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Original Research

Contamination Potential Assessment of Potable Groundwater in Lahore, Pakistan

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Abstract

The water supply in Lahore, Pakistan, is totally dependent on groundwater, which is creating a number of challenges due to mismanagement of groundwater resources and an exploding population. An unconfined aquifer is receiving pollutants from a poor drainage system, non-scientific landfills, and through untreated effluents from industries and domestic sources. A study was conducted to evaluate groundwater qualities: total dissolved solids, total hardness, pH, alkalinity, and turbidity. Using geographic information system (GIS), drinking water quality zones were developed with groundwater chemical analysis data. Applying World Health Organization (WHO) drinking water standards, 61% of the total area is excellent, 27% is good, 9% is moderate and 3% has poor quality, while only 5% of the area is excellent, 29% is good, 34% is moderate, and 32% is not suitable for drinking purposes using Pakistan Standards and Quality Control Authority (PSQCA) drinking water standards. According to 2010 groundwater chemical analysis data, most areas have suitable zones for drinking purposes; however, there is high risk of continuous contamination. Finally, this study identifies highly contaminated groundwater zones and makes it convenient to find actual pollutants. Therefore, plans are needed to protect the aquifer.

Keywords: groundwater quality, potable water, risk assessment, contamination, drinking purpose, GIS, Lahore

Introduction

The rapid growth of large, sprawling cities can quickly outpace the development and exploitation of required natural resources, making it very difficult to balance the demand for natural resources with their availability. The pollution potential in groundwater and river water is significant due to runoff from dump sites that deteriorate portable water resources [1]. The dumping sites need to be assessed regarding their effects on human health and the ecosystem [2]. High levels of toxic elements in urban groundwater have linked to sewage and cultivation activities [3]. Polar and non-polar chemicals are infiltrating from municipal landfill leachate [4]. Organic, inorganic, the toxic chemicals and heavy metals concentrations are continuously high in various parts of the world [5]. Contaminated urban soil is affecting human health directly and indirectly [6].

Groundwater is one of the most significant and rapidly consumed natural resources, requiring a balance among human demand, the rate of socio-economic progress, and ecosystem maintenance [7-9]. The need to maintain a balance means that it is not possible to fulfill ever-increasing demands for groundwater with an ever-growing population.

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Over-exploitation of groundwater combined with less recharge results in increased pollution and rapid deterioration of water quality. Many factors have led to changes in groundwater composition around the world, but human activities are the most significant [10]. Emília Silva depicted during a study that groundwater exposure to pesticides is determined by such environmental, agricultural, or geological factors as precipitation, crops, soil, and irrigation practices. Groundwater results show high pesticide contamination levels during spring and autumn [11]. Tannery effluents contain high concentrations of toxic metals and chemicals, which are badly affected by shallow groundwater and deep groundwater of such industrial areas in Pakistan [12].

Deterioration of groundwater supplies related to human activities may result from poorly designed landfills, open drains, and a lack of sewage and wastewater treatment. These problems are particularly acute in developing countries where poor water management systems exacerbate the problems. In Pakistan, groundwater is considered a primary resource to be managed for a variety of societal needs, but its major use is for domestic consumption.

Pollutant distribution can be mapped with geographic information systems (GIS), a popular tool for analyzing, storing, and displaying spatial data so that it can be used for decision making in various areas such as environmental and engineering fields [13-15]. GIS is a powerful tool for developing and managing thematic data, and can be used to map out groundwater quality areas based on chemical analysis data [16]. Many researchers have used GIS to map water quality zones and to investigate the suitability of groundwater for various purposes, such as human consumption, as well as domestic, industrial, and agricultural activities. Developing groundwater risk assessment maps can provide preliminary data for any area and can be used to direct future study. Such maps can also outline areas of environmental health risk so that problems can be minimized and precautionary measures can be taken.

This study involved analysis of physico-chemical data from groundwater samples collected in Lahore in order to find and specify groundwater zones and to assess their suitability as sources of drinking water. Groundwater potential zones were developed by assigning weights to each parameter and plotting the data using geospatial techniques. However, during the current study two different drinking water standards were applied for comparison, those of WHO and PSQCA, to assess the groundwater in Lahore for its suitability for human consumption The study identified a number of areas with poor water quality, which can be used to identify sources of pollutants, thus allowing municipal officials to take precautionary measures to protect the aquifer.

The Study Area

Lahore is a rapidly growing city lying between latitudes 31º20′ and 31º50′ N and longitudes 74º05′ and 74º37′ E in the province of Punjab, Pakistan. The study area is located on the east bank of the Ravi River. Its boundaries extend from the Hudiara Drain in the south, across the Ravi River to Degh Nala in the west, then northward to Muridke on the General Trunk Road and finally eastward to the border with India [17] (Fig. 1). Lahore is located on a low alluvial plain,

