Spatio-Temporal Dynamics of Ground Water Level of Lahore Metropolitan and its Relationship with Urbanization and Rainfall

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Introduction/Importance of Study: Lahore, the capital of Punjab Province, has a population of 14.1 million people. The city relies entirely on groundwater to meet its water needs. However, unsustainable water usage has led to a significant decline in groundwater levels.

Novelty Statement: This study aims to investigate the root causes of groundwater depletion in Lahore and propose effective protective measures. The excessive extraction from around 600 tube wells, some reaching depths of 600 to 1000 feet, has resulted in non-functional wells and severe water shortages.

Material and Method: The study employed various tools and techniques, including Google Earth Engine, image classification methods, and R Studio (ordinary Kriging). An overlay analysis assessed the spatial relationship between land use/land cover and groundwater levels. The analysis revealed a significant correlation between urbanization, population growth, and groundwater depletion in Lahore.

Results and Discussion: The rate of groundwater depletion has increased from an average of 2.133 feet per year (0.65 meters per year) between 1980 and 2000 to over 3 feet per year (over 1 meter per year) since 2013. Contributing factors include rapid urbanization, increased water demand due to population growth, and inadequate rainwater recharge. This rapid depletion poses a serious threat to Lahore's groundwater resources, emphasizing the urgent need for sustainable water management practices.

Concluding Remarks: The rapid depletion of groundwater is a critical issue for Lahore, necessitating immediate implementation of sustainable water management practices and groundwater recharge strategies. Effective measures are essential to mitigate the impacts of rapid urbanization and population growth on groundwater resources, ensuring a reliable water supply for the future.

Keywords: Lahore, Population, Rainfall, Groundwater, Tube wells, Google Earth Engine (GEE), R Studio, Kriging, Land Use/Land Cover, Urbanization.

Introduction:

Water is often misused and undervalued despite being a fundamental element essential for sustaining life on Earth. Quality drinking water is crucial for survival [1]. In recent years, significant efforts have been made to assess groundwater depletion related to rapid urbanization. Researchers have stressed the importance of addressing groundwater degradation, as groundwater plays a vital role in climate regulation and is increasingly strained by the growing human population [2]. Globally, groundwater serves as a primary drinking source [3], with about 99 percent of fresh water stored in underground aquifers, which supply at least 25% of the world's population. Over the past 50 years, the total water extracted for human use has nearly tripled, from 1382 km^3/year (1950–2000) to 3973 km^3/year, with consumption projected to reach 5235 km^3 by 2025. Water is a crucial resource for industrial, agricultural, and domestic uses [4]. Numerous studies indicate that groundwater is being overexploited worldwide [5]. Globally, groundwater depletion is estimated at 100 to 200 km^3 per year, accounting for about 15 to 25% of total groundwater withdrawals (UN-water, 2022). The most severe depletion occurs in regions such as Central Asia, the USA, North China, and the Middle East [6]. Pakistan, in particular, is considered a water-stressed country and is expected to face severe water scarcity in the near future. Unsustainable water use, inefficient irrigation methods, rapid urbanization, and population growth have placed immense pressure on both surface and groundwater resources [4].

Lahore, the capital of Punjab and the second-largest city in Pakistan, has a long history of groundwater over-extraction, leading to a significant decline in the water table. As of 2020, Lahore's population increased from 12,642,000 to 14,407,000, reflecting a growth rate of 13.96%. The city depends entirely on groundwater, drawn through 600 tube wells within the jurisdiction of WASA Lahore, which contributes to the rapid depletion of the groundwater table at a rate of about 1.0 to 2.0 meters per year.

The primary causes of groundwater depletion and pollution in Lahore are rapid urbanization, industrialization, and urban growth [7]. The "Lahore 2040 Final Master Planning Report" highlights that due to population growth, urbanization, and excessive pumping, the Lahore aquifer has been declining since the 1970s. The number of tube wells has fluctuated annually, leading to some becoming unusable and resulting in severe water shortages. The average annual rainfall in Lahore is about 650 mm, insufficient for significant aquifer recharge due to high extraction rates and low flow in the Ravi River. Except for the monsoon season from July to September, the city experiences dry conditions in winter and summer, exacerbating groundwater depletion and tube well failures. This water-related issue has broader implications for livelihoods [Source: WASA Lahore]. Water, combining organic and inorganic elements, is crucial for life and biological processes, emphasizing the need for its careful conservation and protection [1]. A person can only survive about four days without water, whereas food can sustain life for weeks or months. Water is vital for diverse physiological functions [8]. While water exists in various forms, not all sources are accessible for public use. Groundwater, one of the most critical sources of fresh water, is essential for agriculture and domestic use, holding 13 times more water than rivers, lakes, and soil combined.

Researchers and policymakers have recognized the urgent need to develop effective strategies for rehabilitating and replenishing depleted aquifers [9]. Key aspects of aquifer management include reducing groundwater extraction to minimize stress on aquifers [10]. Sustainable development can be achieved by improving water use efficiency and implementing strict regulations on groundwater extraction. However, limiting groundwater use alone is insufficient for full aquifer restoration. Managed Aquifer Recharge (MAR) approaches are valuable in this context [11]. MAR involves directing treated wastewater or excess surface water to injection wells, infiltration basins, or other structures designed to artificially replenish aquifers. MAR has been implemented globally at various scales. Combining efforts to optimize water supply structures with MAR techniques can help mitigate over-exploitation and contribute to the long-term sustainability of groundwater resources while providing immediate relief by reducing extraction pressure on aquifers [12] (UNESCO, 2021).

