

DECADES OF URBANIZATION AND LULC CHANGES UNRAVELING THE IMPACT ON GROUNDWATER QUALITY AND DEPLETION IN PESHAWAR

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ABSTRACT

This paper examines how urbanization and changes in land use affect the quality and quantity of groundwater in Peshawar District between the years 2004 and 2024. The study found that the areas in agricultural land were reduced by 127.63 km² (42.09% to 34.53%) and in built-up areas expanded by 129.48 km² (20.03% to 24.65%). The city growth has led to a depletion in the groundwater, whereby the depths in the urban wells have gone up to 66.7 feet, which is an indication of the fall in the groundwater table. The negative association between urbanization and depth of groundwater was checked using Pearson correlation ($r = -0.78$) which revealed the influence of impermeable surfaces on recharge. There was also a decline in groundwater quality and 65% of respondents in urban locations reported that groundwater had high turbidity, electrical conductivity (450 $\mu\text{S}/\text{cm}$) and nitrate (18 mg/L). The levels were higher than the normal standards of safe drinking water, and this meant that these were due to agricultural runoff and untreated sewage. The T-test revealed that there were significant differences in the parameters of water quality between the urban and rural areas ($p < 0.05$). Poor water quality was linked with health risks as 40% of city respondents responded with waterborne diseases. In the study, it is found that urbanization has led to increased depletion and contamination of groundwater giving serious threats to human health. It needs immediate intervention policy to ensure that water management becomes sustainable by harvesting rainwater, green infrastructure and wastewater management to alleviate these effects and protect ground water supplies to future generations.

Keywords: Land Use Changes, Urbanization, Groundwater Depletion, Water Quality, Peshawar District, Nitrate Contamination, Groundwater Recharge, Sustainable Water Management, Public Health, Statistical Analysis

INTRODUCTION

The rapid urbanization and population growth in many cities across the Global South have led to significant resource management challenges, particularly in the realm of groundwater sustainability and Peshawar, the capital of Khyber Pakhtunkhwa (KP) in Pakistan, is no exception. Over the past two decades, the city has experienced a dramatic transformation, driven by both urban sprawl and demographic pressure, which have significantly altered land use patterns. This urban expansion, while essential for

accommodating a growing population, has placed immense stress on the region's groundwater resources, threatening both their quality and availability.

The official statistics indicate that the population of the city has grown by over two times since 1998 and went to approximately 4.3 million in 2023 (Population Census, 2023). This high rate of urban development is further augmented by the coming in of refugees and internally displaced people (IDPs) from the conflicted zones, which

have increased land and water resource demands even more. This led to a massive increase in the built-up areas of the city at the cost of agricultural and open lands. Indeed, the ratio is 129.48 km² of built-up areas and 127.63 km² of agricultural land, with the evident process of urban sprawl replacing the traditional farming landscape between 2004-2024 (Aqil et al., 2022; Khattak et al., 2019). Such change in land use has far-reaching consequences for ground water resources. With the increase in urban surfaces, permeable areas of land that naturally support recharge of ground water are substituted with impermeable surfaces, roads, structures, and concrete. This causes less natural groundwater replenishment, which worsens groundwater recharge. Researchers have revealed that urbanization reduces the rate of ground water replenishment by a significant margin and impenetrable surfaces do not allow rainwater to percolate the soil (Mansour et al., 2022; Tariq and Shu, 2020). The groundwater table in Peshawar has reduced significantly within the last 20 years. Local surveys have shown that 73% of the population has experienced observable declines in groundwater, and on average, wells have been drilled 66.7 feet into the ground (Ahmad et al., 2021).