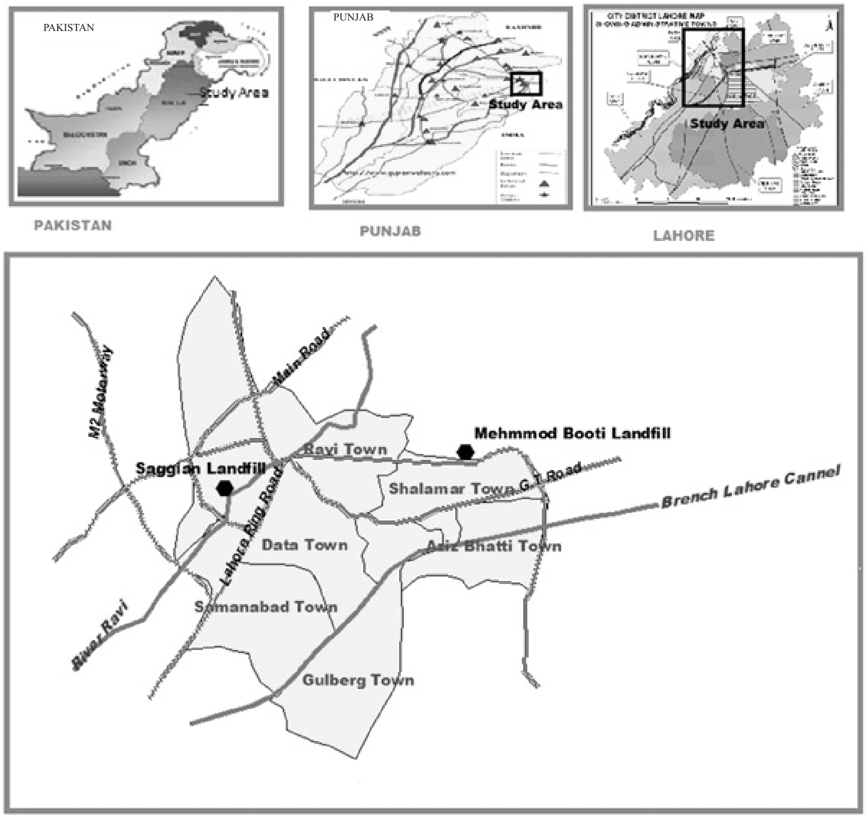


Fig. 1. Map of the study area.

an area undergoing rapid development with little concern for geo-environmental consequences. A rapidly growing population, increasing groundwater depletion, pollution, and scarcity are considered the biggest challenges for this groundwater-dependent city. Both the temperature and rainfall vary greatly from season to season with a mean temperature that ranges from 34ºC in June to 12ºC in January and an average rainfall of 575 mm per year, which can vary from 300 to 1200 mm. The evapotranspiration is about 1750 mm per year, which is the principal reason why extensive irrigation is needed for agricultural purposes (NESPAK 1993: [18]). In Lahore the groundwater table currently varies between 14 to 43 m, and is dropping an average of 0.84 m per year. Thus the increasing withdrawal of potable water means that the main city area is facing a rapid groundwater decline. During our study we determined that from 1960 to 1987 the water table dropped more than 15 m in some parts of Lahore (NESPAK 1993: [18]). Currently, the groundwater moves from North to South at a velocity 1-1.5 cm/day [19].

Modern soils in the area consist of silt, clay, loamy clay and sand; however, loamy clay gradually increases with distance from the Ravi River [20]. The aquifer underlying the Lahore area is composed of unconsolidated alluvial sediments composed of varying proportions of silt, sand, and clay.

In 1901 the population of Distract Lahore was 0.203 million, but it increased to more than 5 million by 1990. From 1981 to 1998 the population increased 3.32% annually and now exceeds 10 million, with a growth rate of 3.3% per year (Solid Waste Management Lahore, unpublish). The city of Lahore is divided into nine administrative units, or towns that, provide services and facilities to local communities. Our study focused on six of these towns: Ravi, Gulberg, Data, Ganj Baksh, Samanabad, Shalimar, and 21% of Aziz Bhatti. The current study area includes about 229 km^2 and had a population in 2011 of about 5.6 million. Groundwater chemical data from the investigated areas were used to identify zones of potential contamination.

The Ravi River has always been the main recharge source for the aquifer but since 1960 increased consumption by India has seriously affected the recharge efficiency. In addition, the river presently receives 47% of all municipal and industrial pollution load discharged into all the rivers of Pakistan [21]. The Hudiara drain receives effluents from India with high concentrations of pollutants and then collects additional contaminated waste water from Pakistan before flowing into the Ravi River. The waste water from various sources contains organic, inorganic, industrial, municipal and animal waste as well as fertilizers and insecticides, which seep through the soil and significantly degrade groundwater quality. There are three active waste dumps around Lahore, all of which are unplanned and which contribute significant amounts of groundwater pollution. At least three-fourths of the total waste generated in Lahore every day (3,800 tons) is dumped at these sites without proper treatment. Landfill sites along the Ravi River are open dumps that continually pollute the soil, groundwater, and river water. Estimates suggest that more than 65% of the rainfall in the basin could potentially be utilized for agriculture, groundwater recharge, and drainage outflow, thus an assessment of potential groundwater contamination is needed to provide a guideline for future water resource management in Lahore.

Data Used and Methodology

A topographic map (1:50,000) was used to develop the base map of the study area. A comprehensive study of the geology and hydrogeology was conducted to investigate and understand the significant groundwater issues in the area. The Water and Sanitation Agency (WASA) of Lahore is a local government department responsible for maintaining the local water supply and sanitation system. The data used in this current study were collected from WASA, and five parameters were selected to determine water quality.

Using the Integrated Land and Water Information System (ILWIS), groundwater quality maps of total dissolved solids (TDS), total hardness (TH), pH, turbidity, and alkalinity were prepared and classified for spatial analysis, which involved two phases: phase I involved preparation of a thematic map while phase II focused on development of groundwater quality zones.

Phase I

The thematic map contains comprehensive information about the city boundaries, road network, water fields (sweet water zones), landfills, and towns within Lahore (Fig. 1). The groundwater samples were all collected from production wells, and water quality was assessed based on the available physico-chemical data. The chemical analysis data were used for water from 340 pumping wells in April 2010.