Urbanization negatively impacts groundwater quantity, quality, and recharge [13]. The conversion of natural, agricultural, and less populated lands into urban areas alters local hydrology [14]. Research indicates that urbanization causes more than half of precipitation to run off, with only a small amount infiltrating deeply [15]. The literature review shows that urbanization and changes in land use and land cover have severe adverse effects on local ecology. Existing studies have generally focused on bivariate relationships between urbanization and land use/land cover changes [16], urbanization and temperature changes [17], urbanization and rainfall patterns [18], or urbanization and groundwater levels [19]. This research aims to investigate physical changes in Lahore from 2000 to 2020, their relation to groundwater level reductions, changes in rainfall patterns, and fluctuations in groundwater tables. It also seeks to identify urbanization patterns through remote sensing and map groundwater levels relative to urbanization.

Study Area:

Lahore, the capital of Punjab province, covers an area of 1772 km² and is situated geographically between 31°15'-31°45' N and 74°01'-74°39' E. It is bordered by Sheikhupura district to the north and west, Wagah to the east, and Kasur to the south, with the Ravi River flowing to the north (Figure 1). The city is located at an elevation of 712 feet above sea level and experiences a semi-arid climate with five distinct seasons: winter, summer, spring, autumn, and monsoon. June is the hottest month, with temperatures frequently exceeding 40°C, while July is the wettest, characterized by heavy rainfall, evening thunderstorms, and potential cloudbursts. January is the coolest month, marked by dense fog. Summer temperatures range from a mean maximum of 48°C to a minimum of 38°C, whereas winter temperatures range from a mean maximum of 25°C to a minimum of -1°C.

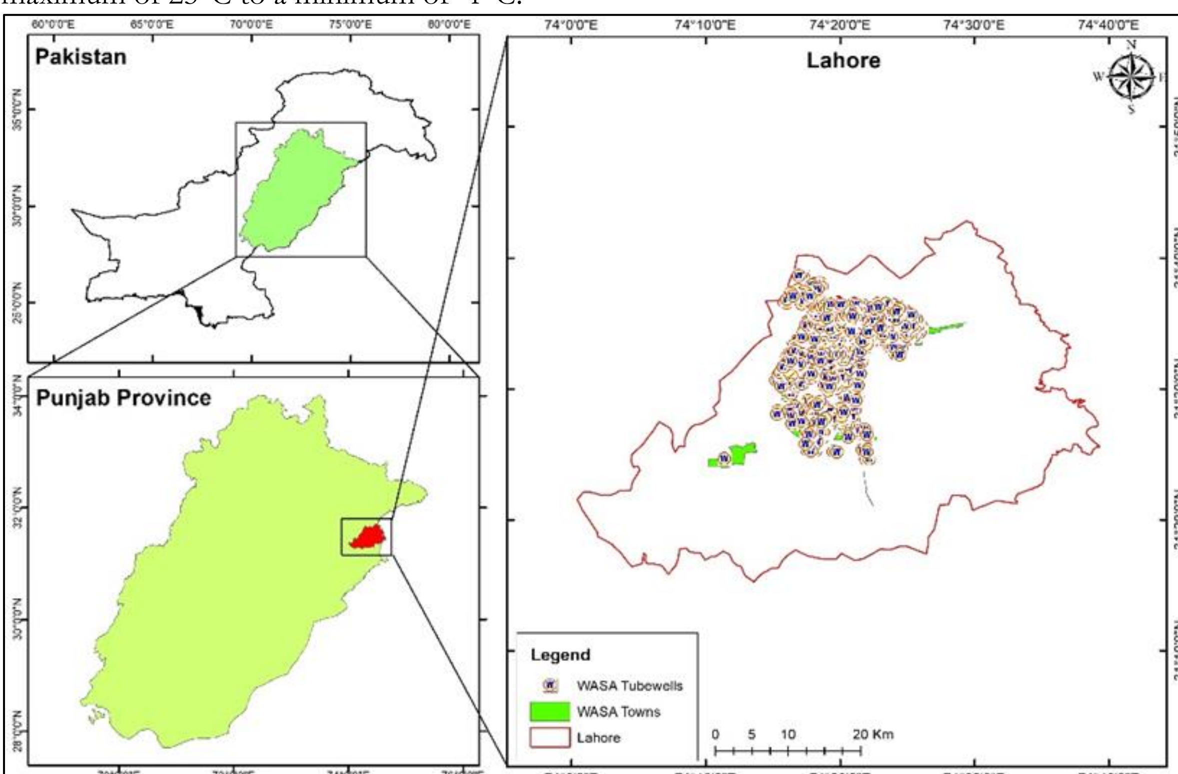

Figure 1: Geographical Location of the Study Area and Distribution of Tube Well Locations in Lahore

In the study area, groundwater levels are declining due to excessive water use for drinking, washing, and other purposes. WASA has installed numerous tube wells, with depths ranging from 600 to 1000 feet, exacerbating the drop in water levels. This not only threatens the aquifer's groundwater levels but also impacts water quality and taste. The current groundwater extraction rate is approximately 1.45 million cubic meters per day. According to WASA reports, the groundwater level has decreased by an average of 61 feet since 1961. Specific areas of Lahore have experienced notable declines: Ravi Road (17 feet), Ichra (10 feet), Kot Lakhpat and Misri Shah industrial areas (9 feet each), Mustafa Abad (29 feet), Gulberg (7.3 feet), Greentown and Baghbanpura Pull (5 feet each), Data Nagar (2.3 feet), Samanabad (4 feet), Mughalpura (6 feet), Shahdara and Shimla Hill (7 feet each), Mozang (6.4 feet), Garden Town (6 feet), and Township (4.2 feet).