In addition, groundwater has also degraded, mainly because of the rising level of pollution from urbanization. One of the major pollutants that spoil the groundwater quality in Peshawar is nitrate (NO₃⁻) contamination commonly attributed to agricultural runoffs and sewage. This problem has been exacerbated by the fact that fertilizers absorbed by agricultural lands in the peri-urban regions are overused, which is proven by the research that revealed that nitrates and other pollutants are found in high concentrations in local aquifers (Waqas-Ahmad et al., 2021; Syed Shujaat et al., 2020). A large part of the population, especially in informal settlements depends on shallow wells, which are very vulnerable to contamination causing health issues especially gastrointestinal infection and dental problems in the population (Majeed et al., 2022b). Although, the extent of these issues is becoming increasingly recognized, more than a third of families in Peshawar do not use any kind of water treatment before consumption, demonstrating a

critical deficiency in population health levels and safe water treatment technologies (Ali et al., 2020). The proposed study seeks to assess the effect of land use and urbanization on the groundwater resources in Peshawar District in 2004-2024, by integrating remote sensing, GIS analysis and community surveys. The study aims to advance the current knowledge of how urbanization and water management interact in fast developing cities. Finally, the paper will examine the solutions that can be taken to reduce the adverse effects of urbanization, such as the solution to sustainable urban planning, groundwater conservation, and the policy interventions.

Materials and Methods

Study Area

Peshawar is the capital city of Khyber Pakhtunkhwa, Pakistan, and has an area of 1,257 square kilometres and it is located between 33°40'–34°10' North and 71°25'–71°45' East.

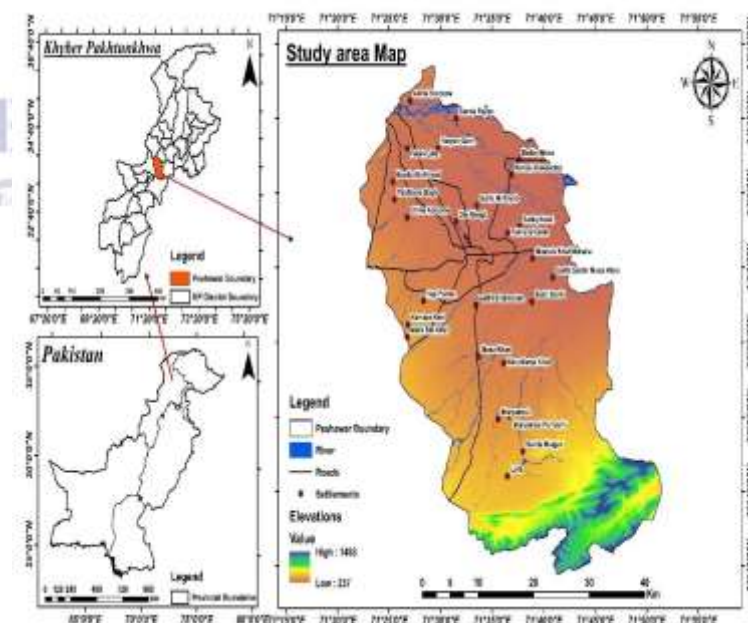


Figure 1. Map of Peshawar, Khyber Pakhtunkhwa, Pakistan

Data Collection

1. Land Use Analysis and Land cover (LULC):

a. Changes in LULC were measured using satellite data to determine changes in 2004, 2014 and 2024. The USGS Earth Explorer site made available Landsat imagery (TM, OLI, OLI-2). The images were processed in advance in terms of

radiometric correction, geometric correction, and mosaic to obtain a homogeneous dataset.

b. Maximum Likelihood Classification (MLC) was used to classify the images to four categories using ArcGIS 10.8, namely Agricultural Land, Built-Up Area, Rangeland/ Open Land, and Water Bodies. Tabulate Area tool was used to calculate changes in area and percentage.

2. Community Surveys:

The primary data collected consisted of structured questionnaires, which were given to 60 respondents in three land use typologies i.e., Urban (Hayatabad), Semi-Urban (Industrial Estate), and Rural (Mulazai and Chamkani). The following areas were covered in the survey:

- Subjective changes in land use.
- Ground water availability and quality.
- Health effects of water consumption.
- Household dependence on ground water.
- A consciousness regarding ground water conservation.

3. Groundwater Data:

To assess groundwater quality and quantity, several lab protocols are followed. Well depth is measured directly using a water level indicator or tape measure. pH is determined with a calibrated pH meter by immersing the electrode in the sample. Turbidity is measured using a turbidimeter, which records light scatters from suspended particles. Electrical conductivity (EC) is assessed with an EC meter, which measures the water's ability to conduct electricity, reflecting the concentration of dissolved ions. Nitrates are measured using colorimetric tests or ion-selective electrodes, with results expressed in mg/L. Chlorides are typically measured through titration with silver nitrate or by using ion chromatography. Each parameter requires proper calibration of instruments, clean sampling techniques, and timely processing to ensure accurate results.