Phase II

The second phase of the project involved creation of spatial zones based on the physico-chemical parameters presented in Table 1. The spatial zones were generated and classified based on the desirable and permissible limits of individual parameters as defined by WHO and PSQCA for drinking water standards. The weights were assigned to each class of individual surfaces based on described drinking water criteria of each standard. Human judgment is integrated in the data analysis, especially during assignment of weights for each class of an individual parameter after considering the impact and effects on human health.

Assigning high and low weights followed the procedures of WHO [22], PSQCA [23], and other standards such as those of Sawyer and McCarty [24]. They established a total hardness (TH) classification based on four categories as follows: for soft water the value must be less than 75 mg·L^{-1}, moderately hard water have values between 75-150 mg·L^{-1}, values between150-300 mg·L^{-1} represent hard water, and values higher than 300 mg·L^{-1} indicate very hard water [25]. Increasing values identify the degree of suit-

Table 1. Classification of each category of groundwater quality for domestic purposes and the assigned weights, Lahore Pakistan.

Class	Criteria	Weight
TDS (mg/l)		
Very low	<250	5
Low	250-500	4
Moderate	500-750	3
High	750-1000	2
Very high	>1000	1
Total hardness		
Softwater	<75	4
Moderately hard water	75-150	3
Hardwater	150- 300	2
Very hard water	>300	1
PH		
Acidic	<6.5	1
Neutral	6.5-7.5	4
Low Alkalic	7.5-8.5	3
High Alkalic	>8.5	1
Turbidity		
Very good	<0.5	4
Acceptable	0.5-2.5	3
Limited acceptable	2.5-5.0	2
Rejected	>5	1
Alkalinity		
Low	<100	5
Acceptable	100-200	4
Not acceptable	200-300	3
Rejected	>300	2

ability of the drinking water; for example, the highest weight, 4, is assigned for soft water class (<75 mg·L^{-1}), whereas for very hard water (>300 mg·L^{-1}), the lowest weight, 1, is assigned.

We used the geostatistical program ArcGIS9.3 to develop groundwater contamination maps for each parameter. Some other interpolation methods are also popular but the geostatistical technique has a superior number of functions for data analysis, e.g exploratory spatial data analysis tools can be used to handle statistical properties and can be used to create various types of maps (probability, prediction, quantile, simple, and ordinary) using kriging and co-kriging. In addition, auxiliary tools are available for data transformation, declustering, and detrending: ordinary and Indicator kriging provide two different types of information; Ordinary Kriging is useful for developing contamination potential prediction maps, whereas indicator kriging is best for identification of probability.

Database tables were developed for each parameter with XY-coordinates and the concentration of pollutants. These tables were used to create suitable variogram models to portray the spatial structure of each parameter using GIS software (logarithms were applied to the data where the distribution was not normal). Ordinary kriging was then used to interpolate the variogram models and their parameters.

Criteria for Acceptable and Unacceptable Water Quality

In this phase the criteria for suitability and non-suitability of the water samples were elucidated for analysis. A classification was established based on the water quality standards stipulated by the WHO and PSQCA. Ranges for each parameter were assigned by considering the standards of both organizations, and are presented in Table 4 below.

Spatial surfaces were developed for each of the physico-chemical parameters based on the desirable and permissible limits of individual parameters according to WHO and PSQCA in order to show the spatiotemporal distribution of groundwater quality. Weights were assigned to each parameter in the individual surfaces based on drinking water criteria in Table 1.

Groundwater Quality Mapping

The rapid growth of the urban population in Lahore has resulted in unplanned settlements where the sewage system is undeveloped. In addition, old sewer lines have outlived their usefulness, leading to extensive leakage. The principal source of pollutants for groundwater in Lahore is sewage, mostly derived due to infiltration from sewer leakage, landfill sites, drains, and rivers. Some groundwater samples were found to have alkalinity, turbidity, hardness, and total dissolved solid values well above the desirable limits.

