

Assessment of Groundwater Depletion at Local Scale Using Satellite Data: A Case Study of Lahore District, Pakistan

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Abstract

With rapid urbanization, population growth, and excessive water withdrawal from groundwater, the issue of groundwater depletion has become a critical concern in Lahore, Pakistan. This study evaluates groundwater depletion at the local scale using satellite observations and ground-based data. The methodology employed included well water data from 220 sites over the period 2000 to 2019, obtained from the Water and Sanitation Agency (WASA); spatial interpolation with Inverse Distance Weighting (IDW) using ArcGIS; and Mann-Kendall trend analysis. International Centre for Global Earth Models (ICGEM) satellite data from the Gravity Recovery and Climate Experiment (GRACE) were also used to understand groundwater variations. The Mann-Kendall test indicated that water table depth increased significantly during the study period, with a positive trend ($Z = 4.7693$, $p < 0.001$, $\tau = 0.7789$). Water levels in the groundwater dropped from 24.28 m in 2000 to 41.83 m in 2019, with a mean water-table decline of about 0.92 m/year. Results indicate that GRACE satellite data can well represent large-scale changes in groundwater, with the greatest depletion seen in the urbanized central and southern parts of Lahore District. It is concluded that satellite-based assessment is an effective approach for monitoring groundwater dynamics, and that there is a pressing need for sustainable interventions in groundwater management in Lahore.

Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite project, launched in 2002, put groundwater — a key natural resource essential to the health of people and ecosystems — firmly on the map. This project has revolutionized our ability to monitor changes in the Earth's water cycle, including groundwater resources (Rodell et al., 2009). GRACE is a joint project between NASA and the German Aerospace Center (DLR), using a pair of satellites to capture changes in the Earth's gravitational field caused by changes in mass distribution on and in the Earth. The variations in groundwater storage that occur when water is extracted from aquifers or added to them by precipitation can be detected by these satellites, which measure changes in the gravity field (Tapley et al., 2004).

Groundwater depletion is a serious threat to human health and the environment, from Pakistan to California and India, and is becoming an increasingly global problem (Aeschbach-Hertig and Gleeson, 2012). New instruments developed with the GRACE satellite are helping to address this problem and have the potential to bring greater sustainability through more efficient monitoring. Groundwater is abstracted from aquifers while being replenished by precipitation; as the quantity of water in the subsoil changes, this produces a change in the gravitational field of the Earth that can be observed from space using satellite measurements (Chen et al., 2016).

Lahore, the second-largest city of Pakistan and the capital of Punjab province, depends mainly on groundwater for its water supply. In recent years, Lahore's inhabitants have used technologies including hand pumps, motorized pumps, and conduit wells to extract 160 million liters of groundwater per day, supplied through water distribution networks and water purification facilities (Kanwal et al., 2015). The

Lahore aquifer lies within the interfluvial area between the Chenab and Ravi rivers, known as Rachna Doab, occupying a large alluvial plain traversed by the Indus River and its tributaries (Basharat et al., 2016).

The depletion of groundwater in Lahore is caused by several factors, including rapid urbanization, population growth, and unsustainable water use. The water table has dropped to over 40 m in the city center due to over-abstraction of groundwater by public and private tube wells and reduced recharge (Basharat and Rizvi, 2011). Water levels have been declining at a rate of 0.45–1.50 m/year due to unchecked groundwater extraction without corresponding recharge efforts, and without access to surface water sources (Basharat et al., 2016). Roughly 1,161 million cubic meters (MCM) of groundwater is lost each year, and groundwater recharge is around 15% less than groundwater extraction (Basharat et al., 2016).

The use of satellite data to track groundwater depletion at the local scale offers several advantages over previous methods. Groundwater level data from satellite remote sensing can be used to measure groundwater levels over large extents with high frequency, making it suitable for monitoring rapidly urbanizing regions such as Lahore (Akhter et al., 2021). The International Centre for Global Earth Models (ICGEM) and GRACE satellite-derived measurements have the potential to provide groundwater fluctuation information at large scales, with monthly gravity field estimates offering information on spatial and temporal variability (Feng et al., 2013).

The objective of this study is to assess groundwater depletion in Lahore District using satellite data and ground-based observations; to identify areas within the district experiencing significant groundwater depletion; to examine the groundwater depletion trend over time; to map groundwater depletion across Lahore District; and to identify the factors responsible for declining groundwater levels. The results are intended to support evidence-based decisions for sustainable water resource management in Lahore.

1 Materials and Methods

1.1 Study Area

Lahore is the administrative capital of Punjab province, Pakistan, situated at 31°34'55.36"N, 74°19'45.75"E at an elevation of 217 m (712 ft). The district covers an area of about 404 km² and is bordered by Sheikhpura, Wagah, and Kasur districts. Lahore lies to the south of the Ravi River and has a semi-arid climate with five distinct seasons: summer, the rainy monsoon, dry autumn, foggy winter, and spring. June is the warmest month, with maximum temperatures exceeding 40°C, and January is typically foggy.

The Lahore aquifer lies within the interfluvial area of Bari Doab, bounded by the Ravi River to the north-west and the Sutlej and Beas rivers to the south-east. In Lahore, groundwater is the primary water source, with rainfall, the Ravi River, and irrigation canals serving as the main sources of recharge.

Figure 1 Location Map of Lahore District, Pakistan showing the boundaries of study area, major rivers (Ravi River) and administration of the district. The inset map depicts the location of Lahore in the province of Punjab and the country of Pakistan.

