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 is the capital city of Punjab Province, with the population of 14.1 million people. To fulfil the water needs of its residents, Lahore is totally dependent on groundwater. Unwise water usage has led to a significant decline in groundwater levels.

Novelty Statement: The aim of this study to analyze the root causes of groundwater depletion in Lahore and propose protective measures. Excessive extraction from 600 tube wells, some reaching depths of 600 to 1000 feet. The consequences of this over-extraction include non-functional tube wells and severe water shortages complains.

Material and Method: By the utilization of various tools and techniques, including Google Earth Engine, image classification methods, and R Studio (ordinary Kriging) were used. The spatial relationship between land use/land cover and groundwater levels assessed through overlay analysis. 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 ft. / year (0.65 m / year) during 1980-2000 to over 3 ft. / year (over 1 m/ year) after 2013. Factors contributing to this decline 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, highlighting the urgent need for sustainable water management practices.

Concluding Remarks: This rapid depletion is a serious threat to Lahore's groundwater and needs the immediate implementation of sustainable water management and ground water recharge. Effective measures are crucial to mitigate the impact 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 frequently misused and undervalued. It is a fundamental element sustaining life on Earth. We cannot survive without quality drinking water [1]. In the past decade, many efforts have been made to assess groundwater depletion associated with rapid urbanization. Many researchers have emphasized the importance of groundwater degradation. Groundwater is extremely valuable in influencing climate change and the rapid increase of the human population, much like other natural resources [2]. Groundwater is used for drinking purposes worldwide [3]. About 99 percent of fresh water is found in underground aquifers, which are used by at least 25% of the world's population to meet their water needs. The total amount of water extracted for human needs has nearly tripled in the last 50 years (1950–2000) from 1382 km/year to 3973 km/year, and by 2025, consumption is expected to reach 5235 km. Water is key requirement of industrial, agricultural, and human use [4]. Numerous studies show that this resource is overexploited globally [5]. Globally, groundwater depletion is estimated at 100 to 200 km^3 per year, which is around 15 to 25% of total groundwater withdrawals (UN-water, 2022). The most severe depletion occurs in Central Asia, the USA, North China, and the Middle East [6]. This is particularly true for Pakistan, which is currently considered a water-stressed country and is projected to face severe water scarcity in the near future. Unsustainable uses of water resources, inefficient irrigation methods, rapid urbanization & population growth, and decentralized management have put enormous pressure on surface and groundwater resources [4]. Lahore is capital of Punjab and second greatest city of Pakistan. Long history of groundwater over reflection with diminished spring stimulate has incited water table slump liberally. As of 2020, its population was 12,642,000 which is increased to 14,407,000 with the growth rate of 13.96%. The city relies entirely on groundwater to meet its water needs. Water is drawn through 600 tube wells installed in the WASA Lahore jurisdiction and then pumped into the main water distribution system, which leads to rapid depletion of the groundwater table (about 1.0 to 2.0 meters per year).

The primary cause of groundwater depletion and pollution is rapid urbanization in the city, which along with industrialization and urban growth, significantly impacts groundwater quantity as well as quality [7]. According to the "Lahore 2040 Final Master Planning Report", due to population growth, urbanization and excessive pumping, the Lahore aquifer has been facing a declining trend since the 1970s. The number of tube wells were also changing with each passing year. As a result, some existing tube wells were unusable and due to the reason city began to face a severe water shortage. Therefore, the groundwater source itself does not appear to be a reliable source in the future. The average annual rainfall in Lahore is about 650mm, which does not contribute much to the recharge of the aquifer because the rate of groundwater, as extraction rate is much higher than the rate of recharge and the second main reason is the low flow of the Ravi River Except for the Monsoon season in July to September, winter and summer are almost dry, resulting in further depletion of groundwater levels and tube well failures. Obviously, this is a water-related problem, but from a broader perspective, the livelihood itself is caused by it (Source WASA Lahore). Because of its combination of organic and inorganic elements, it is a fundamental component supporting life on Earth and functions as an essential nutrient. It is essential for biological processes, which emphasize the needs for its careful conservation and protection against pollution [1]. The critical importance of water is, a person can only survive four days without it, whereas without food it can extend to weeks or months. Water is important for its diverse physiological functions [8]. Water exists in various forms, however, not all these sources are accessible for public use. Groundwater is one of the most crucial sources of fresh water, and a vital resource for agriculture and domestic use. It is the third largest global water reservoir, 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 reinstating depleted aquifers [9]. One key aspect of aquifer management is to reduce groundwater exploration to minimize the stress on aquifers [10]. A sustainable development can be achieved by improving the efficiency of water usage and implementing strict regulations to limit groundwater extraction. However, limiting groundwater use alone is not sufficient to fully restore depleted aquifers. MAR approaches are useful in this situation [11]. With MAR, treated wastewater or excess surface water is directed to injection wells, infiltration basins, or other specially designed structures in order to artificially replenish aquifers. MAR has been used on a global scale at various operational scales. Over-exploitation of aquifers can be mitigated by combining efforts to optimize the structure of the water supply with the application of MAR techniques [12]. These methods contribute to the long-term sustainability of groundwater resources in addition to offering immediate relief by reducing the strain of extraction on aquifers (UNESCO, 2021).

