studies employing the DRASTIC model in different groundwater aquifer plains demonstrated that the groundwater vulnerability index's parameters rely particularly on the aquifer's features [68]. The aquifer media exerts a major role in the transport of pollutants as described by [69], which also contributes significantly to the excessive recharge [70]. This implies that the DRASTIC methodology is appropriate for mapping vulnerabilities in this particular region. It also concurs with the findings of a number of previous studies assessments, such as those conducted by [8] for Bangladesh, [71] for Iran, [72] for Nigeria, [73] for India, and [70] for the UAE.

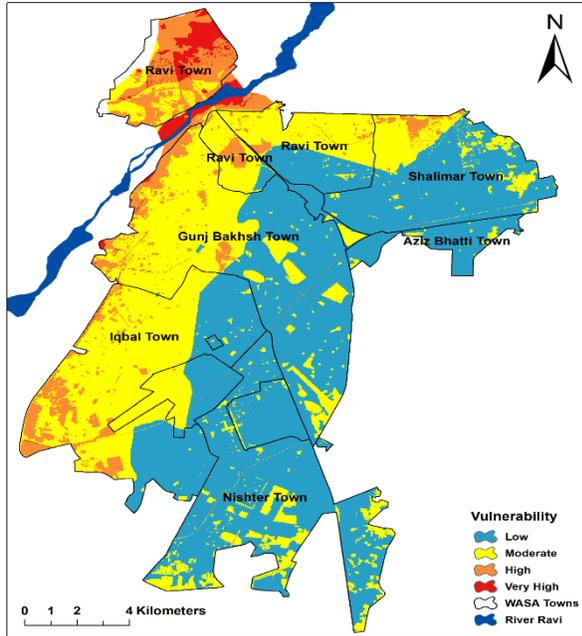


Figure 4. Map of modified DRASTIC vulnerability index in the study area.

In the recent past, a lot has been uttered in the media about the arsenic contamination in the groundwater of Lahore. In order to validate the results of DRASTIC model, the available arsenic contamination data of 446 tubewells from WASA Lahore was used to find out the spatial variability of groundwater arsenic in the study area. The groundwater arsenic concentrations map (Figure 5) shows that the higher values are concentrated in the north western part of the study area. These findings are in line with the findings of [74] who reported that the relatively higher arsenic concentrations along River Ravi might be attributed to the percolation of effluents from the soakage pits along several unauthorized industries in the study area. The leachate from these deep pits contains several toxins and severely contaminate the groundwater. Consequently, the arsenic concentrations in the vicinity of River Ravi are relatively higher. In order to further validate the results, the Pearson’s coefficient of correlation for groundwater arsenic with modified DRASTIC index was computed at WASA town level. The results showed that the arsenic concentrations were positively correlated with modified DRASTIC vulnerability index in Gunj Bakhsh Town, Ravi Town and Shalimar Town, whereas, they were negatively correlated with modified DRASTIC index in Aziz Bhatti Town, Iqbal Town and Nishtar Town. The correlation results in all the WASA towns were not significant ($p > 0.05$) except in Ravi Town, where it was found significant ($p < 0.01$). The highly significant positive correlation of arsenic with modified DRASTIC index in Ravi Town could be explained as

the water table in this area is relatively lower and the vulnerability index is higher as compared with other parts of the study area. Consequently, the use of pesticides on the agricultural areas and the effluents seepage from industrial waste is a menace for the aquifer. In addition to this, the toxin carried by River Ravi combined with the arsenic from geogenic sources aggravate its concentration in the aquifer. It could be inferred from groundwater arsenic concentrations map that the geogenic sources (weathering and erosion of bedrocks) might also have a substantial contribution to this extensive contamination of arsenic in groundwater. This is because neither the industries nor unlined drains exist in the whole study area. Furthermore, the modified DRASTIC model does not indicate higher vulnerability in most of the eastern parts of the study area yet the arsenic concentrations above WHO guideline ($10 \mu\text{g/L}$) are distributed in the entire area.

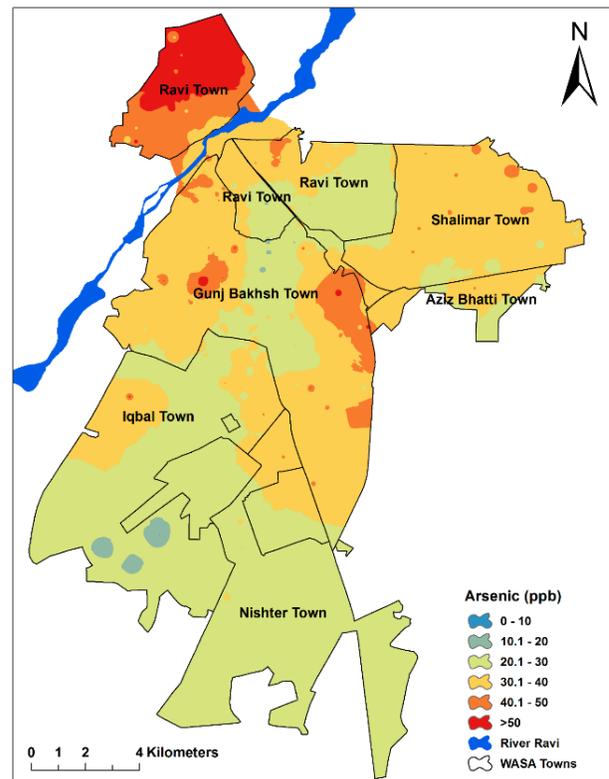


Figure 5. Map showing groundwater arsenic concentrations in the study area

Conclusion

Establishing a sustainable groundwater resource requires an extensive apprehension of groundwater vulnerability. The modified model ascertained in this research has been separated into four vulnerability classes ranging from low to very high vulnerability zones, with percentage areas for each class being calculated. To evaluate the overall vulnerability of the study region for groundwater potential, the various

hydrogeological factors were incorporated that include water table levels, land use/cover, slope, hydraulic conductivity, vadose zone characteristics, soil media, and aquifer media layers. The vulnerability index showed that the values are higher along River Ravi and nearby areas, moving away from River Ravi these values decrease. The presence of high values of arsenic are also concentrated along River Ravi. The highly significant positive correlation of arsenic with modified DRASTIC vulnerability index in Ravi Town indicates that the anthropogenic activities in the town may also contribute to groundwater arsenic in addition to geogenic sources. It is anticipated that the information resulting from the vulnerability investigation may allow the managers to be proactive in planning preventive measures, taking pre-emptive interventions and implement a revised water quality strategy to save the population living in the vulnerable areas of Lahore.

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