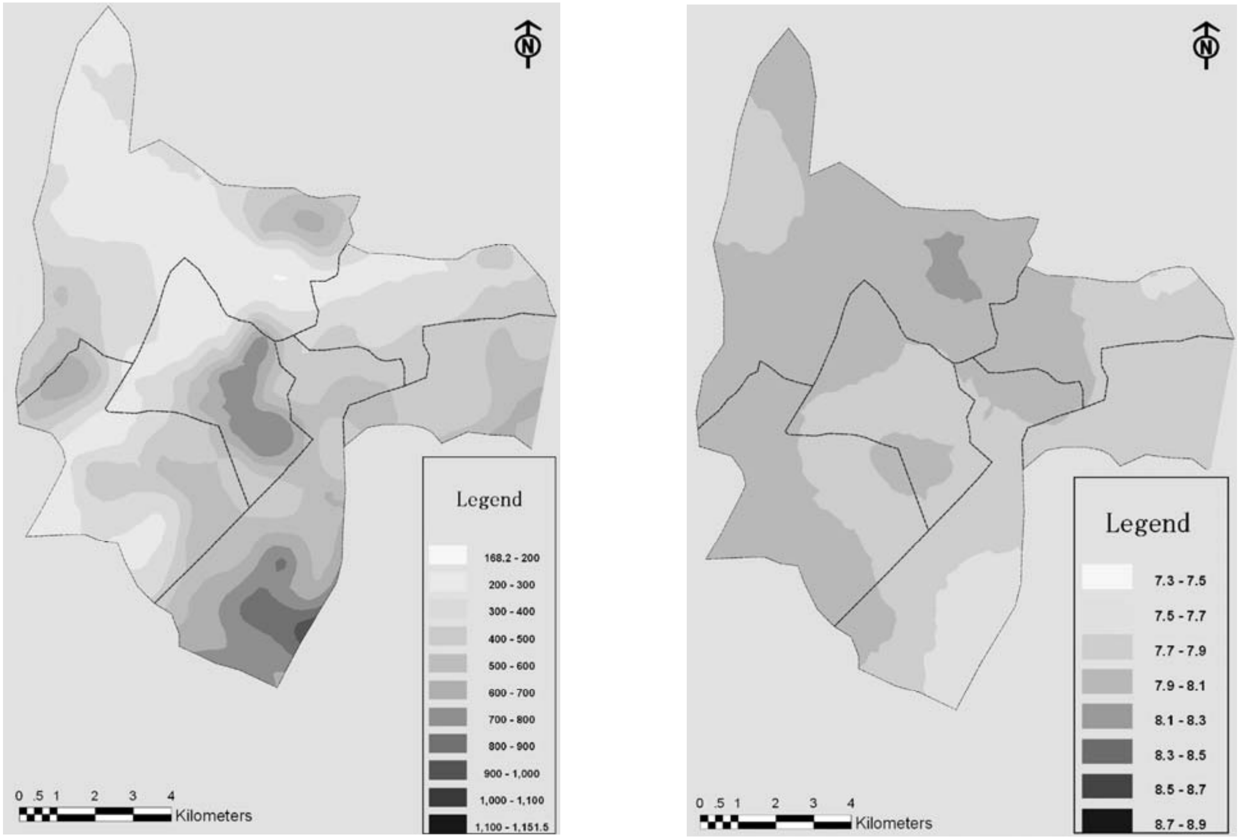
Groundwater quality thematic maps were developed for TDS, TH, pH, alkalinity, and turbidity within the study area, and these were integrated using the addition function available in the ArcGIS software. The final groundwater quality maps were created by overlaying the five thematic maps. The spatial integration for final groundwater quality zone mapping was carried out using the ArcGIS Geostatistical Analyst extension. We then delineated four areas (excellent, good, moderate, and poor) within the study area based on the quality of the groundwater for drinking purposes using the standards proposed by both WHO and PSQCA (Figs. 3A and B).

Results and Discussion

Groundwater quality maps are crucial in assessing the suitability of groundwater for various purposes, such as drinking, domestic consumption, agriculture, etc. Figs. 2A-E

A) TDS distribution in Lahore City

C) pH distribution in Lahore City



B) Total hardness distribution in Lahore City

D) Alkalinity distribution in Lahore City

Fig. 2. A) Spatial distribution of TDS in groundwater of Lahore, B) Spatial distribution of TH in groundwater of Lahore, C) Spatial distribution of pH in groundwater of Lahore, D) Spatial distribution of alkalinity in groundwater of Lahore.

E) Turbidity distribution in Lahore City

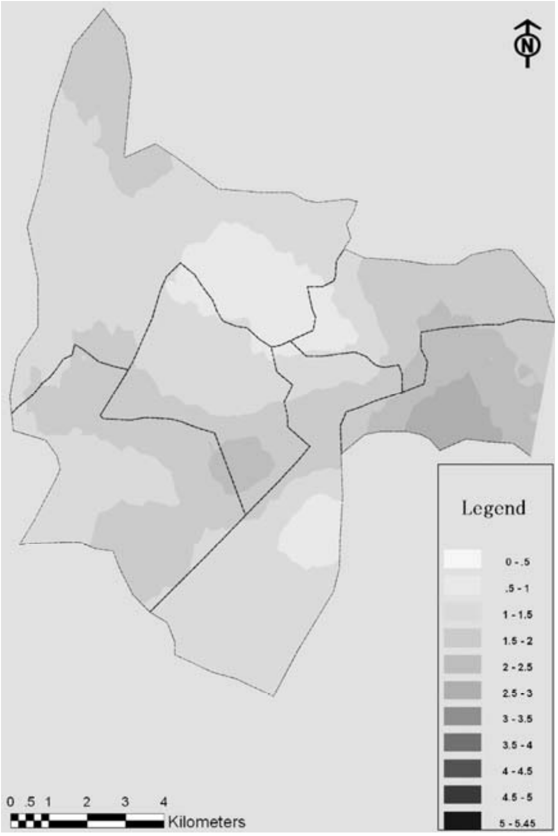


Fig. 2. Continued: E) Spatial distribution of turbidity in groundwater of Lahore.

show the spatial distribution of TDS, TH, pH, alkalinity and turbidity in the study area. Each of these characteristics has a particular criterion defining its suitability for drinking purposes (Table 1). According to WHO (1996) standards, TDS, TH, pH, and turbidity should be below 1000 mg/l, 500 mg/l, 6.5-8.5 and 5 NTU, respectively; otherwise the water is regarded as unsuitable for drinking purposes [26]. However, the standards set by PSQCA are much more stringent than those of WHO. PSQCA standards call for drinking water to have values for TDS, TH, pH, and turbidity below 500 mg/l , 250 mg/l, 6.5-8.5, and 0.5 NTU, respectively. Alkalinity criteria have not been set by either WHO or PSQCA for potable water. In Canada the recommended range of alkalinity is 80-120 ppm and in India values below 200 ppm are considered suitable for drinking and domestic use. Maps of groundwater quality suitable for drinking was prepared and areas were classified as excellent, good, moderate or poor (Table 3). Based on this mapping, water of suitable quality is present in the northern, western, and southern parts of the area, whereas that in the eastern part is of poor quality.