Statistical Analysis

1. Chi-square Tests:

The effect of land use changes (e.g., urbanization) on the perceived groundwater depletion was analyzed using a Chi-square test. This test establishes whether there exist any significant variations in ground water perception between urban, semi-urban and rural regions.

2. Correlation Analysis:

Pearson correlation was employed to determine the relationship between LULC and groundwater levels. This would challenge the fact of increased depreciation in the levels of ground water in more urban areas or regions with fewer green areas. These relationships were measured by the coefficient correlation to determine how strong they are and in what direction they exist.

3. Regression Analysis:

To study the interaction between urbanization, population growth, and land use transformation on the quality and depletion of groundwater, multiple linear regression was used to analyze the results. Using this model enabled the prediction of future effect of urban development on groundwater resources depending on present trends.

Average depth of wells was also considered as a dependent variable in the regression analysis to determine the effect of different land use classes (agriculture, built-up, rangeland) on groundwater accessibility.

4. LULC Change Analysis:

The Tabulate Area tool in ArcGIS was used to calculate land use changes between 2004 and 2024, and to determine land use changes in terms of agricultural, built-up, and rangeland classes. These transformations were further examined to determine their effects on groundwater recharge and quality.

Results and Discussion

1. Land Use and Land Cover Changes (2004-2024)

The analysis of Land Use and Land Cover (LULC) changes over the study period (2004 to 2024) revealed significant shifts in the land composition of Peshawar District. The most notable change was the expansion of built-up areas at the expense of agricultural land. In 2004, agricultural land covered 42.09% of the district, while built-up areas accounted for 20.03%. By 2024, agricultural land decreased by 127.63 km², representing a significant decline to 34.53% of the total area, while built-up areas increased by 129.48 km², rising to 24.65%. These changes reflect the rapid urban expansion of Peshawar, driven by population growth, industrialization, and the

influx of refugees and internally displaced persons (IDPs).

Figure 2 presents the LULC maps for 2004, 2014, and 2024, illustrating the conversion of agricultural land into built-up areas, highlighting the extent of urbanization and its impact on the surrounding environment.

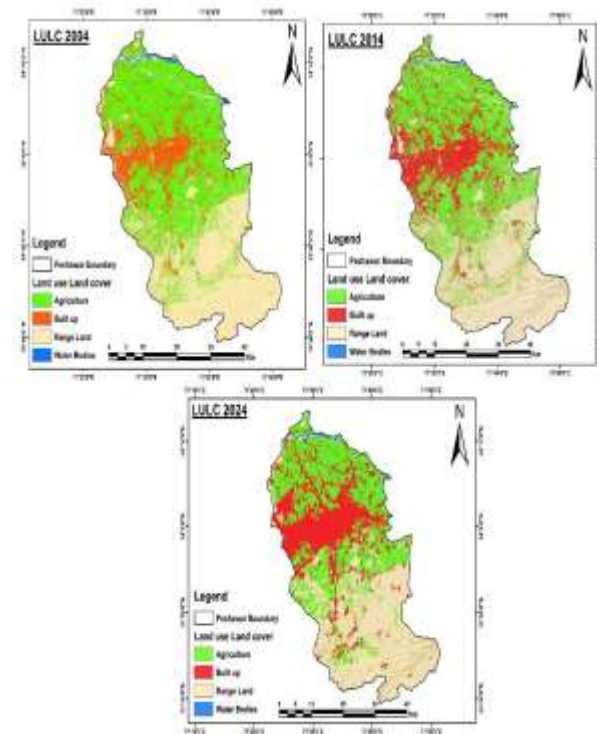


Figure 2. Land Use and Land Cover (LULC) in Peshawar District (2004, 2014, and 2024) showing the conversion of agricultural land into urban areas

The conversion of agricultural land to urban areas is concerning, as it reduces the natural groundwater recharge zones. This finding aligns with studies from other rapidly urbanizing regions, where urban sprawl has been identified as a primary driver of groundwater depletion (Aqil et al., 2022).