Urbanization has a negative effect on the quantity and quality of groundwater as well as its recharge [13]. The transformation of natural, agricultural, and less populated lands into urban settlements has changed the hydrology of the area [14]. Research indicates that urbanization cause more than half of precipitation to run off and only a low amount of water goes for deep infiltration [15]. From the above review of literature, it is clear that urbanization and subsequent changes in land use and land cover has severe adverse implications for the local ecology. However, the existing studies have, in general, focused on examining bivariate relationships between urbanization and LULC changes [16], due to the urbanization and changes in temperature [17], urbanization and changes in rainfall pattern [18], or urbanization and changes in groundwater level [19]. The purpose of this research is to investigate the physical changes in Lahore during the years 2000 to 2020 and its relation with the reduction of ground water level in Lahore and changes rainfall pattern and identify the fluctuation in ground water table and to identify the urbanization pattern through remote sensing and map the ground water levels with respect to the urbanization.

Study Area:

Lahore is the capital city of Punjab province, which covers 1772 km2 area, geographically it is located at 31°15'-31°45' N and 74°01'-74°39' E, its boundary is expended by district Sheikhupura to the north and west, Wagah to the east, and Kasur to the south, and the Ravi River flows to the north (Figure 1). The city is located at the height of 712 ft from mean sea level. Lahore features a five season semi-arid climate and the seasons are winter, summer, spring, autumn and monsoon. The hottest month of the year is June when temperatures routinely exceed 40oC. The wettest month is July, with heavy rain falls and evening thunderstorms with the possibility of cloudbursts. The coolest month is January with dense fog. The mean maximum and minimum temperatures in summer are 48oC and 38oC and in winter 25oC and -1oC respectively. In the study area, the groundwater level is falling due to the reckless use of water for drinking, washing, bathing and for different purposes. WASA has installed many tube wells to meet public water demand. These tube wells were installed at depths of 600 to 1000 feet, which will cause the water level to drop further. This not only threatens the groundwater level of the aquifer in Lahore, but also affects its quality and taste. The groundwater extraction rate is approximately 1.45 million cubic meters per day. According to the WASA report, the groundwater level has dropped to 61 feet on average since 1961. The groundwater levels in different areas of Lahore has significantly decreased: 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).

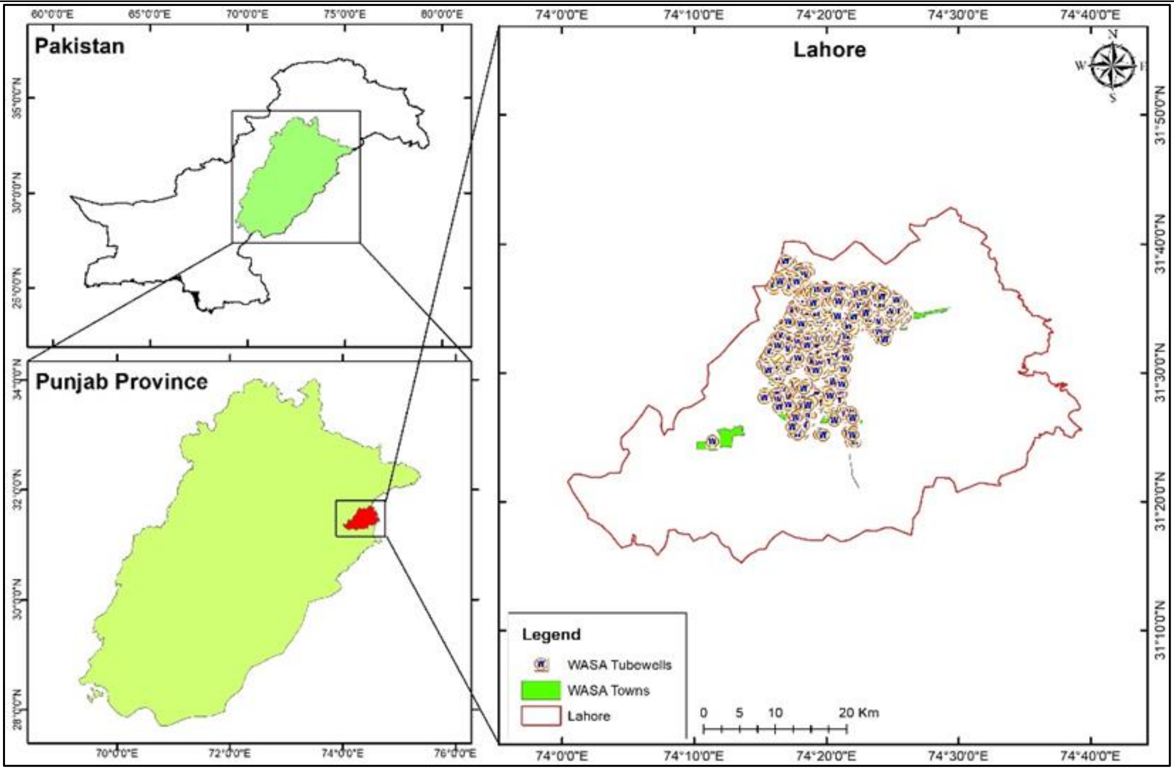

Figure 1: Geographical Location of the Study Area and Distribution of Tube Well Locations in Lahore