1.2 Data Sources

This study drew on several sources of data to characterize groundwater depletion in Lahore District:

Groundwater well data: observed data from 220 wells collected between 2000 and 2019 from the Water and Sanitation Agency (WASA), Lahore. Changes in water table depth were observed during the post-monsoon season using post-monsoon well data, with annual water level changes and water table depths provided for each monitoring well.

Gravity Recovery and Climate Experiment (GRACE) satellite data: retrieved from the International Centre for Global Earth Models (ICGEM) via its website (<https://icgem.gfz-potsdam.de/home>). A collection of monthly gravity field estimates from 2002 to 2019 was downloaded, enabling large-scale groundwater dynamics to be examined. The data provided weighted mean, minimum, and maximum values, as well as grid point data for the Lahore region (lat. 31–32°N, long. 71–73°E).

Satellite imagery and geospatial data — including Landsat, Sentinel, and MODIS products — were accessed and analyzed using the web-based Google Earth Engine platform, which enabled time-series analysis and visualization of changes in groundwater storage in Lahore.

Groundwater data were spatially interpolated and mapped using ArcGIS 10.x software and the Inverse Distance Weighting (IDW) method.

1.3 Spatial Interpolation Using the ArcGIS IDW Method

Groundwater levels across Lahore District were interpolated using Inverse Distance Weighting (IDW). IDW estimates values at unknown locations by assigning weights to surrounding sample points, such that the weight of a point increases the closer it is to the unknown location. The methodology followed these steps:

- Groundwater well data (with known values) were loaded into ArcGIS.
- The Arc Toolbox was opened, and the IDW tool was selected from the Spatial Analyst Tools > Interpolation menu.
- The layer containing the data points of known values was chosen.
- The water table depth was indicated in the Z-value field.
- The location and cell size of the output raster were specified.
- The power (p) and search radius parameters were optimized for best results.
- The IDW tool was run, producing a new raster layer with interpolated values.
- The interpolated surface was checked against the original data points for validation.

IDW interpolation was carried out for each year from 2000 to 2019, and a groundwater level map was produced for each year across Lahore District.

1.4 GRACE Data Analysis Using ICGEM

GRACE satellite data were accessed through the ICGEM website, which provides global gravity field models and associated geodetic data. The analysis procedure included:

1. Registration on the ICGEM website to access data services.
2. Selection of GRACE gravity field models and datasets.
3. Downloading data for the Lahore region (lat. 31–32°N, long. 71–73°E).
4. Processing and analyzing the downloaded data using appropriate software tools.

The ICGEM data provided monthly gravity anomalies in spherical harmonic coefficients, which were used to calculate equivalent water height (EWH) changes representing groundwater storage variations. The parameters used in ICGEM included:

- Grid format: longitude, latitude, value
- Grid step: 0.1°
- Number of grid points: 20,301
- Water density: 1000.0 kg/m³
- Gap value: 9,999 (for missing data)

1.5 Google Earth Engine Analysis

Google Earth Engine was used to process and analyze large geospatial datasets for groundwater assessment in Lahore. The platform enabled:

1. Access to the Earth Engine Code Editor.
2. Definition of the study area using geographic coordinates (31.5204°N, 74.3587°E).
3. Filtering of satellite data for the period 2000–2019.
4. Analysis of equivalent water thickness changes.
5. Generation of time-series plots and maps.
6. Visualization of changes in water storage.

The coding approach in Google Earth Engine used JavaScript to process satellite imagery, filter data by date range and region, and generate outputs showing changes in water storage over time.

1.6 Mann-Kendall Trend Analysis

The Mann-Kendall trend test, a non-parametric statistical method, was used to identify monotonic trends in groundwater level data. The test was applied to water table depth and annual water level changes for the period 2000–2019.

1.7 Data Integration and Comparison

Groundwater estimates derived from GRACE were compared with ArcGIS-interpolated maps to confirm the results and provide a more thorough understanding of groundwater behavior. GRACE data, primarily used for scientific investigations at global and regional levels, were combined with ArcGIS mapping tools to produce detailed visual representations of groundwater depletion trends in Lahore District.

2 Results

2.1 Mann-Kendall Trend Analysis Results

The Mann-Kendall trend test was applied to water table depth data collected from 220 wells in Lahore District between 2000 and 2019. The analysis showed a statistically significant upward trend in water table depth ($Z = 4.7693$, $p < 0.001$), meaning that groundwater levels are falling (i.e., the water table depth is increasing). A τ value of 0.7789 indicates a strong positive relationship between time and water table depth. The S-value of 148 further supports this upward trend, with the alternative hypothesis suggesting that S is not equal to zero.

2.2 Annual Water Table Depth Trend

The annual water table depth in Lahore District showed a consistent increasing trend from 2000 to 2019, as presented in Table 1 and Fig. 2.

Table 1
Annual water table depth and water level change in Lahore
District (2000–2019)

Year	Water Table Depth (m)	Change in Water Level (m)
2000	24.28424	0.41495
2001	23.86928	-0.87086
2002	24.74015	-0.96931
2003	25.70946	-1.94707
2004	27.65654	-0.35437
2005	28.01092	-1.00844
2006	29.01936	-1.03009
2007	30.04945	0.66863
2008	29.38081	0.20764
2009	29.17382	0.02740
2010	29.14640	1.77909
2011	27.36731	-0.28027
2012	27.64759	0.28027
2013	35.71850	-1.21312
2014	36.93162	-0.86970
2015	37.80133	-1.04491
2016	39.84625	-0.93900
2017	39.78525	-1.42813
2018	41.21338	-0.61975
2019	41.83313	0.61975

Between 2000 and 2019, the water table depth rose from 24.28 m to 41.83 m, marking an overall drop of 17.55 m across the two decades. The shallowest water table depth (24.28 m) occurred in 2000, while the deepest (41.83 m) was recorded in 2019. This upward trend in water table depth reflects groundwater depletion at a rate of roughly 0.92 m per year.