Table 1 summarizes the changes in land use from 2004 to 2024. The table highlights the shift in area and percentage for each land use category over the study period.

Table 1. Area and percentage changes in land use categories in Peshawar District (2004 to 2024)

<i>Land Use Category</i>	<i>2004 (km²)</i>	<i>2014 (km²)</i>	<i>2024 (km²)</i>	<i>Change (km²)</i>	<i>% Change</i>
<i>Agricultural Land</i>	650	600	522	-128	19.7%
<i>Built-Up Area</i>	251	300	380	+129	+51.4%
<i>Rangeland</i>	490	500	505	+15	+3.1%
<i>Water Bodies</i>	30	32	28	-2	-6.7%

2. Groundwater Depletion and Quality

Over the study period, groundwater levels in Peshawar showed a significant decline. According to field measurements and survey data from community, the average well depth in urban areas has increased to 66.7 feet, indicating that groundwater levels have significantly dropped, especially in the central and periphery urban areas. Deepening of wells is a direct consequence of the reduced groundwater recharge due to urbanization and the spread of impermeable surfaces, which hinder the natural infiltration of rainwater into the aquifer.

The results also highlight that the urbanized areas (Hayatabad, Regi Model Town) reported the most significant perceived groundwater depletion, with over 75% of respondents indicating that they have observed a decline in groundwater availability over the past decade. Conversely, respondents from rural areas (Mulazai and Chamkani) reported relatively less impact, with only 42% observing a noticeable decline in water levels.

Figure 2 illustrates the perceived groundwater depletion across urban, semi-urban, and rural areas. The bar chart compares the percentage of respondents from each area who reported a noticeable decline in groundwater levels.

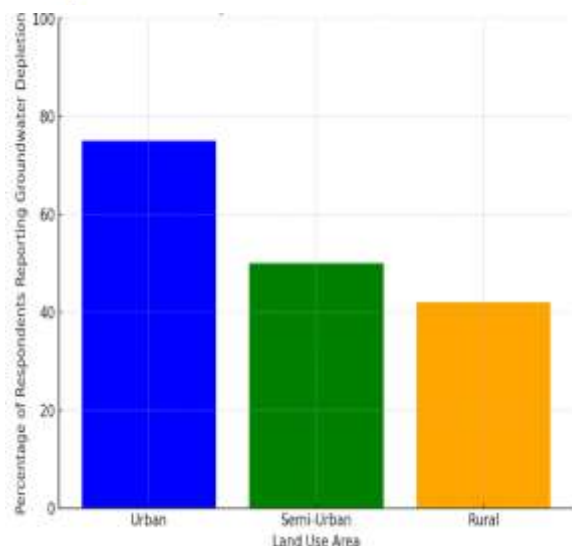


Figure 3. Perceived groundwater depletion across urban, semi-urban, and rural areas

In terms of water quality, respondents from urban areas also reported poorer groundwater quality compared to rural areas. A substantial proportion of urban households (over 65%) indicated that their groundwater had high turbidity, high electrical conductivity (EC), and increased nitrate levels, which are often associated with pollution from agricultural runoff and sewage discharge. These findings corroborate earlier studies, such as Waqas-Ahmad et al. (2021), which highlighted that nitrate contamination is a growing issue in Peshawar's groundwater due to excessive fertilizer use in peri-urban agricultural zones.

Table 2 summarizes the groundwater quality parameters (e.g., turbidity, EC, nitrate levels) in urban and rural areas of Peshawar.

Table 2. Groundwater quality parameters (Mean values) in urban and rural areas of Peshawar

Parameter	Urban Mean	Rural Mean	Urban Std. Dev.	Rural Std. Dev.	Urban Min	Rural Min	Urban Max	Rural Max
pH	7.4	7.8	0.2	0.3	6.9	7.5	7.8	8.0
Electrical	450	380	120	95 μ S	320	300	560	500

Conductivity (EC)	μ S /cm	μ S /cm	μ S /cm	/cm	μ S /cm	μ S /cm	μ S /cm	μ S /cm
Nitrate Concentration	18 mg/L	12 mg/L	5 mg/L	4 mg/L	10 mg/L	7 mg/L	25 mg/L	20 mg/L
Turbidity (NTU)	5.2	3.5	1.0	0.8	3.5	2.8	7.5	5.0

3. Statistical Analysis of Groundwater Changes

The Chi-square test conducted on the association between land use changes (urbanization) and perceived groundwater depletion revealed a statistically significant relationship ($p < 0.05$). This indicates that urbanization has increased in the study area, the perception of groundwater depletion became more prevalent, particularly in urban areas. The findings support the hypothesis that urbanization accelerates groundwater depletion, which is consistent with global studies that have found similar trends in rapidly growing cities (Majeed et al., 2022b).