The overall groundwater level in Lahore has decreased at an average rate of 2.03 feet per year, with the current rate now approximating 3 feet per year, as illustrated in Table 1. This table presents time series data highlighting the corresponding rate of decline. The data indicates a consistent reduction in water levels over time.

Table 1: Average Annual Rate of Groundwater Decline in Lahore Metropolitan

Time Period	Rate of Decline	
	Ft/year	m/year
1980-2000	2.13	0.65
2007-2011	2.6	0.79
2011-2013	3	0.92
2013-2020	Above 3 ft	Above 1 m

Material and Methods:

The research focuses on identifying and predicting fluctuations and changes in groundwater levels due to spatial transformations in Lahore City. Data collection and preparation were key milestones for this study. The methodology adopted for the analysis is detailed in Figure 2.

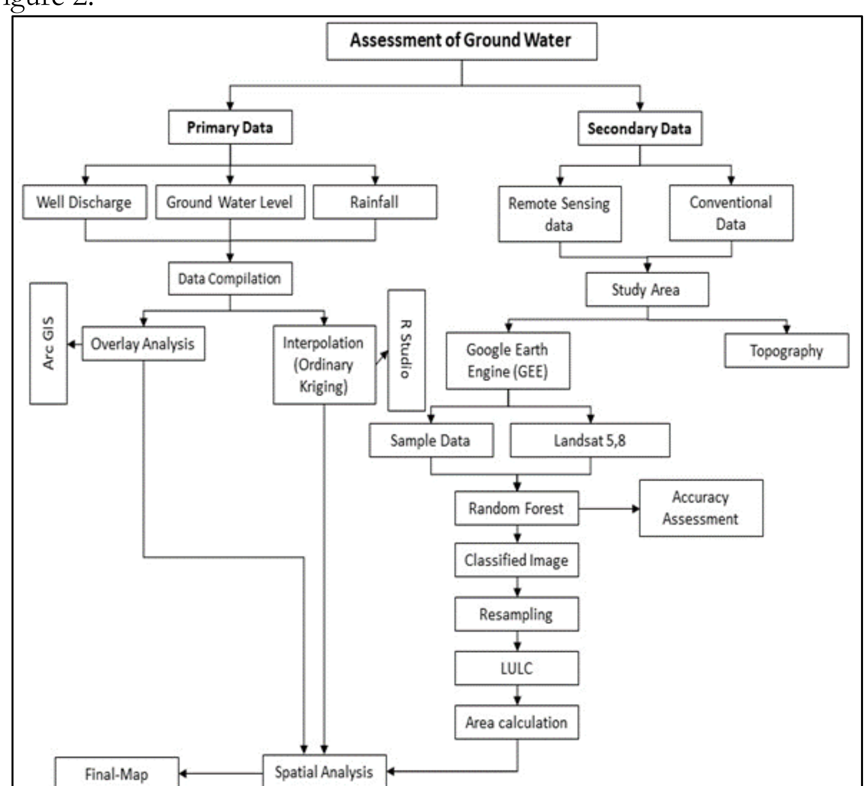

Figure 2: Flow Chart Visualizing the Data Processing and analysis Methodology

The Water and Sanitation Agency (WASA) Lahore oversees water supply, sewerage, and drainage services across 8 towns and 34 subdivisions in Lahore, catering to the city's basic social needs. This research specifically examines groundwater levels in relation to urbanization. A field survey was conducted within the WASA Lahore jurisdiction to gather accurate locations of tube wells using GPS equipment. The collected point data was then plotted in ArcMap. Following the initial survey phase, the collected data was verified with the Hydrology Directorate of WASA Lahore to obtain groundwater level information. The plotted data of tube wells in ArcMap is shown in Figure 3.