Total Dissolved Solids (TDS)

The TDS include all mineral constituents and other solids dissolved in water. The TDS in water is a general indicator of the overall suitability of water for many types of uses. High values of TDS influence the taste, hardness,

A) Final analysis as WHO

B) Final analysis as PSQCA

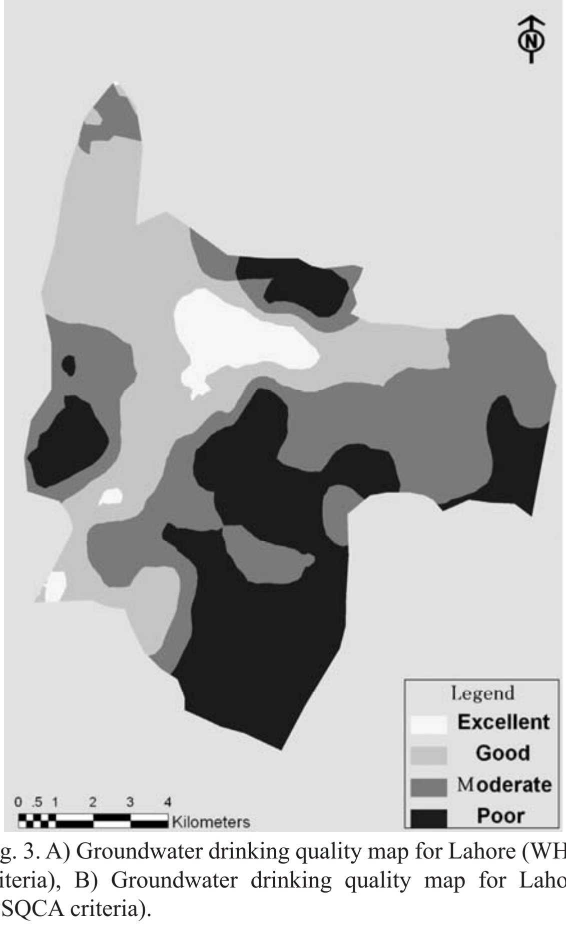


Fig. 3. A) Groundwater drinking quality map for Lahore (WHO criteria), B) Groundwater drinking quality map for Lahore (PSQCA criteria).

Table 2. Drinking water parameters and recommended permissible limits.

Parameter	Range in study area	WHO criteria	No. of samples within WHO range	No. of samples exceeding WHO range	PAQCA criteria	No of samples within PAQCA range	No. of samples exceeding PAQCA range
TDS	168.2-1151.5	1000 mg/l	329	11	500mg/l	215	125
Total hardness	56-435	500 mg/l	340	0	250 mg/l	313	27
pH	7.3-8.9	6.5-8.5	336	4	6.5-8.5	336	4
Turbidity	0-5.45	5 NTU	339	1	0.5NTU	53	287
Alkalinity	76-567	NA	232	108	NA	232	108

Table 3. Classification of groundwater quality for drinking in Lahore City (after overlaying and integrating all the categories applied to drinking purposes (WHO and PSQCA).

Class	% of area (WHO)	Area in km^2 (WHO)	% of area (PSQCA)	Area in km^2 (PSQCA)
Excellent	61%	139.91	5%	11.54
Good	27%	61.83	29%	67.12
Moderate	9%	19.88	34%	77.66
Poor	3%	6.98	32%	72.28

and corrosive property of the water [25, 27]. Water with more than 1000 mg/L of dissolved solids usually has a disagreeable taste and may have a laxative effect or make the water unsuitable in other respects. The TDS concentration in natural water is usually less than 500 mg/L, and water with more than 500 mg/L is undesirable for drinking and many industrial uses. Water with TDS less than 300 mg/L is desirable for dyeing of cloths and the manufacture of plastics, pulp paper, etc. [28]. Irrigation areas using groundwater are encumbered by the potential concentration of sodium and TDS [29]. Subba and Sohani reported that high TDS concentrations are due to the presence of bicarbonates, carbonates, sulphates, chlorides, and calcium, which may originate from natural sources, sewage, urban runoff, and industrial wastewater [30, 31]. They can also be derived from chemicals used in the water treatment process and from pipes or other hardware used in plumbing [32]. The TDS can be removed by reverse osmosis, electrodialysis, exchange, and solar distillation.

To determine the suitability of groundwater for any purpose, it is important to classify it according to its hydrochemical properties based on TDS values [33], which are represented in Table 4 and displayed spatially in Fig. 2A. It is recommended that waters containing more than 500 mg/l of dissolved solids not be used if other less mineralized supplies are available. The maximum contaminant level (MCL) for TDS in drinking water is given as 1000 mg/L by WHO and 500 mg/L by PSQCA (Table 2). However, 97% of the analyzed water samples were classified as acceptable using WHO standards, but only 63% qualified using PSQCA standards. The areas of highest TDS are in Ravi, Data, and Gulberg. There is a landfill located in Ravi and this is the apparent source of the pollutant there. The highest TDS concentrations are near the center of Data and in western Gulberg. Water taken from areas near the river and the cannels have the lowest TDS. The high concentrations occur in areas of over exploitation and low recharge, making it possible for pollutants to seep in quickly. In these areas 0.96% and 31% of the groundwater is unfit for drinking based on PSQCA and WHO standards, respectively, whereas in the overall study area 69% is acceptable using PSQCA standards and 99.1% is an acceptable using WHO criterion. Based on our study of TDS, nearly all of the water samples need treatment before use because most exceed the PSQCA limits.