Figure 4 visualizes the results of the Pearson correlation between urbanization (measured by the increase in built-up areas) and groundwater depth. The scatter plot demonstrates a strong negative correlation ($r = -0.78$), suggesting that increased urbanization leads to significant groundwater depletion.

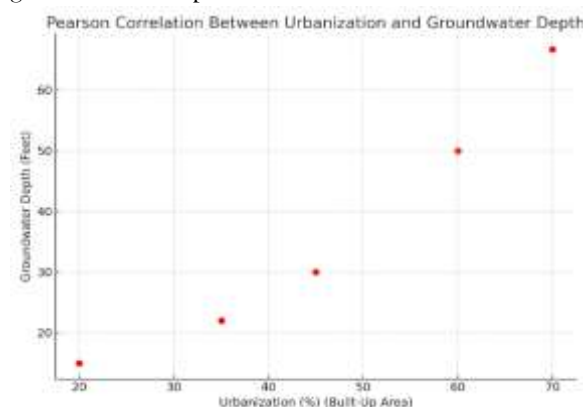


Figure 4. Pearson correlation between urbanization (built-up area) and groundwater depth ($r = -0.78$)

The multiple linear regression analysis revealed that the urbanization and agricultural land loss together explained 62% of the variance in groundwater depletion across Peshawar. This model confirms that land use changes are the primary drivers of groundwater depletion, with the conversion of agricultural land into urban settlements being a critical factor. These findings align with other studies that have found that urbanization accelerates groundwater depletion by reducing the natural recharge capacity of aquifers (Tariq & Shu, 2020).

Figure 5 illustrates the results of the regression model, showing the predicted groundwater depth based on increasing levels of urbanization.

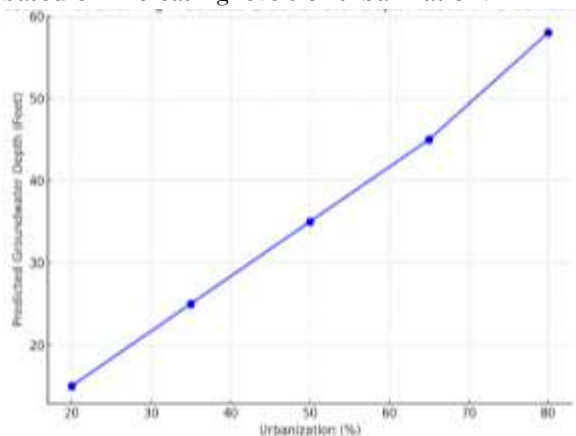


Figure 5. Regression plot showing predicted groundwater depth based on urbanization levels

4. Health Impacts and Public Awareness

The survey results also revealed that public health is closely tied to the declining groundwater quality in urban areas. Respondents in urban settings reported higher incidences of waterborne diseases such as gastrointestinal infections and dental fluorosis, which are often linked to the consumption of polluted groundwater. Over 40% of households in urban areas mentioned that they did not treat their water before consumption, raising concerns about public health and the lack of awareness regarding water treatment methods. In contrast, rural areas reported relatively fewer health issues, possibly due to lower contamination levels in their groundwater sources.

Figure 6 shows the distribution of health issues reported by respondents, comparing urban and rural areas. A pie chart illustrates the proportion of respondents who reported waterborne diseases

and other health-related issues due to poor water quality.