The overall groundwater level in Lahore is dropped with the average rate of 2.03 feet per year, with the current rate at approximately 3 feet per year as shown in the (**Table 1),** which depicts the time series data with corresponding rate of decline rate. The data reveals a consistent decrease in water levels over the 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 regarding the identification and prediction of fluctuations and changes occurred and, likely to be occurred, in ground water table due to spatial changes in Lahore City. The data collection and its preparation for this research proposal was the main milestone to achieve properly. For this research analysis, the following methodology was adopted **(Figure 2)**.

Water and Sanitation Agency, Lahore covers 8 towns and 34 Sub Divisions in Lahore and serving the population of Lahore with water supply, sewerage and drainage system for basic social needs. In this research, the focus was on urbanization-related groundwater levels for this, a filed survey is carried out in the WASA Lahore jurisdiction to collect the accurate locations of tube wells, which were collected in the form of point data through GPS equipment. After the collection of the raw data, it was plotted in ArcMap. Upon the completion of 1st phase of the survey, the second step was to verify the collected data from the concerned office, the Hydrology directorate of WASA Lahore to collect the data of groundwater levels. In **(Figure 3)**, collected tube wells data was plotted in ArcMap.

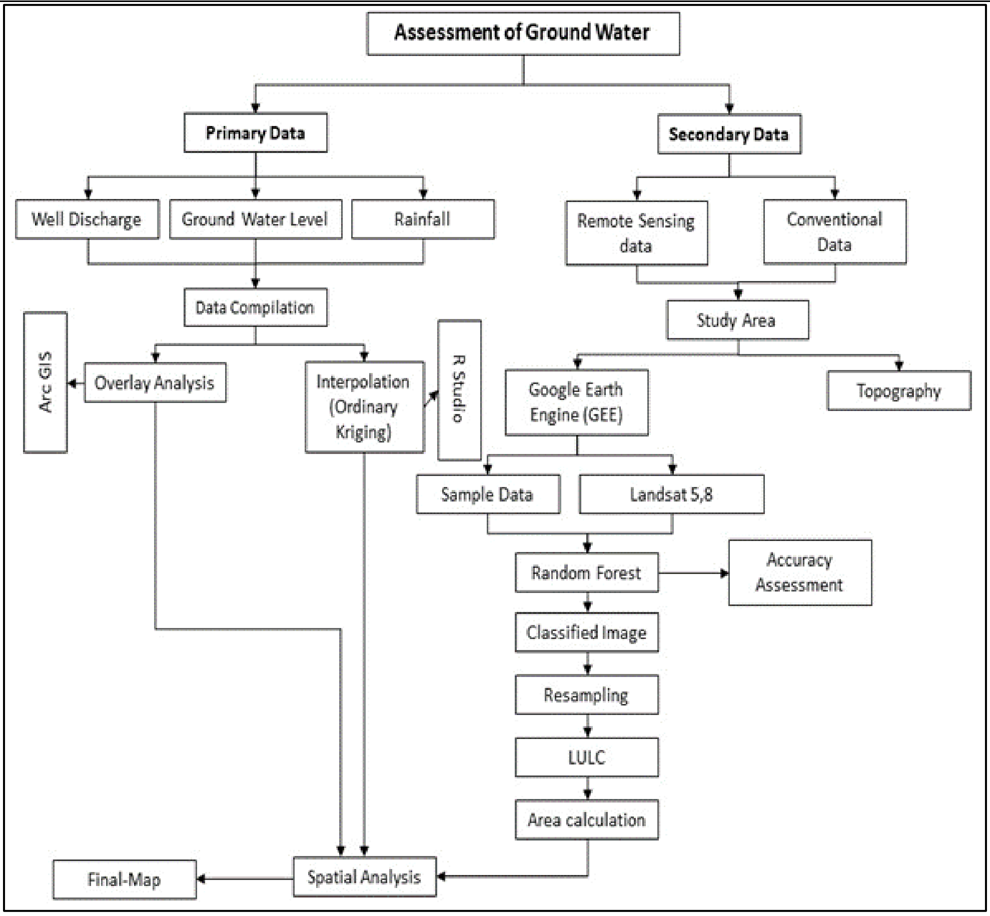

Figure 2: Flow Chart Visualizing the Data Processing and analysis Methodology

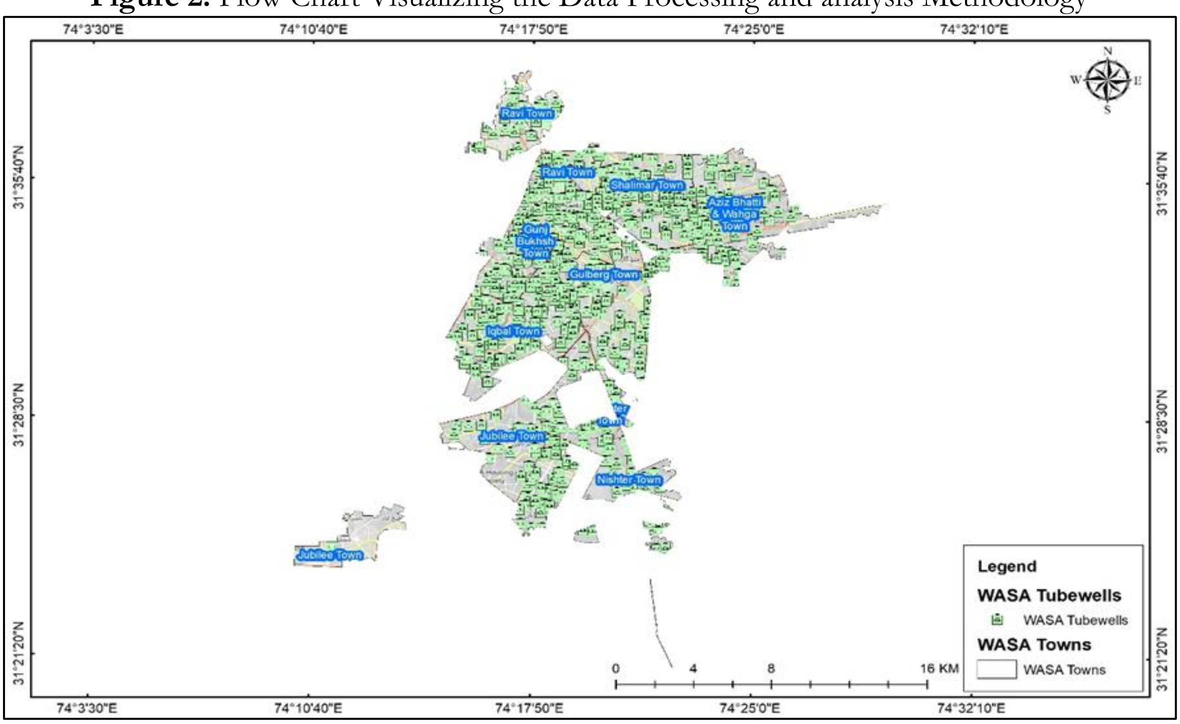

Figure 3: Existing Tube Well Water Supply Network of WASA Lahore

After the collection of primary data than further proceed to secondary data, in which by the use of Remote Sensing (RS) data and conventional data for the study area. Remote sensing (RS) provides comprehensive spatial data which allows us to monitor changes in land use/land cover and urban expansion over time while Geographic Information Systems enable the integration and analysis of various spatial datasets to assess the impacts of urbanization on groundwater recharge areas.