2.3 Spatial Distribution of Groundwater Depletion

Spatial interpolation using the IDW method in ArcGIS revealed the spatial distribution of groundwater depletion across Lahore District. Interpolated maps for selected years (2000, 2008, 2010, 2012, 2014,

2016, 2018, and 2019) showed differing patterns of groundwater decline.

In 2000, water table depth ranged around 24.28 m, with the minimum depth observed in the central and eastern parts of the district; the spatial pattern showed relatively uniform groundwater levels across the district. ICGEM data for 2000 showed a weighted mean value of 884.39 m, with a minimum of -3,202 m and a maximum of 284.1 m for the study area.

By 2008, water table depth had increased to 29.38 m, with groundwater depletion becoming more pronounced in central urban areas and greater variability in densely populated areas. ICGEM data for 2008 showed a weighted mean value of -903.1 m, with a minimum of -3,223 m and a maximum of 438.9 m.

In 2010, water table depth averaged 29.15 m, with a substantial annual change of 1.78 m; depletion continued in urbanized areas, particularly in the central and southern regions. ICGEM data for 2010 showed a weighted mean value of 935.4 m, with a minimum of -2,760 m and a maximum of 163.8 m.

Water table depth in 2012 was 27.65 m, with an annual change of 0.28 m; the spatial pattern indicated some recovery in certain areas, possibly due to recharge from monsoon rainfall. ICGEM data for 2012 showed a weighted mean value of 896.1 m, with a minimum of -3,224 m and a maximum of 187 m.

By 2014, water table depth had increased substantially to 36.93 m, with an annual change of -0.87 m, and severe depletion across most of the district, including urbanized and agricultural areas. In 2016, water table depth reached 39.85 m (annual change - 0.94 m), with depths exceeding 40 m in central urban areas. Water table depth in 2018 was 41.21 m (annual change - 0.62 m), with the most severe declines in the central and southern parts of the district. ICGEM data for 2016 showed a weighted mean value of 914.8 m (min - 3,091 m, max 451.5 m); for 2018 the weighted mean value was 1,069 m (min - 3,310 m, max 691.4 m).

In 2019, water table depth reached 41.83 m, with an annual change of 0.62 m, and continued depletion with the deepest water table depths exceeding 42 m in central urban areas. ICGEM data for 2019 showed a weighted mean value of 919.5 m, with a minimum of -3,124 m and a maximum of 259.1 m.

Figure 3 Spatial distribution of water table depth (m) in Lahore District for selected years (2000, 2008, 2010, 2012, 2014, 2016, 2018, and 2019) derived from ICGEM satellite data. The darker the color, the deeper the water table and the higher the groundwater depletion; the highest levels are found in the central and southern urban areas.

2.4 Annual Water Level Changes

Annual water level changes in Lahore District showed substantial variability over the study period, with both positive (recovery) and negative (decline) trends. The most substantial declines occurred in 2003 (-1.95 m), 2017 (-1.43 m), 2013 (-1.21 m), 2006 (-1.03 m), and 2005 (-1.01 m). Positive changes (recovery) were observed in 2010 (1.78 m), 2007 (0.67 m), 2019 (0.62 m), and 2000 (0.41 m). The

average rate of water level change over the 20-year period was -0.43 m/year, indicating an overall declining trend.

2.5 Satellite-Based Analysis Using Google Earth Engine

Google Earth Engine analysis of satellite data revealed changes in water storage from 2000 to 2019. The satellite-based analysis using NASA GRACE mass grids showed a minimum change in water level of -0.2802 m and a maximum rate of change of 1.77909 m. The GRACE data indicated groundwater fluctuations consistent with the well data analysis, with significant depletion occurring over the study period.

Figure 4: NASA-GRACE satellite observations of Lahore District (2000–2019): (a) map view of water storage anomalies in space; (b) water storage changes (equivalent water thickness) in time over the study period showing the overall trend of decreasing groundwater storage.

The NASA-GRACE satellite view and corresponding map view provided visual confirmation of groundwater depletion patterns in Lahore, with the satellite data capturing large-scale variations in water storage.

3 Discussion

The findings of this study reveal significant groundwater depletion in Lahore District from 2000 to 2019, with water table depth rising from 24.28 m to 41.83 m. The Mann-Kendall trend analysis confirmed a statistically significant positive trend ($Z = 4.7693$, $p < 0.001$, $\tau = 0.7789$), indicating a consistent decline in groundwater throughout the study period.

These results are consistent with earlier research on groundwater depletion in Lahore. Basharat et al. (2016) noted that the water table, about 5 m deep in 1960, had fallen to over 40 m in the city center due to excessive groundwater extraction. This study confirms that trend, with water table depths exceeding 41 m in 2019. The observed depletion rate of approximately 0.92 m/year falls within the range of 0.45 – 1.50 m/year reported by Basharat et al. (2016).

The spatial pattern of groundwater depletion shows that the most severe declines occurred in the central and southern parts of Lahore District, corresponding to areas with the highest population density and urbanization. This pattern matches studies by Hassan et al. (2021), who found that groundwater depletion in urban areas such as Lahore, Rawalpindi, and Faisalabad is mainly driven by urbanization limiting recharge and excessive extraction disrupting the balance between replenishment and pumping.