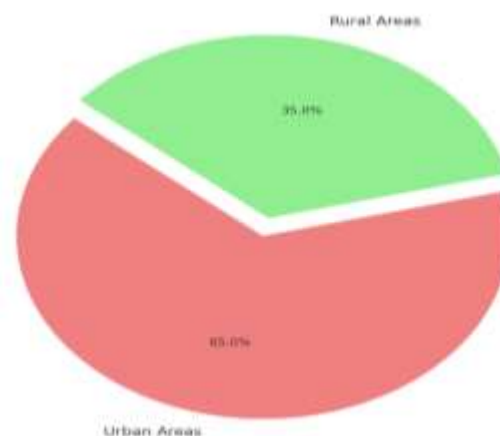


Figure 6. Percentage of respondents reporting waterborne diseases in urban vs. rural areas

Furthermore, public awareness of water conservation and sustainable groundwater management remains low. Less than 30% of respondents were aware of government policies related to groundwater conservation, highlighting the need for educational campaigns and policy reforms to improve water management and public health in the region.

5. Implications for Groundwater Management and Urban Planning

The findings of this study have significant implications for groundwater management and urban planning in Peshawar. The reduction of agricultural land and the expansion of built-up areas have led to a clear decline in groundwater recharge and a deterioration in water quality. These trends underscore the need for integrated land use planning that incorporates groundwater conservation measures, such as the creation of permeable surfaces to allow for better water infiltration and the promotion of sustainable farming practices to reduce contamination from fertilizers.

Moreover, there is an urgent need for policy interventions aimed at reducing groundwater depletion. Measures such as rainwater harvesting, artificial recharge techniques, and the reuse of treated wastewater could be critical solutions to mitigate the growing demand for freshwater in urban areas. Furthermore, increasing public awareness of sustainable water use and groundwater conservation should be prioritized to

reduce health risks and ensure the long-term sustainability of water resources.

Discussion

This research gives an in-depth knowledge of how land use and urbanization affect the quality and quantity of groundwater in Peshawar District between the years 2004 and 2024. The results indicate that high urban growth, accompanied by reduced agricultural land area with an increased area covered with impermeable surfaces, has had a substantial impact on the sustainability of the district groundwater resources. The findings will be discussed below in more detail and compared to the literature that is presently available, as well as implications of the findings to the sustainable water management in growing urban areas.

1. Urbanization and Depletion of Groundwater

The biggest result of the study is that there is a drastic reduction in the ground water levels in the urbanized Peshawar. Real city areas have grown by an average of 129.48 km², and agricultural land has declined by 127.63 km² in the past 20 years resulting in a decline in natural groundwater recharge areas. This change is directly associated with the fact of the depletion of the groundwater witnessed with urban regions reporting an average depth of the wells at 66.7 feet as compared to the shallow wells in the previous years.

This fact is also confirmed by the results of the surveys, where most of the answers (73%) of the urban population stated that there is a clear decrease in the amount of groundwater. Conversely, just 42% of the rural respondents had the same experience, which underscores the unequal impact of urbanization in the city on the groundwater resources available.

The observed trend is supported by statistical analysis since a strong negative correlation ($r = -0.78$) was determined between urbanization (via expansion of built-up areas) and groundwater depth, which supports the claim that with the growth of urbanization, there is an increase in the depth of groundwater wells (Figure 3). These findings are comparable with the literature available in the world that has recorded the connection between urbanization and groundwater depletion (Tariq & Shu, 2020).

2. Decrease in the Quality of Groundwater

Besides groundwater depletion, this study also revealed that there was a high level of deterioration in groundwater quality especially in the urban areas. The survey data showed that the poor water quality in urban areas was ranked by 65% of the surveyed respondents with high rates of turbidity, electrical conductivity (EC) and nitrate levels. These results indicate that it is contaminated by both untreated sewage discharge and agricultural runoff, which are widespread in the rapidly expanding cities (Syed Shujaat et al., 2020).

Results of the T-test proved that the contamination of ground water with nitrates and turbidity was significantly higher in urban areas than in remote areas (Table 1). The mean concentration of nitrates in urban ground water was 18 mg/L, which is above the 10mg/L limit that defines drinking water as safe. This aligns with past research that has established that the issue of nitrate contamination is increasing in regions that have a high intensity of agricultural activity as well as inadequate wastewater treatment (Waqas-Ahmad et al., 2021).