Remote sensing data have limitations in spatial and temporal resolution, which could affect the accuracy of detecting subtle changes. GIS analyses depend on the availability and quality of input data, which may vary, leading to potential inaccuracies. Field surveys provide direct measurements of groundwater levels, quality, and recharge rates. Groundwater monitoring networks offer continuous data essential for assessing long-term trends and immediate impacts. Field surveys and monitoring can be resource-intensive and time-consuming. Spatial coverage is often limited to specific monitoring points, which may not represent broader regional trends.

Combining these methodologies provides a comprehensive understanding of groundwater depletion and urbanization trends. For instance, Remote Sensing and GIS can identify areas of rapid urbanization and potential recharge zones. Field surveys validate model predictions and provide ground-truth data. Socioeconomic and policy analyses ensure that management strategies are realistic and address underlying drivers. Selecting a combination of methodologies helps mitigate the limitations of individual approaches, leading to a more robust analysis. However, each method's limitations must be acknowledged, and efforts should be made to address them through data integration, cross-validation, and adaptive management strategies.

The Lahore topography is predominantly flat, with an average elevation of about 712 feet from sea level. The city lies on the alluvial plains of the Ravi River, which historically provided the city with fertile soil and abundant water resources, contributing to its agricultural and economic development. The city is characterized by extensive urbanization, with built-up areas and infrastructure dominating the landscape. Despite its flat terrain, the city experiences slight undulations, primarily due to natural levees and historical river courses. The lack of significant natural elevation means that Lahore is susceptible to flood prone area, particularly during the monsoon season.

Groundwater depletion and rapid urbanization are closely linked issues, particularly in rapidly growing cities. As a result of Urbanization, water demand increases for residential, industrial, and commercial use, often exceeding the natural recharge rates of aquifers. This over-extraction leads to a significant decline in groundwater levels. In many cities, including Lahore, the expansion of impermeable surfaces like concrete and asphalt reduces natural groundwater recharge by limiting rainwater infiltration. The combined effect of increased demand, reduced recharge, and contamination threatens the sustainability of groundwater supplies, posing serious challenges for future water security and urban planning.