Annual water level changes exhibited substantial variability, with the largest declines occurring in 2003 (-1.95 m), 2017 (-1.43 m), and 2013 (-1.21 m). These periods of accelerated decline may be associated with years of lower rainfall or increased groundwater extraction, while positive changes in 2010 (1.78 m), 2007 (0.67 m), and 2019 (0.62 m) could reflect years with above-average monsoon rainfall or reduced extraction due to policy measures.

The comparison between GRACE satellite data and ArcGIS-interpolated maps showed consistent patterns of groundwater depletion. GRACE data captured large-scale variations in water storage, with weighted mean values ranging from – 903.1 m to 1,069 m over the study period. Although GRACE data has lower spatial resolution than ground-based measurements, it offers valuable insights into regional groundwater dynamics, consistent with findings by Akhter et al. (2021) and Iqbal et al. (2016).

Integrating satellite data with ground-based observations in this study provides a comprehensive approach to assessing groundwater depletion. Remote sensing offers advantages over traditional monitoring, such as wide geographic coverage and repeated observations, enabling the identification of trends and seasonal fluctuations (Akhter et al., 2021). However, limitations such as lower spatial resolution and data latency remain challenges for operational groundwater management at local scales (Shang et al., 2021).

The causes of groundwater depletion in Lahore are complex. The main driver appears to be excessive groundwater extraction for domestic, industrial, and agricultural uses, along with reduced recharge due to urbanization. Desiccation of the Ravi River and land-use changes from urbanization have contributed to the decline in groundwater recharge (Basharat et al., 2016), and uncontrolled extraction without corresponding recharge efforts has driven the water table decline (Basharat et al., 2016). The findings suggest that climate variability plays a secondary role, as the decreasing trend in monsoon rainfall does not significantly affect groundwater levels – indicating that urbanization and extraction have a more dominant influence.

The impacts of groundwater depletion in Lahore are substantial, including reduced water availability, higher pumping costs, potential land subsidence, and water quality degradation. As reported by Basharat et al. (2016), shallow groundwater quality has deteriorated over time, posing a potential pollution risk to the deeper aquifer below. Groundwater depletion also threatens agricultural productivity and food security in the region, as groundwater supplies over 60% of irrigation water in Pakistan (Akhter et al., 2021).

3.1 Trends of Groundwater Depletion in Lahore (2000–2019)

The results of this study indicate an alarming trend of groundwater depletion over the 20-year period (2000–2019) in Lahore District. The water table depth rose from 24.28 m in 2000 to 41.83 m in 2019, an increase of 17.55 m in total, corresponding to an annual mean depletion rate of about 0.88 m/yr – in line with other studies showing depletion rates of 0.45 to 1.50 m/yr for the region (Basharat et al., 2016). The Mann-Kendall trend analysis also found that groundwater levels are steadily decreasing, with a statistically significant increase in the rate of decline ($Z = 4.7693$, $p < 0.001$, $\tau = 0.7789$).

The temporal analysis reveals distinct groundwater depletion phases. Trends between 2000 and 2007 were relatively steady, decreasing from 24.28 to 30.05 m with some year-to-year variation. However, a

stronger downward trend appears after 2010, with water table depths rising sharply from 27.37 m in 2011 to 41.83 m in 2019. This increase coincides with the period of Lahore's fastest urbanization, implying a strong anthropogenic influence on groundwater resources.

3.2 Groundwater Depletion in the Basin

The IDW spatial interpolation applied in ArcGIS showed groundwater depletion to be heterogeneous across Lahore District. The highest depletion was found in dense urban areas, namely the urban center and industrial zones. By 2019, water table depths in areas such as Township, Johar Town, and Gulberg exceeded 40 m, compared to relatively lesser depletion in peri-urban areas.

This spatial heterogeneity can be attributed to several factors. The intensity of groundwater abstraction for domestic, commercial, and industrial use is higher in urban areas with high population density and commercial activity. Impervious surface cover also limits natural recharge opportunities in these areas, since rainwater cannot readily penetrate impervious surfaces (Kanwal et al., 2015). Certain areas are also home to industries such as textiles and food processing, which increase localized groundwater pumping.

The spatial distribution of depletion is also related to proximity to the Ravi River: depletion was generally less severe in the northern parts of Lahore, closer to the river, than in the southern parts. This suggests that, although its flow is diminished, the Ravi River continues to recharge local aquifers to some extent. Over time, however, the river's recharge potential has been considerably reduced due to its desiccation, as noted by Basharat et al. (2016).

This research is distinctive in comparing observed well data (220 wells from WASA) with satellite estimates from GRACE (via ICGEM) and Google Earth Engine. Combining these datasets provided a more complete description of groundwater conditions. The GRACE-derived data from ICGEM presented similar trends, with weighted mean values ranging from 884.39 m in 2000 to 1,069 m in 2018. The trends were consistent, although absolute values differed, since two different measurement principles were involved — gravity anomalies and water table depth. Groundwater storage in both datasets showed a decrease, particularly since 2010.

The spatial pattern of the GRACE data was smoother than the higher-resolution ground-based IDW maps, a normal consequence of GRACE's coarser spatial resolution (on the order of 100,000 km²). GRACE data are therefore better suited to basin-scale evaluations, while well data interpolated with IDW is better suited to generating local-scale detail; the complementary nature of these datasets suggests that the most robust assessment of groundwater dynamics is achieved through an integrated approach combining both.