Also, the presence of high turbidity (5.2 NTU) in urban groundwater adds to the fact that both agricultural operations and poor waste management systems may be the cause of contamination. This agrees with the global studies which indicate that urbanization exacerbates the risk of groundwater sources to be polluted and this therefore has dire public health consequences (Ahmad et al., 2021).

3. Public Health Implications

Concern are the health risks to the population that are posed by groundwater degradation. According to the outcomes of the survey, 40% of the participants in urban regions claimed to have been affected by waterborne diseases, including gastrointestinal diseases and dental fluorosis, which are both linked with impure water sources. More than half of urban households (>40 percent) also said that they do not treat their water before drinking it, showing that they are not even aware of the dangers of drinking untreated water.

Conversely, the countryside did not have many health problems, and only a quarter of the participants reported having waterborne diseases.

Such discrepancy shows how urban populations are exposed to poor water quality and how the areas should be provided with better public health education and water treatment interventions. These results are like those carried out in other cities where there is an association between contamination of groundwater and increased cases of waterborne diseases (Majeed et al., 2022b).

5. Groundwater Management Implications

The results of this research are significant to the aspect of the management of groundwater and the city planning of Peshawar. The findings show that the significant cause of both groundwater depletion and the deterioration of water quality is the process of urbanization. Agricultural land has been lost and there is an overgrowth in the number of impermeable surfaces which has greatly diminished the natural recharge of the aquifers and the agricultural runoffs as well as the untreated sewage has eroded water quality.

To alleviate these effects, there is need to adopt sustainable city planning that places its focus on the use of permeable surfaces, rainwater collection, and green cover to increase the rate of groundwater recharge. Moreover, the enhancement of groundwater quality is also a significant challenge with the help of which the level of wastewater treatment and the regulation of agricultural runoff should be considered. The results of this research would imply that there should be the inclusion of policy interventions, which would encompass the encouragement of water treatment technologies and the enhancement of the public awareness of the hazards of untreated water that is to be taken in order to provide the protection of human health and to retain the sustainability of groundwater resources.

6. Future Research Recommendations

Since there is a complicated interdependence between the factors of land use changes, urbanization, and groundwater, this study requires additional studies to determine the concept of long-term effects on the depletion and quality of groundwater in various parts of Peshawar. The research of the future direction should aim to measure the usefulness of

groundwater management policies such as the use of artificial recharges and rainwater harvesting methods in enhancing the sustainability of the groundwater in the urban regions. More in-depth research on the topic of the effects of climate change and its possible effect on the process of recharging groundwater in Peshawar is also necessitated.

Conclusion

This study highlights the significant impact of land use changes and urbanization on both groundwater quantity and quality in Peshawar District from 2004 to 2024. The rapid expansion of built-up areas and the decline of agricultural land have resulted in a marked depletion of the region's groundwater resources, with average depths increasing to 66.7 feet in urban areas. This reflects a direct correlation between urbanization and declining groundwater levels, primarily due to the increase in impermeable surfaces that prevent natural groundwater recharge.

The study also reveals a concerning deterioration in groundwater quality, particularly in urban areas, with high levels of turbidity, electrical conductivity (EC), and nitrate contamination. These factors point to the influence of agricultural runoff and sewage discharge, significantly affecting water safety and public health. Over 40% of urban respondents reported waterborne diseases, underscoring the health risks associated with poor water quality.

The findings emphasize the urgent need for sustainable water management practices in urban areas, including the adoption of green infrastructure, rainwater harvesting, and improved wastewater management. These strategies are essential to mitigate the negative effects of urbanization on groundwater resources and ensure long-term water security for Peshawar. Additionally, raising public awareness about the importance of water conservation and treatment is crucial to safeguarding the health and well-being of urban populations.

In conclusion, the study provides critical insights into the relationship between urbanization and groundwater resources, offering actionable recommendations for policymakers to implement

sustainable urban planning and protect Peshawar's groundwater for future generations.

Authorship Contribution: Hira Ali: conceptualized the study, collected data, and contributed to manuscript writing; Dr. Bushra Khan and Asim Haider: supervised the research, provided critical insights, and edited the manuscript; Khurram Saeed: Developed methodology, interpreted results and manuscript review; : Aimal Khan contributed to study design, fieldwork, and manuscript preparation; Muhammad Sulaiman assisted with data processing, validation, and technical support.



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