Classification:

Land-use classification is performed in GEE for the year 2000, 2010 and 2020. Landsat 5 and 8 data was used for classification. Study area was classified into four main classes Built-up Area, Barren Land, Vegetation and Water Bodies by collecting training data from GEE. Supervised classification was performed using Random forest machine learning algorithm. Accuracy assessment is performed using confusion matrix. Overall accuracy, producer, user accuracy were calculated using GEE. Furthermore, resampling was performed on the generated raster image and got the LULC map, and examined change analysis. Moreover, area calculation of each class was performed to analyze the area in the raster image.

Ordinary Kriging:

After the necessary arrangement of raw data of tube wells SWL in Microsoft excel, the data was exported to R Studio, to execute ordinary kriging of the given SWL data to generate the surface of groundwater level. Before the ordinary kriging, multiple variogram models were fitted on the data to select appropriate variogram model and then performed ordinary kriging which generates the raster surface of Lahore groundwater. After the necessary arrangement of raw data of tube wells SWL in Microsoft excel, the data was exported to R Studio to performed ordinary kriging of the given SWL data to generate the surface of groundwater level. Before the ordinary kriging, multiple variogram models were fitted on the data to select appropriate variogram model and then performed ordinary kriging which generates the raster surface of Lahore groundwater.

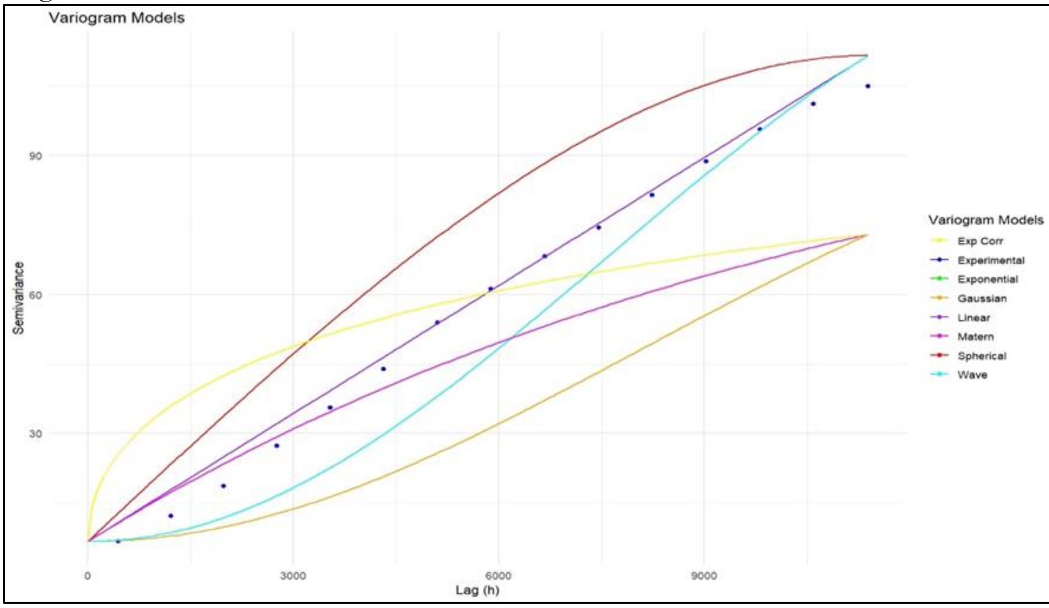

Figure 4: Comparison of Variogram Models for SWL Data

(Figure 4), shows the multiple variogram models used on the tube well data, and (**Table 2)**, depicts the information of the used variogram models with their RMSE.

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 which is best fit on the data is exponentially correlated model with the least RMSE. Lastly, the data was imported in ArcGIS for further processing, with the help of overlay analysis and spatial analyst tool final maps are produced.

Result and Discussion:

LULC Change Analysis:

The objective of changes in LULC was to quantify percentage changes in land cover classes over the last twenty years. The study area was classified into 4 main classes namely; Built-up area, vegetation, barren land and water bodies. Spatial distribution of LULC classes of the Lahore district for the years 2000, 2010 and 2020, respectively are shown in **(Figure 5)**, The total area of each LULC class and its percentage cover, and percentage changes in LULC classes during the 2000-2020 is shown in the **(Table 3)** Remote sensing satellite image analysis shows substantial increase in built-up area due to transformation of LULC from agriculture lands to urban infrastructure. Over the period 2000-2010, built-up areas have increased about 16%, vegetation decreased about 13% and barren land increased about 36%. This is because agricultural land has been converted into housing societies for urban development. Over the period 2010-2020, built up areas have increased at a faster rate (51%) and barren land decreased about 46%. The results show overall a large increase (76%) in built up areas at the cost of vegetation (9% decreases) and barren land (26% decrease) over the last twenty years. So, reduction in vegetation and barren land are contributing for growth of urban areas.