The Google Earth Engine analysis provided additional insight into the correlation between changes in groundwater levels and vegetation indices (NDVI and EVI). Water level declines coincided with variation in vegetation distribution, especially in agricultural areas where water is pumped for irrigation,

corroborating the work of Thomas and Famiglietti (2019), which linked groundwater depletion to surface effects caused by climate change.

3.3 Factors Contributing to Groundwater Depletion

The depletion of groundwater in Lahore results from a number of interrelated factors:

3.3.1 Urbanization and Population Growth

The population of Lahore has grown substantially over the past 12–15 years, with current estimates exceeding 8.83 million (Basharat et al., 2016). This population growth has generated unprecedented demand for water resources. Urbanization has also reduced permeable surfaces, diminishing natural groundwater recharge; this land-use change has had a major impact on the hydrological balance between 2000 and 2019.

3.3.2 Excessive Groundwater Extraction

Lahore relies mainly on groundwater for its water supply, with estimated consumption from public tube wells of about 160 million liters/day (Kanwal et al., 2015). The number of private tube wells has also grown significantly, with more than a million now operating across Punjab province (Shang et al., 2021). This imbalance between recharge and pumping has produced a groundwater deficit of about 15% annually (Basharat et al., 2016); the estimated annual loss of groundwater is 1,161 million cubic meters (MCM), against annual recharge of 1,013 MCM.

3.3.3 Reduced Surface Water Availability

Desiccation of the Ravi River is a major contributor to groundwater depletion. Historical flows have been drastically reduced due to upstream water diversion in India and decreased precipitation. Historically, the Ravi River significantly recharged Lahore's aquifer system, but it now contributes little to groundwater replenishment (Basharat et al., 2016); upstream dams and diversions have further altered natural streamflow.

3.3.4 Agricultural Water Demand

While Lahore itself is mainly urban, other parts of the district support intensive agriculture. The Punjab region is considered the agricultural hub of Pakistan, where more than 60% of irrigation water is sourced from groundwater (Akhter et al., 2021). Groundwater use for water-intensive crops such as rice and sugarcane is a major factor in depletion, and this pressure has been exacerbated by the expansion and intensification of agricultural land use.

3.3.5 Climate Variability

The Mann-Kendall analysis identified both positive and negative trends for precipitation and temperature across different months, but the groundwater depletion trend did not show a direct relationship with climatic variables. This suggests that anthropogenic activity, rather than climate variability, is the main

driver of groundwater scarcity in Lahore. Significant variation was also observed during the monsoon season, with some months showing a decreasing trend in rainfall important for recharge. Groundwater levels did fall during some months of higher precipitation, but this does not indicate effective recharge, since surface conditions such as impervious cover limit infiltration.

3.4 Seasonal and Interannual Variability

Year-to-year water-level changes were larger than the overall trend across the study period, with major shifts observed in 2003 (-1.947 m), 2010 (+ 1.779 m), and 2017 (-1.428 m). This variability arises from several factors.

By the post-monsoon period (September–November), groundwater levels tend to recover, while pre-monsoon (April–June) levels are typically most depleted; the overall trend nonetheless remains negative, indicating that recharge is insufficient at either the seasonal or annual scale to meet extraction demands. The 2010 floods were a severe event that temporarily reduced aquifer depletion (Akhtar et al., 2021), underscoring the significance of extreme precipitation events for recharge, though their reliability under a changing climate remains uncertain. Year-to-year fluctuations in water management policy — particularly canal and irrigation operations — also affect groundwater use patterns and water table behavior.

3.5 Water Quality Implications

This study focuses primarily on groundwater quantity, but declining groundwater levels can also affect groundwater quality. As water levels drop, a number of water quality issues can arise.

Extraction of deeper groundwater is associated with a higher mineral content, including salts (Basharat et al., 2016); groundwater has become unsuitable for drinking and farming in parts of the Chaj Doab and some areas of Lahore due to high salinity. Lower groundwater levels also reduce the dilution capacity of the aquifer, which may increase the concentration of contaminants such as arsenic (Shahid et al., 2018) — a pattern documented in many Asian countries that could plausibly emerge in Lahore as water tables continue to fall. Although Lahore is not coastal, a related process of deeper saline water rising as fresh groundwater is pumped can similarly affect water quality.

3.6 Implications for Water Resource Management

Several conclusions from this study carry significant implications for water resource management in Lahore.

Current extraction levels are unsustainable, exceeding recharge by around 15%; sustainable extraction rates set according to aquifer recharge capacity are fundamental to the long-term security of water supplies. Experimental research on Managed Aquifer Recharge (MAR) has demonstrated reductions in depletion rates: Ashiq et al. (2020) showed that winter-season depletion from recharge wells decreased from 1.05 m to 0.72 m using large-diameter recharge wells, suggesting that expanding MAR efforts could meaningfully improve groundwater sustainability. Increasing alternative water sources — such as

treated wastewater reuse, rainwater harvesting, and better management of surface water – could also reduce dependence on groundwater. Finally, the lack of effective regulation of groundwater extraction has allowed unchecked withdrawal, underscoring the need to implement and enforce regulations governing tube well installation and extraction rates.

3.7 Methodological Considerations and Limitations

This study used a variety of methods to determine the extent of groundwater depletion, and several points merit consideration.

Data quality and availability: well data with good coverage were available for this study (2000–2019), although the density of the monitoring network and the uniformity of measurement methods could affect the analysis. The wells sampled represent a subset of the total number of wells in Lahore, and additional sampling would improve spatial resolution.

Limits and uncertainties of GRACE data: GRACE offers valuable large-scale data, but its coarse spatial resolution (about 100,000 km²) may not capture local variation in sufficient detail, and uncertainties remain in signal restoration and processing methods (Long et al., 2016). The comparison between GRACE and well data indicated overall good agreement, with differences attributable to the different measurement principles involved.