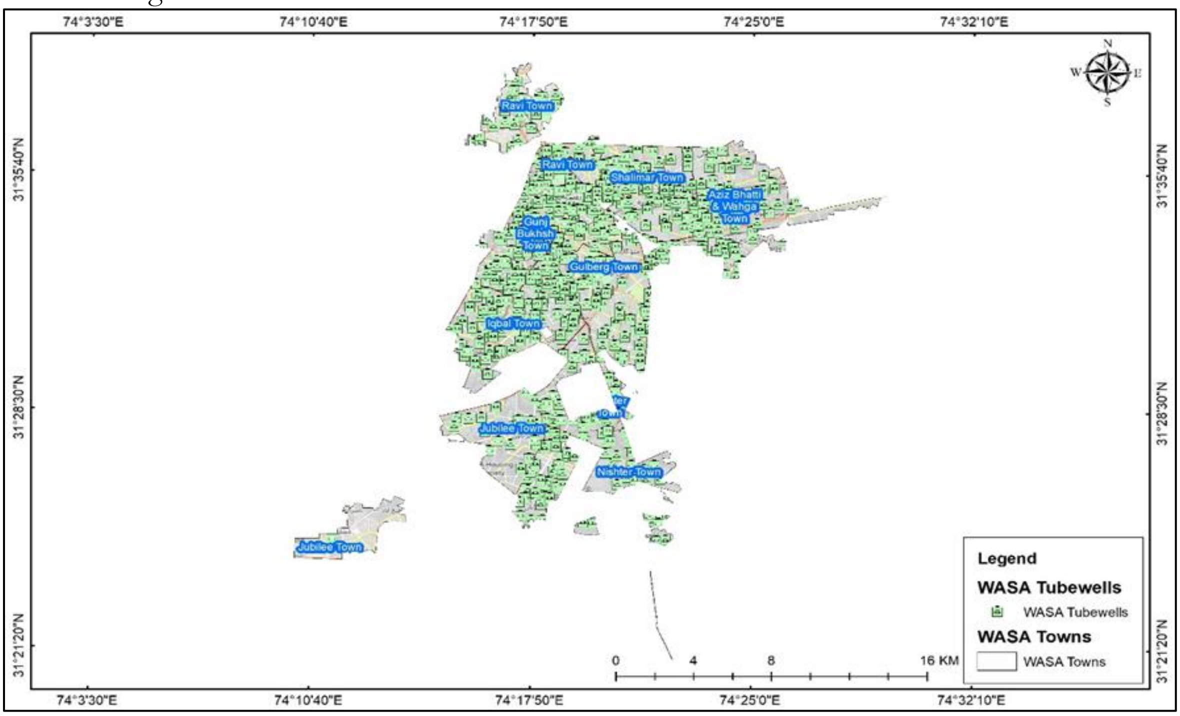

Figure 3: Existing Tube Well Water Supply Network of WASA Lahore

After collecting primary data, the study progressed to the analysis of secondary data, utilizing Remote Sensing (RS) and conventional data for the study area. Remote Sensing provides extensive spatial data, enabling the monitoring of land use/land cover changes and urban expansion over time. Geographic Information Systems (GIS) facilitate the integration and analysis of various spatial datasets to assess the impact of urbanization on groundwater recharge areas.

However, Remote Sensing data have limitations in spatial and temporal resolution, which can affect the accuracy of detecting subtle changes. GIS analyses depend on the quality and availability of input data, potentially leading to inaccuracies. Field surveys offer direct measurements of groundwater levels, quality, and recharge rates, providing continuous data crucial for assessing long-term trends and immediate impacts. Yet, field surveys and monitoring can be resource-intensive and time-consuming, with spatial coverage often limited to specific points that may not represent broader regional trends.

Combining these methodologies provides a comprehensive understanding of groundwater depletion and urbanization trends. Remote Sensing and GIS can identify areas of rapid urbanization and potential recharge zones, while field surveys validate model predictions and offer ground-truth data. Socioeconomic and policy analyses ensure that management strategies are practical and address underlying issues. Using a combination of methodologies helps mitigate the limitations of each approach, leading to a more robust analysis. Acknowledging and addressing the limitations through data integration, cross-validation, and adaptive management strategies is essential.

Lahore's topography is predominantly flat, with an average elevation of about 712 feet above sea level. Situated on the alluvial plains of the Ravi River, the city historically benefited from fertile soil and abundant water resources, contributing to its agricultural and economic development. Despite its flat terrain, Lahore experiences slight undulations due to natural levees and historical river courses. The lack of significant elevation makes the city prone to flooding, particularly during the monsoon season.

Groundwater depletion and rapid urbanization are closely linked, especially in rapidly growing cities. Urbanization increases water demand for residential, industrial, and commercial uses, often surpassing natural aquifer recharge rates. This over-extraction leads to a significant decline in groundwater levels. The expansion of impermeable surfaces, such as concrete and asphalt, reduces natural groundwater recharge by limiting rainwater infiltration. The combined effects of increased demand, reduced recharge, and contamination threaten the sustainability of groundwater supplies, posing serious challenges for future water security and urban planning.

Classification:

Land-use classification was conducted in Google Earth Engine (GEE) for the years 2000, 2010, and 2020, using Landsat 5 and 8 data. The study area was categorized into four main classes: Built-up Area, Barren Land, Vegetation, and Water Bodies, based on training data collected from GEE. Supervised classification was carried out using the Random Forest machine learning algorithm. Accuracy assessment was performed using a confusion matrix, and overall accuracy, producer accuracy, and user accuracy were calculated within GEE. Additionally, resampling was applied to the generated raster images to produce Land Use/Land Cover (LULC) maps and to conduct change analysis. The area of each class was also calculated from the raster images to analyze spatial changes over time.

Ordinary Kriging:

After organizing the raw data of tube well static water levels (SWL) in Microsoft Excel, the data was exported to R Studio for analysis. Ordinary Kriging was used to create a groundwater level surface for Lahore. Prior to applying Ordinary Kriging, several variogram models were tested to identify the most suitable model. Following the selection of the appropriate variogram, Ordinary Kriging was performed to generate a raster surface representing groundwater levels across Lahore.