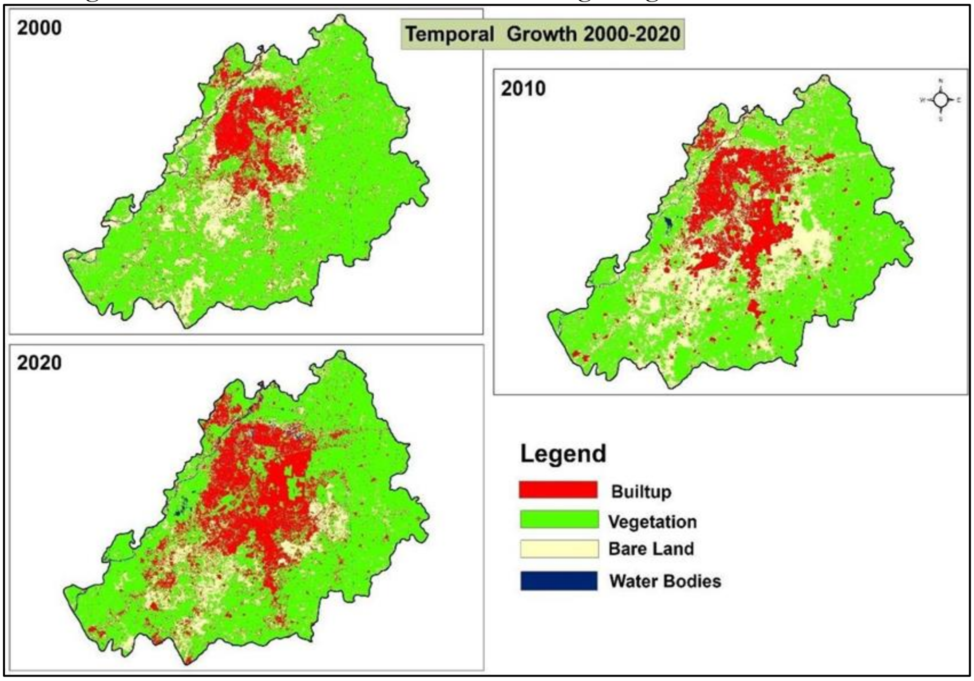

Figure 5: Temporal Growth of Lahore City

The **(Table 3)** depicts the statistical information of the classified image of the Lahore and change percentage 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 characterized by frequent monsoon gusts started in July and lasted until mid-September. The historical rainfall data of Lahore showed in **(Figure 6)**.

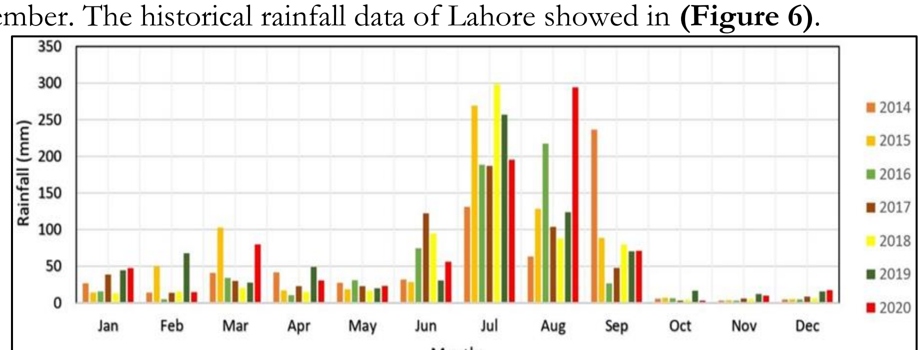

Figure 6: Annual Rainfall of Lahore

Lahore is located in a semi-arid subtropical region. The average monthly rainfall is very low, and it varies from month to month. July and August have the highest rainfall during the monsoon period, which accounts for about 40% of the annual groundwater recharge. The average annual rainfall is 650 mm, between 300 and 1200 mm. In **(Figure 7)**, the monthly average precipitation in millimeters is as follows:

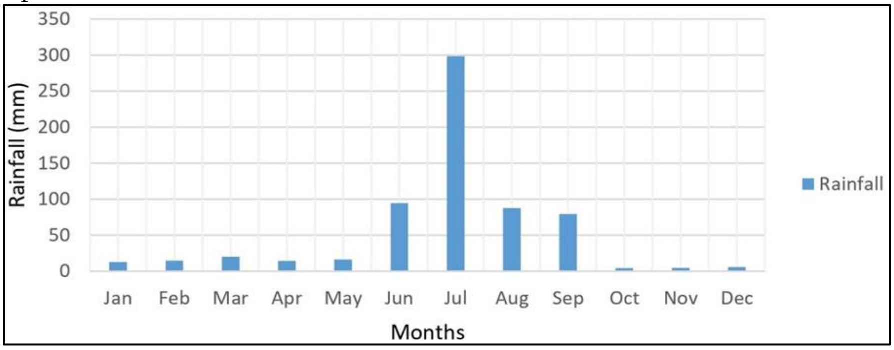

Figure 7: Monthly Rainfall of Lahore Year (2018)

The solid waste dumped in the sewer which is the main cause of water accumulation and blockage in the sewer. During the monthly rains every year and specifically in the monsoon season heavy rainfall cause rainy water to accumulate on roads and streets of Lahore citizens which is problematic. Because the slopes are flats in many areas of the city, which drops only 0.2 to 0.4 meters per kilometer, which is also the reason to the accumulation of rainwater during the monsoon.