Limitations of the interpolation model: IDW is widely used and assumes spatial autocorrelation based on distance; results from more sophisticated interpolation methods (e.g., kriging) or process-based models could differ, though IDW remains suitable for the scale and characteristics of this dataset.

The 20-year study period is useful for examining recent trends but may not fully represent longer-term patterns; incorporating paleo-hydrological data or a longer groundwater record would strengthen future analyses.

3.8 Comparison with Regional and Global Patterns

Groundwater depletion in Lahore is consistent with patterns documented elsewhere in the region and the world. In north-west India, particularly in Punjab, Haryana, and Rajasthan, groundwater depletion has been extensive (Rodell et al., 2009), with depletion rates of around 1.4 m per year comparable to those observed in Lahore. In the North China Plain, groundwater is heavily depleted, with equivalent water thickness (EWT) losses exceeding 2.2 cm per year (Feng et al., 2013), showing similarities to Lahore in both driving factors and consequences. In California's Central Valley, the aquifer is highly depleted, particularly in the southern Tulare River basin (Famiglietti et al., 2019), and policy responses such as California's Sustainable Groundwater Management Act (SGMA) offer potential lessons for Lahore. This global perspective highlights groundwater depletion as a problem that transcends borders and requires attention to research, policy, and management at an international level.

3.9 Future Research Needs

Based on the results of this study, several research directions are proposed: integrated hydrological modeling using process-based models that incorporate climate, land use, and groundwater dynamics to better understand depletion mechanisms and support scenario testing; socio-economic analysis of the economic drivers of groundwater extraction and the impacts of depletion on livelihoods, to inform evidence-based policy; further investigation of the impacts of groundwater quantity loss on water quality; groundwater modelling to assess the impact of climate variability and change on future groundwater availability; and further research into the feasibility and effectiveness of Managed Aquifer Recharge techniques suited to the geology of Lahore.

3.10 Policy Implications

The findings of this study support several policy recommendations: improving monitoring networks by increasing the density and frequency of groundwater monitoring, including real-time systems; enforcing extraction regulations, particularly for industrial and commercial users; supporting water-efficient technologies and practices across sectors to reduce pressure on groundwater resources; investing in recharge infrastructure, such as recharge wells and basins, to help offset the recharge deficit; integrating land-use and water planning so that groundwater considerations inform urban development; building institutional capacity for sustainable water management; and promoting public awareness and education campaigns to encourage responsible water use.

3.11 Summary of Discussion

This study provides clear evidence of severe groundwater depletion in Lahore District over 2000–2019, with the water table falling by about 17.55 m at an average rate of 0.88 m per year. The Mann-Kendall test confirmed a statistically significant increase in water table depth ($Z = 4.7693$, $p < 0.001$). Spatial analysis showed a heterogeneous depletion pattern, with the highest depletion in urban centers.

These results underscore the value of combining multiple data sources — 220 well observations, GRACE satellite data via ICGEM, and Google Earth Engine analysis — to produce a more complete and robust assessment of groundwater change. Over-extraction of groundwater, agricultural water demand, reduced surface water availability (particularly from desiccation of the Ravi River), population growth, and urbanization emerge as the principal drivers of depletion, with climate variability playing a comparatively minor role.

Groundwater depletion carries wide-ranging implications, including water scarcity, land subsidence, water quality deterioration, and socioeconomic impacts. Addressing these challenges will require a holistic approach spanning regulatory reform, investment in recharge infrastructure, water efficiency measures, and institutional capacity building. The findings of this study add to the growing body of evidence on groundwater depletion in South Asia and provide a foundation for evidence-based groundwater management in Lahore. The methodological framework — combining spatial analysis, statistical trend detection, and satellite data analysis — offers a model for further studies in other urbanizing regions dependent on groundwater.

These findings carry important implications for water resource management in Lahore, underscoring the urgent need for sustainable groundwater strategies, including regulation of abstraction, water conservation measures, and artificial recharge projects. As suggested by Ashiq et al. (2020), managed aquifer recharge (MAR) can help reverse the downward trend in groundwater levels, with experimental recharge wells showing potential to reduce depletion rates.

4 Conclusion

This research examined groundwater depletion in Lahore District by combining satellite data with ground-based information collected from 220 wells between 2000 and 2019. The Mann-Kendall trend test showed a statistically significant positive trend ($Z = 4.7693$, $p < 0.001$, $\tau = 0.7789$), pointing to a steady decline in groundwater over the study period. Water table depth rose from 24.28 m in 2000 to 41.83 m in 2019, a total drop of 17.55 m, averaging roughly 0.92 m per year.

The spatial pattern of groundwater depletion revealed that the most pronounced declines occurred in the central and southern sections of Lahore District, matching the areas of highest population density and urban growth. Annual water level changes varied considerably, with the largest declines recorded in 2003 (-1.95 m), 2017 (-1.43 m), and 2013 (-1.21 m).

GRACE satellite data captured large-scale groundwater fluctuations that aligned with ground-based measurements, showing weighted mean values from - 903.1 m to 1,069 m during the study period. Google Earth Engine analysis of satellite data verified water storage changes from 2000 to 2019, with a minimum water level change of -0.2802 m and a maximum rate of change of 1.77909 m.

Combining satellite data with ground-based observations offers a thorough approach to assessing groundwater depletion, providing benefits over traditional methods, such as broad geographic coverage and repeated measurements. The main causes of groundwater depletion in Lahore are excessive extraction for domestic, industrial, and agricultural uses, along with diminished recharge resulting from urbanization.