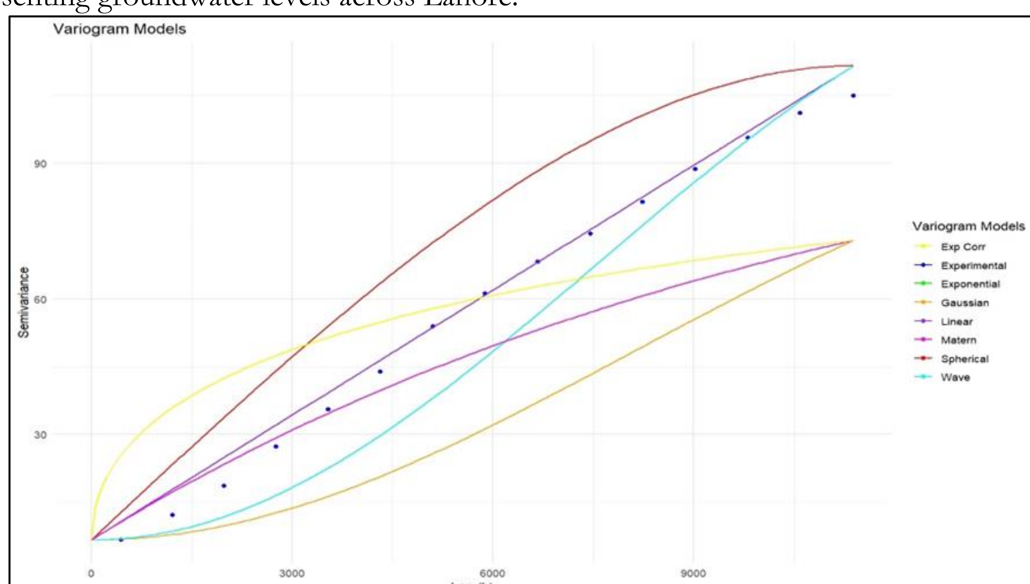

Figure 4: Comparison of Variogram Models for SWL Data

(Figure 4) illustrates the various variogram models applied to the tube well data, while (Table 2) presents information on these variogram models along with their Root Mean Square Error (RMSE) values.

Table 2: Summary of Variogram Models and their Predictive Accuracy for SWL Data Analysis

Variogram	RMSE (2014)	RMSE (2020)
Spherical	36.65591	45.06039
Exponential	30.39176	37.55113
Linear	34.08401	41.97575
Gaussian	35.61756	43.80662
Wave	36.80944	45.24384
Matern	30.39176	37.55113
Exponentially correlated	26.69377	33.14961

The model that best fits the data is the exponentially correlated model, which has the lowest RMSE. Subsequently, the data was imported into ArcGIS for further processing. Using overlay analysis and spatial analyst tools, final maps were produced.

Result and Discussion:

LULC Change Analysis:

The objective of analyzing changes in land use/land cover (LULC) was to quantify the percentage changes in land cover classes over the past twenty years. The study area was classified into four main categories: built-up area, vegetation, barren land, and water bodies. The spatial distribution of LULC classes in the Lahore district for the years 2000, 2010, and 2020 is illustrated in (Figure 5). The total area of each LULC class, its percentage cover, and the percentage changes in LULC classes from 2000 to 2020 are detailed in (Table 3).

Remote sensing satellite image analysis reveals a substantial increase in built-up areas due to the conversion of agricultural land into urban infrastructure. Between 2000 and 2010, built-up areas increased by approximately 16%, while vegetation decreased by about 13%, and barren land increased by around 36%. This shift is attributed to the conversion of agricultural land into housing societies for urban development. From 2010 to 2020, built-up areas expanded at an accelerated rate of 51%, while barren land decreased by 46%. Overall, there has been a significant increase of 76% in built-up areas over the last twenty years, at the expense of vegetation (a 9% decrease) and barren land (a 26% decrease). This reduction in vegetation and barren land has contributed to the growth of urban areas.

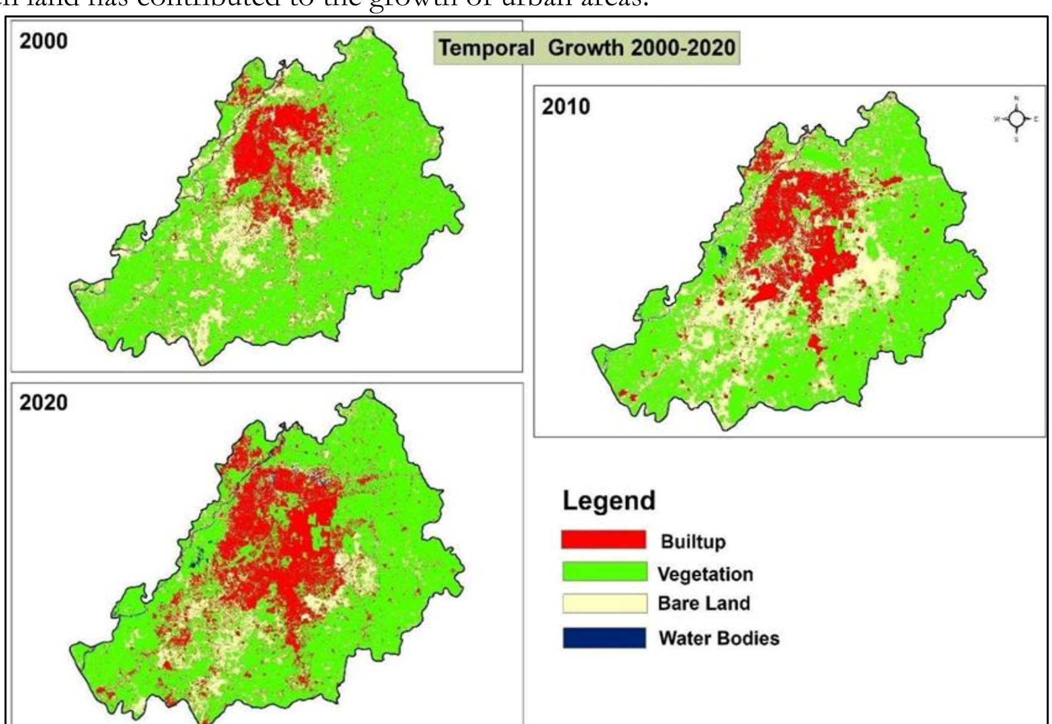

Figure 5: Temporal Growth of Lahore City

(Table 3) presents the statistical information of the classified images for Lahore, including the percentage changes in land cover over the years.