Total Hardness (TH)

Calcium and magnesium are generally responsible for hardness in water. The TH of water may be divided into two main categories: carbonate compounds that are present temporarily and bi-carbonate compounds that are permanent. The combination of these two constitutes TH. Temporary hardness can be removed by boiling water, but permanent hardness requires more complex treatment. The maximum permissible limit of total hardness (TH) for drinking purposes is 500 mg/L and the most desirable limit is 100 mg/L as per the WHO international standard. For TH, the most suitable limit is 80 to 100 mg/L [34]. Groundwater exceeding 300 mg/L is considered to be very hard and unfit for most purposes [24].

In cultivated areas where lime and fertilizers are used, excessive hardness may also be due to other chemicals such as nitrates [35]. The removal of temporary hardness by heat causes deposition of calcium and magnesium carbonates as a hard scale in kettles, cooking utensils, heating coils, and boiler tubes resulting in a waste of fuel.

Table 4. Criteria for acceptable and unacceptable water quality.

Class	Criteria	Remarks
TDS (mg/l)	<500	Acceptable for PSQCA
	<1000	Acceptable for WHO
	>1000	Rejected
Total hardness	<250	Acceptable for PSQCA
	<500	Acceptable for WHO
	>500	Rejected
pH	<6.5	Rejected
	6.5-8.5	Acceptable for WHO and PSQCA
	>8.5	Rejected
Turbidity	<0.5	Acceptable for PSQCA
	<5	Acceptable for WHO
	>5	Rejected
Alkalinity	<120	Good
	<300	Acceptable
	>300	Rejected

In addition, the presence of calcium and magnesium changes chemical composition of water and makes soap insoluble. Hard water can form scum and curd on boiling, can cause boiled vegetables to become hard, can cause discoloration of fabrics, and can lead to medical problems such as diarrhea, excessive gas, kidney stones, and heart problems [26, 36].

All of the analyzed samples from Lahore had TH within the prescribed limits of WHO, but 27 have concentration exceeding PSQCA standards (Table 2). As shown in Table 1, most of the analyzed samples fall into the low hardness category. The highest TH occurs in the northern part of Ravi near a landfill site and factories, indicating that landfill leachate and industrial effluents are the main sources of total hardness in the study area. The groundwater in 97% of the study area is considered suitable for drinking based on PSQCA standards, whereas all samples qualify under WHO guidelines, indicating that the current level of total hardness is not a major threat to human health.

pH

pH is one of the most commonly analysed parameters in soil and water testing. It represents the acidic or alkaline potential of a solution and is measured on a scale of 1-14. A pH of 7 represents a neutral solution; less than 7 is acidic and greater than 7 is basic. The most acidic solution has a pH of 1, whereas the most basic has a value of 14.

The pH of drinking water generally is not a health concern because most groundwater has a value between 7.3 and 8.9 with an average of 8.1 (Table 2). However, extremely low pH levels may cause various health issues, such as irritation to the eyes, the skin, and mucous membranes. Likewise, very high pH values (10-12.5) can cause swelling of hair fibers and gastrointestinal irritation. The U.S. Environmental Protection Agency (EPA) does not regulate the pH level of drinking water. Instead, it is classified as a secondary contaminant whose impact is considered aesthetic [37]. However, the EPA recommends that public water systems maintain pH levels of between 6.5 and 8.5, a good guide for individual well owners [38]. Detergents and soap-based items are the common items most likely to enhance pH levels. Municipal water suppliers generally raise pH levels up to 9 to prevent corrosion of pipes. During wastewater treatment, the pH should be reduced to similar levels before being released into rivers or estuaries [39].

Both WHO and PSQCA recommend that pH levels for drinking water be in the range of 6.5 to 8.5. Most of the analyzed groundwater samples from Lahore City are slightly alkaline and only 1.2% deviate from the accepted range (Table 2).

The spatial distribution of pH in groundwater from Lahore is shown in Fig. 2C. The presence of untreated municipal and industrial effluent in the Ravi River and various domestic and industrial chemicals at Mehmood Booti landfill are potential causes for the somewhat increased pH levels in these areas. All but four of the analyzed samples have pH values not within the permissible limits. Essentially all the groundwater in the study area has pH values within the prescribed PSQCA and WHO criteria. Somewhat low pH values occur in northwestern and eastern parts of the aquifer. Slightly higher groundwater pH was found in Ravi.

Table 5. Statistical parameters of water samples in the study area.

Parameter	Min. Value	Max. Value	Avg. Value	SD	Variance
TDS	168.2	1121	441.5171	208.6935	43552.96
Total Hardness	62	387	170.6322	54.65707	2987.395
pH	7.3	8.9	7.886364	0.227325	0.050919
Turbidity	0	5.45	1.424739	1.000185	1.00037
Alkalinity	76	446	169.943	65.29803	4263.833

Alkalinity

Alkalinity is the buffering capacity of a water body. It measures the ability of water bodies to neutralize acids and bases, thereby maintaining a fairly stable pH. Without this buffering capacity, any acid added to a lake would immediately change its pH. Katherine Zeratsky, R.D, L.D., of the Mayo Clinic, says that even though proponents claim alkaline water can neutralize acid and boost your energy level and metabolism, there are no clinical studies that substantiate these claims [40]. Alkalinity is not considered detrimental to humans but is generally associated with high pH values, hardness, and excess dissolved solids. Highly alkaline waters may also have a distinctly flat, unpleasant taste [41]. Acidogenic and methanogenic factors can alter concentration of alkalinity in water bodies [42].