The results highlight the urgent need for sustainable groundwater management in Lahore, including regulating abstraction, promoting water conservation, implementing artificial recharge projects, and enacting policies that balance extraction with natural recharge rates. Future work should focus on assessing the effectiveness of management actions, investigating climate change impacts on groundwater resources, and developing integrated water resource management plans for the Lahore area.

Declarations

Author Contribution

Data Availability

i generate data through icgem and grace satellite

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Figures

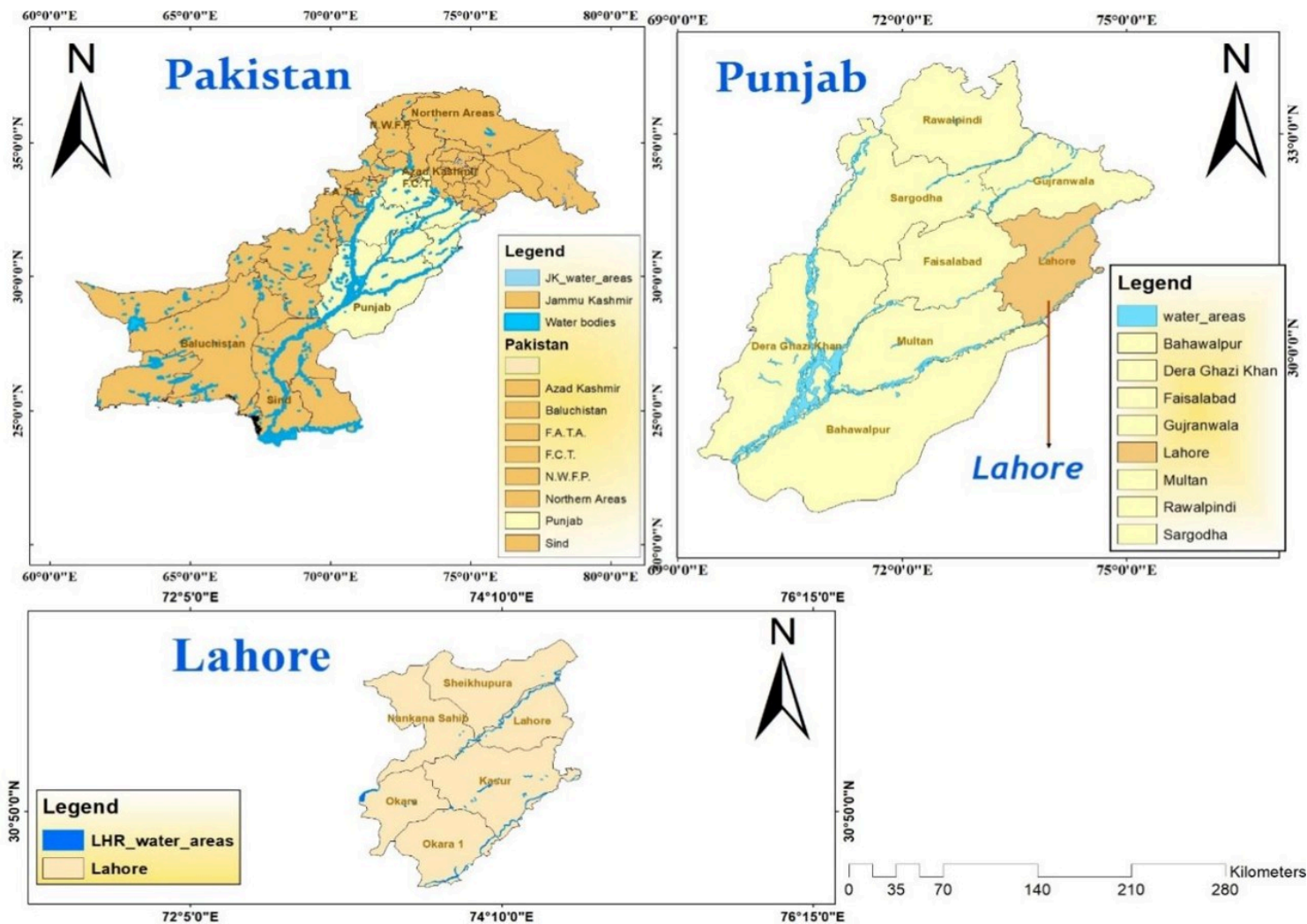


Figure 1

Location Map of Lahore District, Pakistan showing the boundaries of study area, major rivers (Ravi River) and administration of the district. The inset map depicts the location of Lahore in the province of Punjab and the country of Pakistan.