Table 3: Area of LULC classes and percentage differences over the period 2000-2020

LULC Type	2000 Area (km^2)	%	2010 Area (km^2)	%	2020 Area (km^2)	%	(%) change 2000-2010	(%) change 2010-2020	(%) change 2000-2020
Built up Area	231.2	13.98	269.3	16.28	407.1	24.64	16.49	51.35	76.31
Vegetation	1110.7	67.15	964.6	58.32	1015.6	61.47	-13.15	5.4	-8.46
Barren Land	302.4	18.28	412.8	24.96	222.6	13.47	36.50	-46.02	-26.32
Water Bodies	9.8	0.59	7.3	0.44	6.9	0.42	-25.2	-4.75	-28.76

Rainfall:

The rainy season, marked by frequent monsoon gusts, begins in July and continues until mid-September. Historical rainfall data for Lahore is illustrated in (Figure 6).

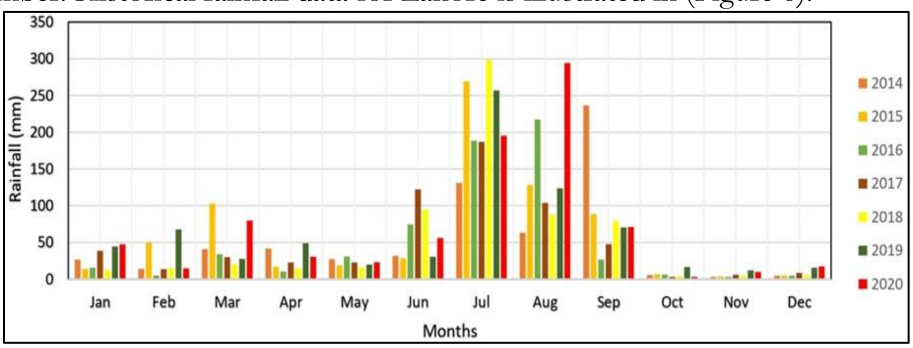

Figure 6: Annual Rainfall of Lahore

Lahore is situated in a semi-arid subtropical region characterized by low average monthly rainfall with considerable variation throughout the year. The monsoon period, particularly in July and August, experiences the highest rainfall, contributing approximately 40% of the annual groundwater recharge. The average annual rainfall in Lahore is 650 mm, though it can range from 300 to 1200 mm. Monthly average precipitation in millimeters is detailed in (Figure 7).

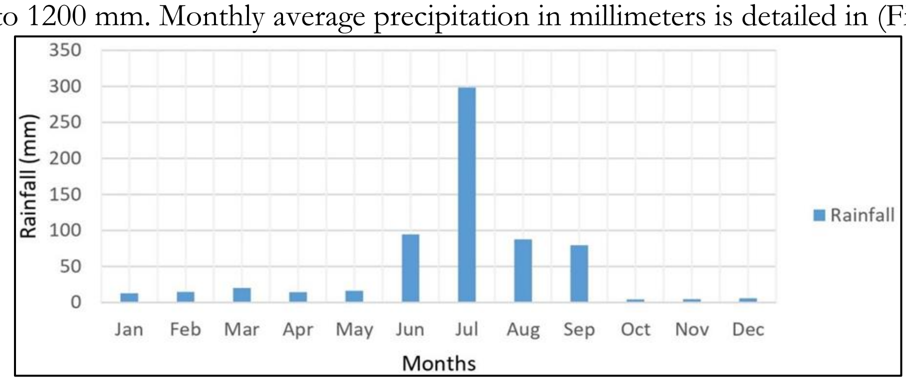

Figure 7: Monthly Rainfall of Lahore Year (2018)

Solid waste dumped into the sewer systems is a major cause of water accumulation and blockages. During the monthly rains and particularly in the monsoon season, heavy rainfall often leads to water pooling on the roads and streets of Lahore, creating significant issues. The city's flat topography, with slopes ranging from only 0.2 to 0.4 meters per kilometer, exacerbates rainwater accumulation during the monsoon.

Urbanization in Lahore has led to significant changes in the city's spatial patterns over recent years. The population of Lahore, which was approximately 6 million in 2000, grew to over 10 million by 2020, turning it into a "megacity." This rapid population growth has intensified pressure on the city's already stressed groundwater resources, as Lahore relies entirely on groundwater to meet its water needs. (Figure 8) illustrates recent population growth trends through a bar graph.