Alkalinity comes from rocks and soils, salts, certain plant activities, and certain industrial wastewater discharges (detergents and soap-based products are alkaline). If an area's geology contains large quantities of calcium carbonate ($CaCO_3$, limestone), water bodies tend to be more alkaline. Water with low alkalinity tends to be acidic, with a high pH. Thus household plumbing can be damaged by the corrosive action of the water, which can leach out copper and lead from the pipes. Eye irritation is one side affect of low alkalinity. Highly alkaline water can lead to dry skin, and cause scaling on pipes and plumbing fixtures [38]. High alkalinity levels can also cause many health problems such as the formation of kidney stones, production of excess gas, and severe irritation of the eyes, skin and mucus membranes [43]. A good balance in alkalinity is important in groundwater. However, alkalinity levels are usually looked at together with pH levels to get a better idea of complete water quality.

Alkalinity is not included in the WHO and PSQCA drinking water standards. In Canada the recommended range of alkalinity is 80-120 ppm and in India 200 mg/L is considered the upper acceptable limit. The alkalinity of the analyzed samples range from a minimum of 76 mg/L to a maximum of 567 mg/L, and the highest levels occur along the eastern side of the study area, particularly in Gulberg, Shalimar, and Aziz Bhatti towns (Fig. 2D). Drains and irrigation activities are the most likely sources of the high alkalinity in these areas. Ravi, Samanabad; and Data towns all have groundwater with low alkalinity, although there is apparently some seepage from the east. Overall, 18% of the analyzed water samples have alkalinities of 200 mg/L or greater, and are considered poor-quality water. The remaining 82% have values less than 200 mg/L and are considered to be of good quality.

Turbidity

Turbidity pertains to water cloudiness or the level of pellucidity. High turbidity reflects an abundance of impurities that may be due to silt, plant fibers, microorganisms, wood ash, sawdust, coal dust, or chemicals. Most turbidity in rivers and lakes is due to plankton or to soil erosion related to mining, logging, or dredging operations (American Public Health Association (APHA)). However, groundwater turbidity usually occurs in fractured bedrock aquifers and in these cases the turbidity may be due to blasting, construction activities, or surface water intrusion [44]. Fishery wastewater and the addition of NaCl from other sources always grow flocs and bacteria, which increases turbidity as outcome [45]. Turbidity may also indicate the presence of disease-causing organisms such as viruses, bacteria, or parasites (U.S. EPA publication). Ideally, turbidity must be less than 1 NTU because higher values indicate health risks due to bacterial contamination [41]. Turbidity in excess of 5 is undesirable for aesthetic reasons. Groundwater turbidity is more likely due to inorganic materials such as iron and manganese. Such inorganic materials are considered unsuitable because they can seriously affect pipes and plumbing systems.

Turbidity levels should be less than 5 NTU based on WHO standards or less than 0.5 NTU based on PSQCA criteria (Table 2). Only one of the analyzed water samples had turbidity above 5 NTU (Table 2), thus most of the water in the study area is safe for drinking and domestic purposes according to WHO. Fig. 2E indicates that the whole study area meets WHO standards for drinking water, whereas only 9.8% of the area qualifies based on the PSQCA limits. A turbidity distribution map shows that the eastern part of Ravi Town and a small part of Gulberg have the lowest values, whereas the southern part of Aziz Bhatti has the highest. The high turbidity is due mainly to rapidly decreasing water levels and groundwater movement, which activates bottom particles. Huge construction projects currently in progress are also thought to affect turbidity levels.

Groundwater Quality Maps

Composite drinking water quality maps produced by integrating the five thematic maps for TDS, TH, pH, alkalinity, and turbidity, based on WHO and PSQCA standards (Table 4), are presented in Figs. 3A and 3B. The study area was divided into four groundwater risk potential zones, ('excellent,' 'good,' 'moderate,' and 'poor'), and the spatial integration was carried out using ArcGIS Geostatistical Analyst extension. Using the WHO standards, only a small area in the southern part of the study area has poor quality water (Fig. 3A), whereas applying the PSQCA standards, poor water quality exists in the northern, southern, and eastern parts of the area (Fig. 3B). Gulberg has the lowest groundwater quality, whereas Ravi generally has good quality water.

Based on WHO drinking water standards, 61% of the area is classified as having excellent quality water, 27% good water, 9% moderate water, and 3% poor water. Applying the PSQCA standards yielded very different results with 5%, 29%, 34%, and 32%, area is excellent, good, moderate, and poor, respectively (Table 3). Only in the case of pH are the WHO and PSQCA standards the same and neither set of standards provides recommended values for alkalinity. Our results show that 96.8% to 100% of the 340 samples investigated (considering each parameter separately) met the WHO standard, whereas15.6% to 98.8% met PSQCA standards (Table 2).

The combined maps (Figs. 3A and B) show that excellent quality water is available for 61% of the total area using the WHO standards, but only 5% of the area using the PSQCA standards. Conversely, WHO standards would identify poor quality water in only 3% of the area, whereas PSQCA standards place the value at 32%. Overall, the groundwater quality in Lahore needs to be treated before drinking but the unconfined aquifer faces increasingly serious threats of degradation unless a groundwater management plan is adopted to protect from pollutants.

A statistical summary of the five investigated parameters is presented in Table 3. The average values of all parameters satisfy WHO standards whereas only turbidity values lie within the PSQCA standard limits.