Due to increasing trend of urbanization in Lahore, spatial patterns of the city are getting change for the last few years. Population of Lahore was nearly 6.0 million in 2000 and it became a "megacity" with a population of more than 10 million in 2020. The rapidly increasing population of this already densely populated city is increasing water pressure because the city is completely dependent on groundwater resources to meet its water needs. In **(Figure 8)**, the bar graph shows the information of population growth in recent years.

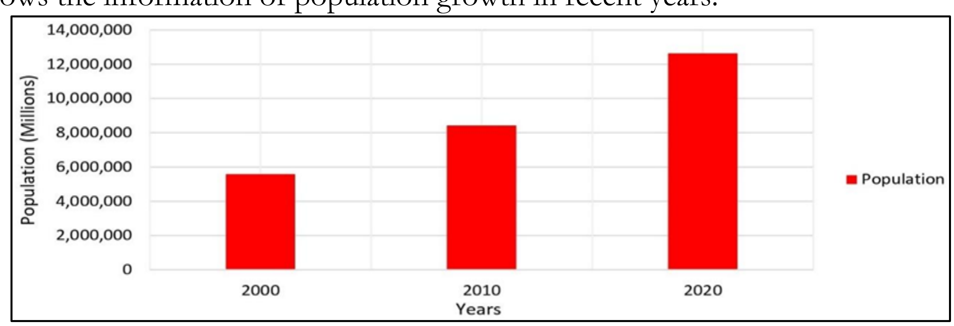

Figure 8: Population Profile of Lahore City

The number of tube wells were increased over the years. In 2014, the water extracted from around 400 pumping wells and in 2020 the number reached to 600 tube wells. In the **(Figure 9)**, SWL of both the years was mapped, and the area was classified into six classes, water table was high in the dark green area with the depth of 11 to 19m in the year 2014, but it was decreased in the 2020 and the water table dropped to 2m approximately. The second class ranges from 20 to 27m in 2014 and depletion rate was also around 2m. After that huge decrement detected in 2020 as compared to year 2014 and the change ratio was near 3 to 4m in the last six years which was alarming. The overall trend in the **(Figure 10)**, between the year 2014 and 2020 showed clear decline in water table, area of Gulberg Town and Nishter Town and some area of Aziz Bhatti Wahga Town were under stress because of the dense population in these areas, whereas some of the areas where population was less and these areas are near to agriculture land had some recharge as well.