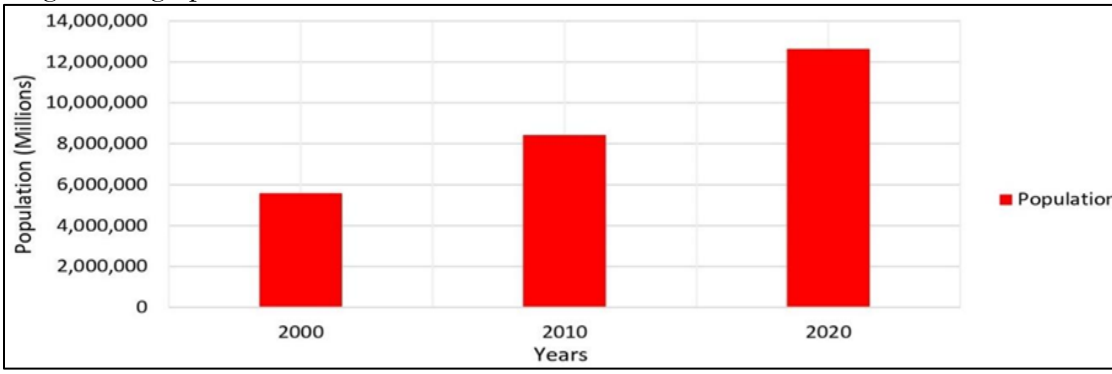

Figure 8: Population Profile of Lahore City

The number of tube wells increased significantly over the years. In 2014, water was extracted from approximately 400 pumping wells, but by 2020, this number had risen to 600. (Figure 9) shows the static water levels (SWL) for both years, with the area classified into six categories. In 2014, the water table was relatively high in dark green areas, with depths ranging from 11 to 19 meters. By 2020, however, the water table had dropped to approximately 2 meters. The second class, which had depths ranging from 20 to 27 meters in 2014, also experienced a depletion of about 2 meters. A significant decline was observed in 2020 compared to 2014, with a change ratio of approximately 3 to 4 meters over the past six years, indicating a concerning trend. (Figure 10) illustrates a clear overall decline in the water table between 2014 and 2020. Areas such as Gulberg Town, Nishter Town, and parts of Aziz Bhatti Wahga Town experienced severe stress due to dense populations, while some less populated areas near agricultural lands showed some signs of recharge.