Results for Individual Towns in Lahore

The current study included the six most populous towns in Lahore, providing a range of conditions and circumstances such as geological features, agricultural development, construction activities, population, and human activities. The highly polluted Ravi River cuts through Ravi; other towns have poor drainage systems, and no land use planning and development guidelines. Gulberg is considered the most well planned and modern area among all the towns. Most parts of Gulberg are developed for domestic, commercial, and industrial requirements. Gulberg has the highest levels of groundwater contamination with an average TDS value of 600 mg/L, whereas Ravi has the lowest average value of 318.5 mg/L (Fig. 4). All of the towns have acceptable contamination levels based on WHO standards for TDS, but the water in Gulberg exceeds the maximum TDS value set by PSQCA. The average groundwater values of TH in all the towns are within the limits set by both WHO and PSQCA, but Gulberg has the highest average value (182.5mg/L) and Data the lowest (163 mg/L) (Fig. 4).

All of the groundwater in Lahore has pH values within the limits set by both WHO and PSQCA, but there are variations; with Ravi Town having the highest value (8) due to the presence the river and a landfill. Turbidity levels are acceptable in the entire study area based on WHO standards, but all are above acceptable levels set by PSQCA. The highest average turbidity of 2.55 mg/L is present in Aziz Bhatti and the lowest value (1.04 mg/L) is in Gulberg (Fig. 4). Gulberg, Shalamar, and Aziz Bhatti all have alkalinity values higher than 200 mg/L (a value accepted elsewhere), but the other towns all have lower values (Fig. 4). From the data it is apparent that wide variations exist between the various towns that make up Lahore.

Conclusions

Lahore is currently faced with a number of groundwater issues, such as water shortages, locally high pollution, low recharge, and over-exploitation of the resource. The major sources of pollution in the study area are poor drain systems, contaminated river water, and unregulated landfills. All of these problems will only become worse unless steps are taken in the very near future. It is expected that the present study will provide some guides for the development of a comprehensive land use and water management program.

The spatial distribution analysis of groundwater quality in the study area indicates that currently most groundwater falls within guidelines and standards for drinking water set by WHO and PSQCA. However, there is a wide disparity between the standards set by WHO and PSQCA: by WHO standards, 97% of the study area has potable groundwater whereas using PSQCA standards, the area of potable water falls to 68%. The contamination potential is extremely high in Gulberg, but relatively low in Ravi. Pollutants are continually infiltrating into the aquifer and the local authorities have no strategy to protect the groundwater resource. If the present level of contamination continues, or increases, no potable water will be available in Lahore after a few years. The results of the current study should help the general public, local administrators, and government agencies recognize the current and future threats to groundwater quality of Lahore. The government needs to develop and implement an effective groundwater management system based on scientific data. For this to be successful the public must be made aware of the present water quality crisis and the causes of the problem. Because groundwater will continue to be

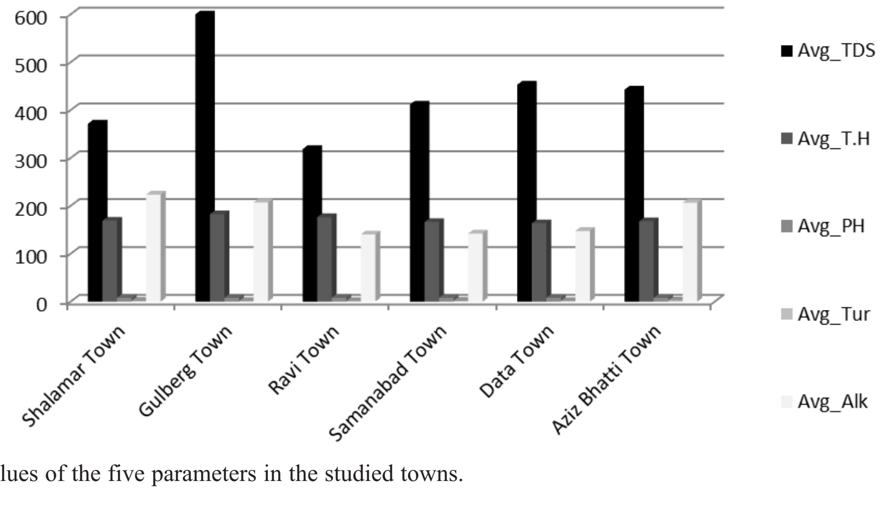


Fig. 4. Average values of the five parameters in the studied towns.

the major source of drinking water in Lahore, the resource must be managed and protected. A groundwater monitoring system must be set up and methods developed for dealing with current and future depletion and pollution of the resource. We present the following recommendations for preventing further groundwater quality deterioration and developing a strategy for future protection:

(i) Quantify the domestic sewage that enters the various water bodies in the city. This will assist in planning for effective sewage treatment plants and minimizing groundwater pollution from this source. Old and leaking sewage lines need to be replaced.

(ii) Identify groundwater recharge locations and structures, and ensure that these are protected from surface pollution. To this end, landfills sites and solid waste disposal areas must be properly located and scientifically managed. Agricultural activities, particularly those using large quantities of fertilizer and pesticide, must be excluded from the recharge sites. The recharge structures must be designed with the help of GIS tools.

(iii) Take steps to rehabilitate and protect old recharge sites and sources. Much of the former recharge is now blocked with development in the city, so new sites and sources are also needed. New sources of recharge could include filtered and treated waste water from a variety of sources. This will require construction of water treatment plants and enforcement of laws restricting pollution of surface areas and rivers

(iv) Enforce existing environmental protection laws and develop additional rules and regulations as necessary. Violators must be dealt with appropriately and incentive policies must be developed to ensure compliance with all environmental rules and regulations.

(v) Continuously monitor groundwater levels and quality so that problems can be recognized and dealt with quickly.

(vi) Take immediate steps to inform and educate the general public and governing officials about the problems and costs of preserving the water supply. The relevant municipal and provincial departments must share information and make a combined effort to protect this resource for the future.

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