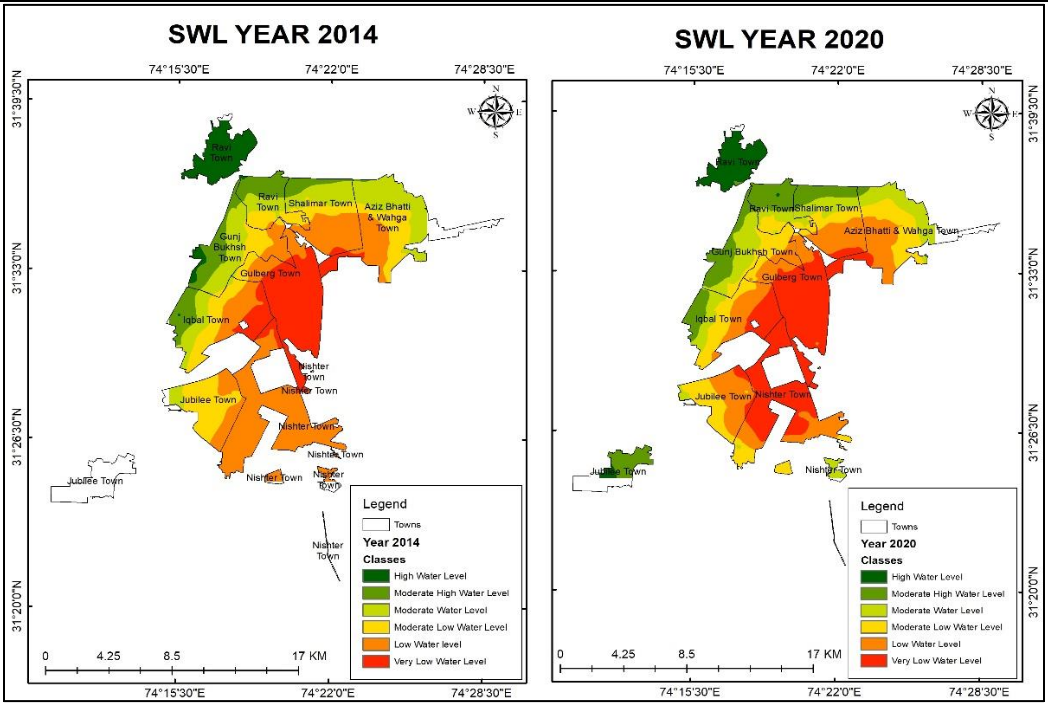

Figure 9: Kriging Results of the Tube Wells Installed in the Study Area

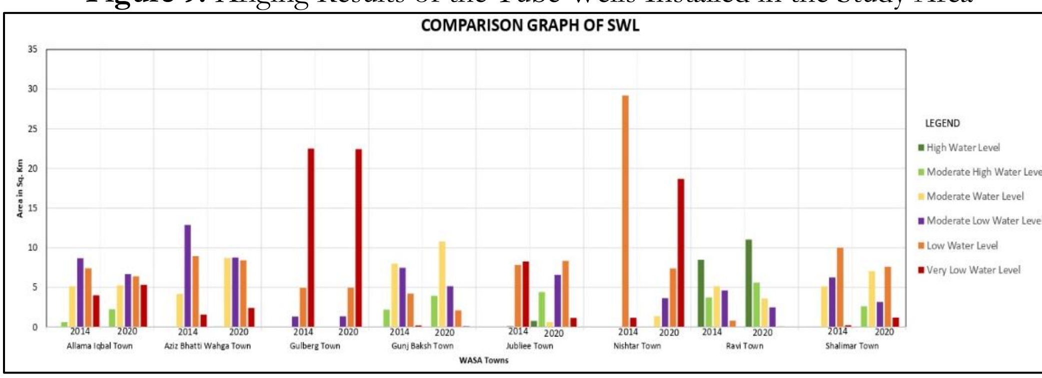

Figure 10: Change Comparison of SWL over the Years

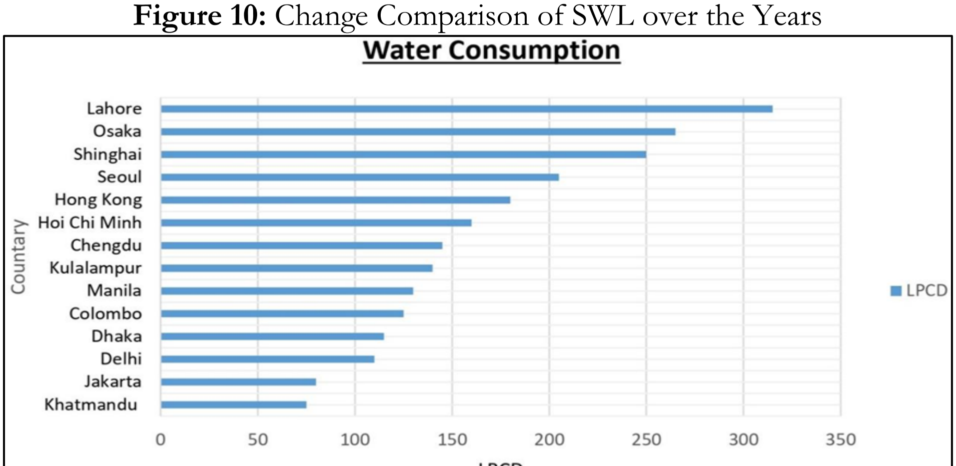

Figure 11: Water Consumption (LPCD)

The **(Figure 11)**, had the information of global LPCD, which showed high consumption pattern of water by the residents of Lahore. People used this valuable natural resource unethically, they used to wash their cars, ramps and many house hold things with it. If the exploration will not controlled than the depression area will increased rapidly with the rate of over 2m annually to fulfil the needs of Lahore citizens.

Discussion:

In the last decade, water uses in Lahore had increased at a higher rate than population growth, causing significant stress on the city's aquifer. Urbanization and industrialization intensify this issue, which is leading to water shortage and pollution, because of untreated sewage is discharged in river Ravi which is causing water pollution. Additionally, water scarcity and potential groundwater depletion further worsen the situation. Blue water scarcity can be referring to at least four different phenomena's. It may be climate driven in terms of limited runoff generation, pollution-driven in the sense of water quality degradation, making the water unusable; demand-driven in terms of high water demand in relation to water availability. Presently, Lahore is facing all types of water scarcity. It's just a game of demand and supply. To address water scarcity problems and achieve a balance between supply and demand of water, it needs improved water governance and demand management. There are two major threats to groundwater degradation; contamination and over pumping. One of the major concern was tube well operation timings which were not observed in the past years, the operation time was around 18 hours/day. According to WASA officials tube well timings were start to observe by the end of 2018, and it will reduce from 18 hours to 10 hours/day. This step is beneficial to stop the over exploitation and due to this, water table is stable in the Lahore city whereas in some towns water table is improved in 2020. In order to effectively manage groundwater, authorities has to introduce frameworks and tools suitable for its conditions. Different strategies need to be proposed for commercial users and domestic users who rely on groundwater for their livelihoods. In addition to supply-side solutions, Management also needs to work hard on demand-side solutions. It would be an attractive option to reduce the water demand.

Conclusion:

Lahore is facing significant water shortage due to **rapid urbanization and industrialization, which increased stress on the city's aquifer**. Untreated sewage discharge in River Ravi effects the water quality and contamination is reported. To address these multifaceted challenges, **it is imperative to implement improved water governance and demand management strategies**. Due to recent measures, such as **reducing tube well operation timing from 18 to 10 hours per day, which had shown stability in the ground water and it was noted as positive results, with some areas even reporting improvement**. Effective groundwater management necessitates the development of different effective frameworks and suitable tools for Lahore, differentiating between commercial and domestic users. A comprehensive approach is required that includes both supply-side and demand-side solutions is essential for mitigating water shortage and achieving 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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