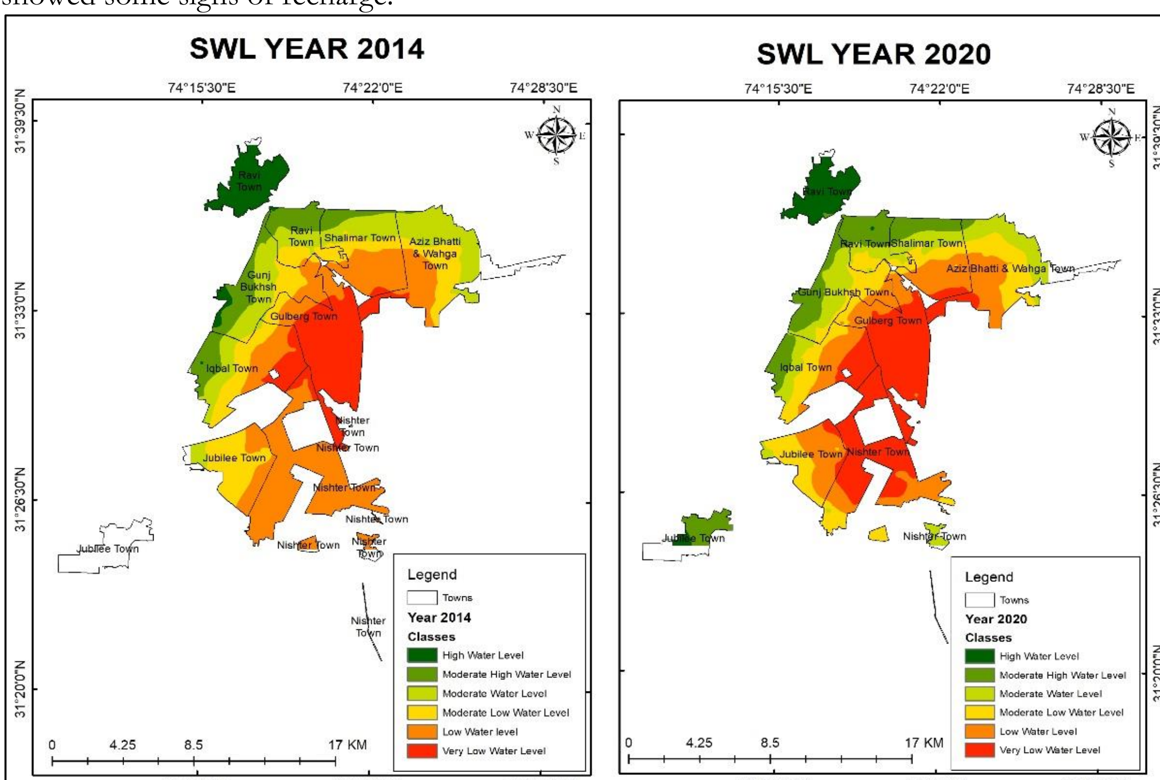

Figure 9: Kriging Results of the Tube Wells Installed in the Study Area

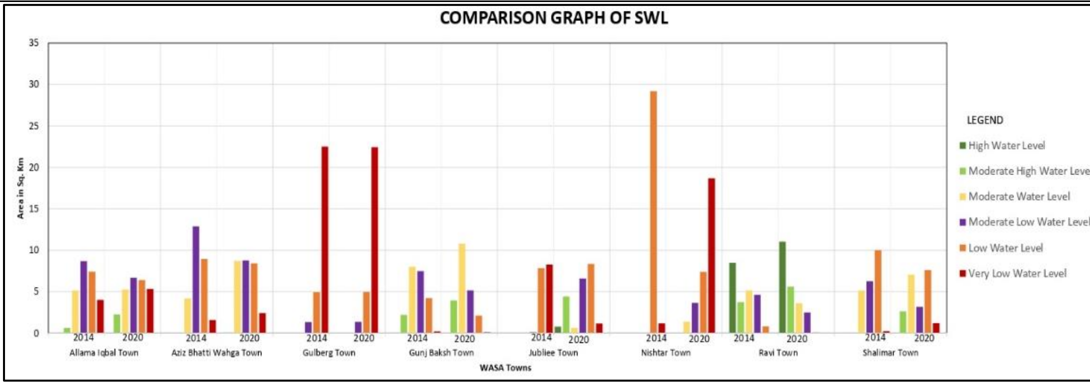

Figure 10: Change Comparison of SWL over the Years

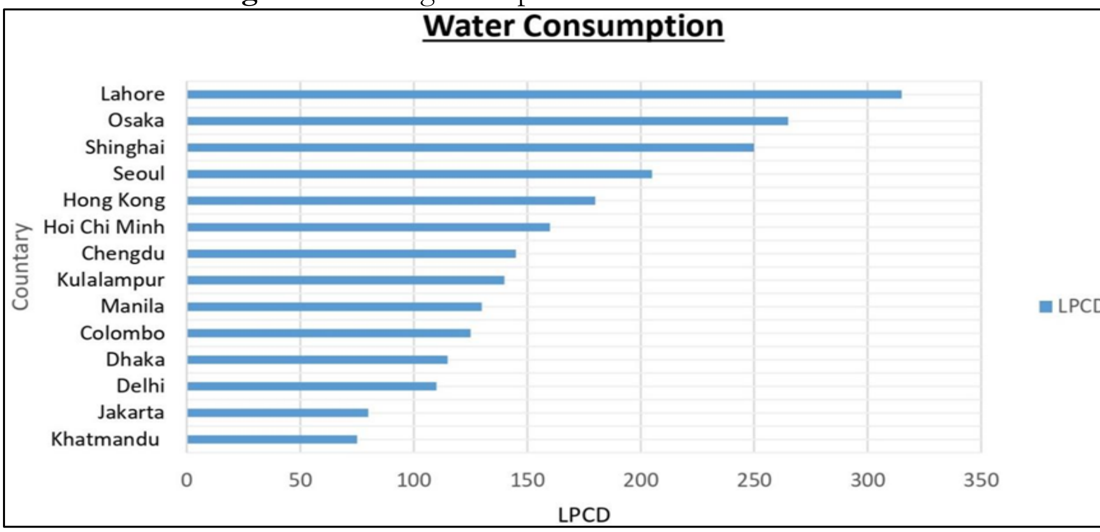

Figure 11: Water Consumption (LPCD)

(Figure 11) provides data on global Liters Per Capita per Day (LPCD), highlighting the high-water consumption patterns among Lahore residents. This valuable natural resource is often used wastefully, with people washing cars, ramps, and various household items. If groundwater extraction is not controlled, the area of groundwater depletion could expand rapidly, with a potential annual decline rate of over 2 meters, driven by the increasing needs of Lahore's population.

Discussion:

Over the last decade, water use in Lahore has increased at a rate exceeding population growth, placing significant stress on the city's aquifer. Urbanization and industrialization exacerbate this issue, leading to water shortages and pollution. Untreated sewage discharged into the Ravi River further compounds the problem, contributing to water quality degradation. Additionally, water scarcity in Lahore is driven by several factors, including limited runoff due to climate conditions, pollution, and high demand relative to water availability. Currently, Lahore faces all forms of water scarcity, presenting a challenge of balancing demand and supply. To address these challenges, improved water governance and demand management are essential. Key threats to groundwater include contamination and over-pumping. Historically, tube wells operated for around 18 hours a day without regulation. However, as of late 2018, WASA officials have reduced operation times to 10 hours a day. This change has helped stabilize the water table in Lahore, with some improvement noted in certain towns by 2020. Effective groundwater management requires the introduction of suitable frameworks and tools. Strategies must address both commercial and domestic users who rely on groundwater. Alongside supply-side solutions, demand-side management is crucial to reducing water demand and ensuring sustainable water use.

Conclusion:

Lahore is experiencing significant water shortages due to rapid urbanization and industrialization, which have put considerable stress on the city's aquifer. Untreated sewage discharge into the Ravi River has compromised water quality, leading to contamination. To tackle these complex issues, it is crucial to implement improved water governance and demand management strategies. Recent measures, such as reducing tube well operation times from 18 to 10 hours per day, have shown positive results, stabilizing groundwater levels and even leading to improvements in some areas. Effective groundwater management in Lahore requires the development of tailored frameworks and tools for both commercial and domestic users. A comprehensive approach is necessary, incorporating both supply-side and demand-side solutions to mitigate water shortages and achieve a sustainable balance between water supply and demand.

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Author's Contribution:

All the authors had different contributions to this research work and are mentioned here accordingly. Conceptualization (M.U.M, M.U, S.A), formal analysis (M.U.M), methodology (M.U and S.A), writing original draft preparation (M.U.M, S.A), writing review and editing (S.A, J.Q, M.U.M), visualization (M.U.M, J.Q, A.M). All authors have read and agreed to the published version of the manuscript.

Conflict of Interest: The authors declare they have no conflict of interest in publishing this manuscript in this Journal.

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