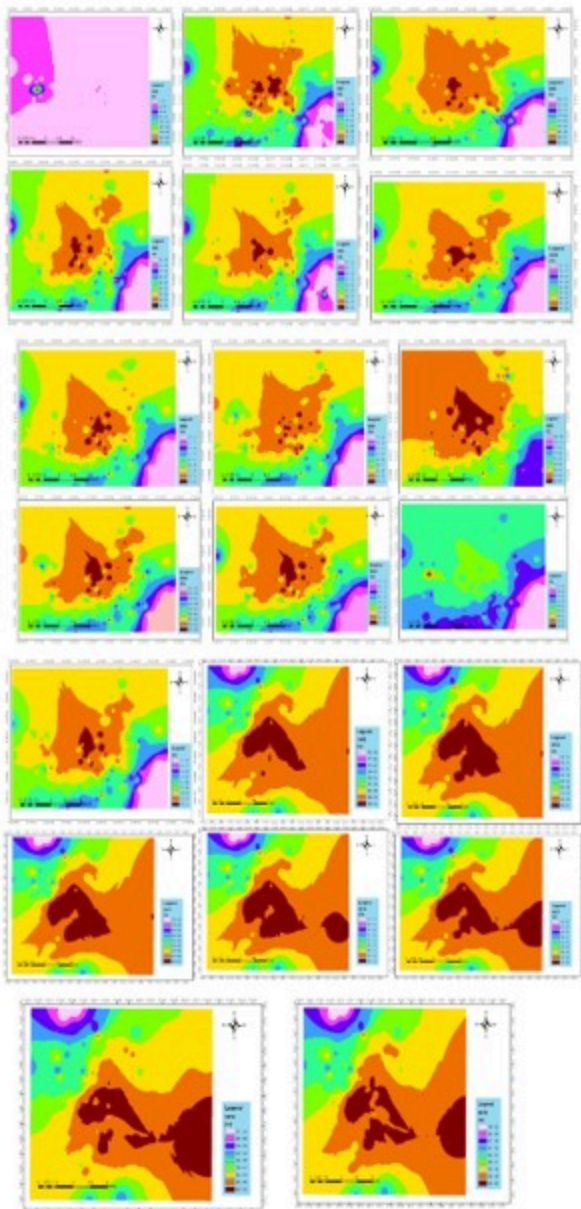


Figure 2

Annual water table depth (m) and annual water level change (m) in Lahore District (2000–2019)

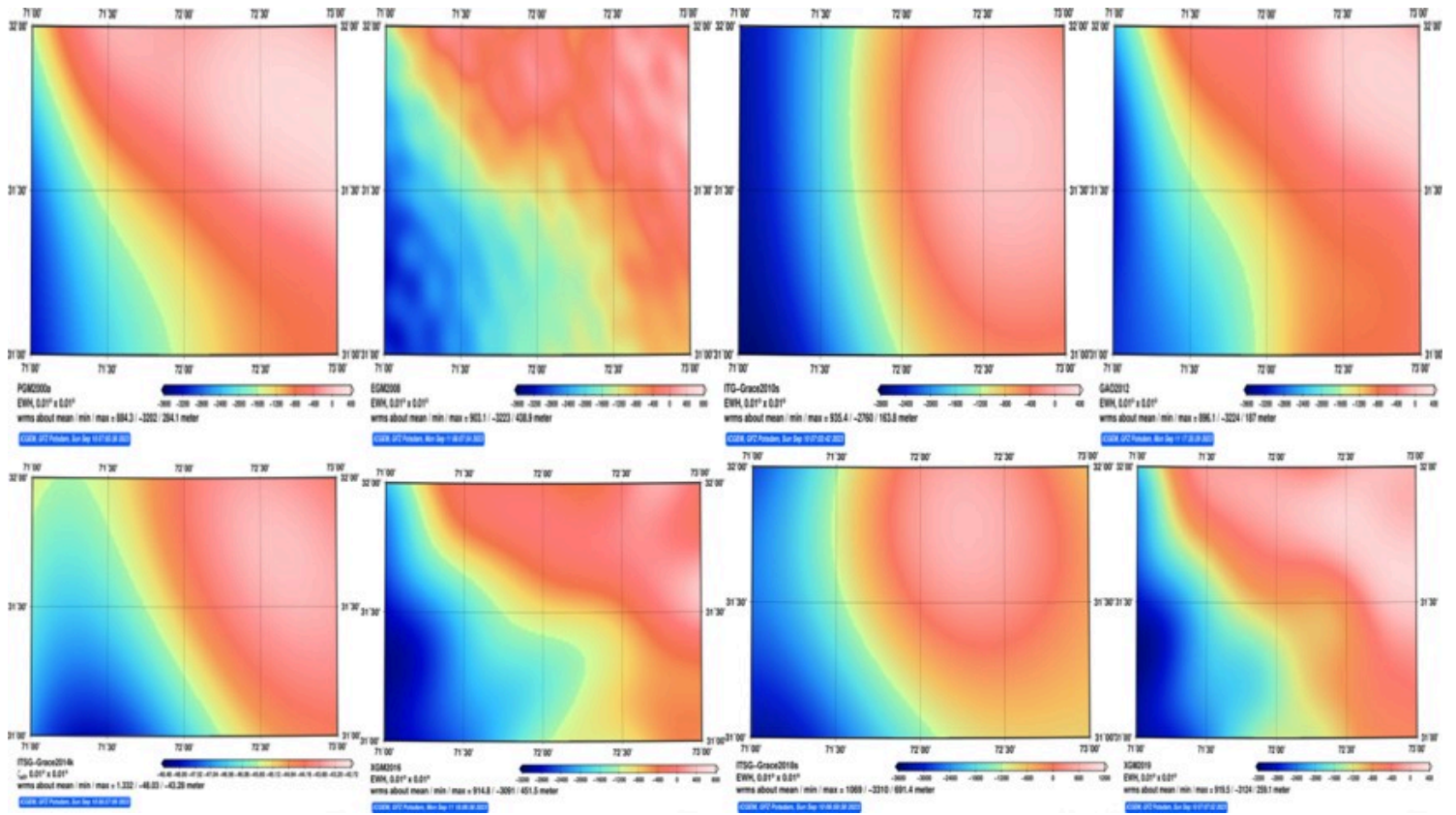


Figure 3

Water table depth in Lahore District (2000, 2008, 2010, 2012, 2014, 2016, 2018, 2019) using ICGEM data

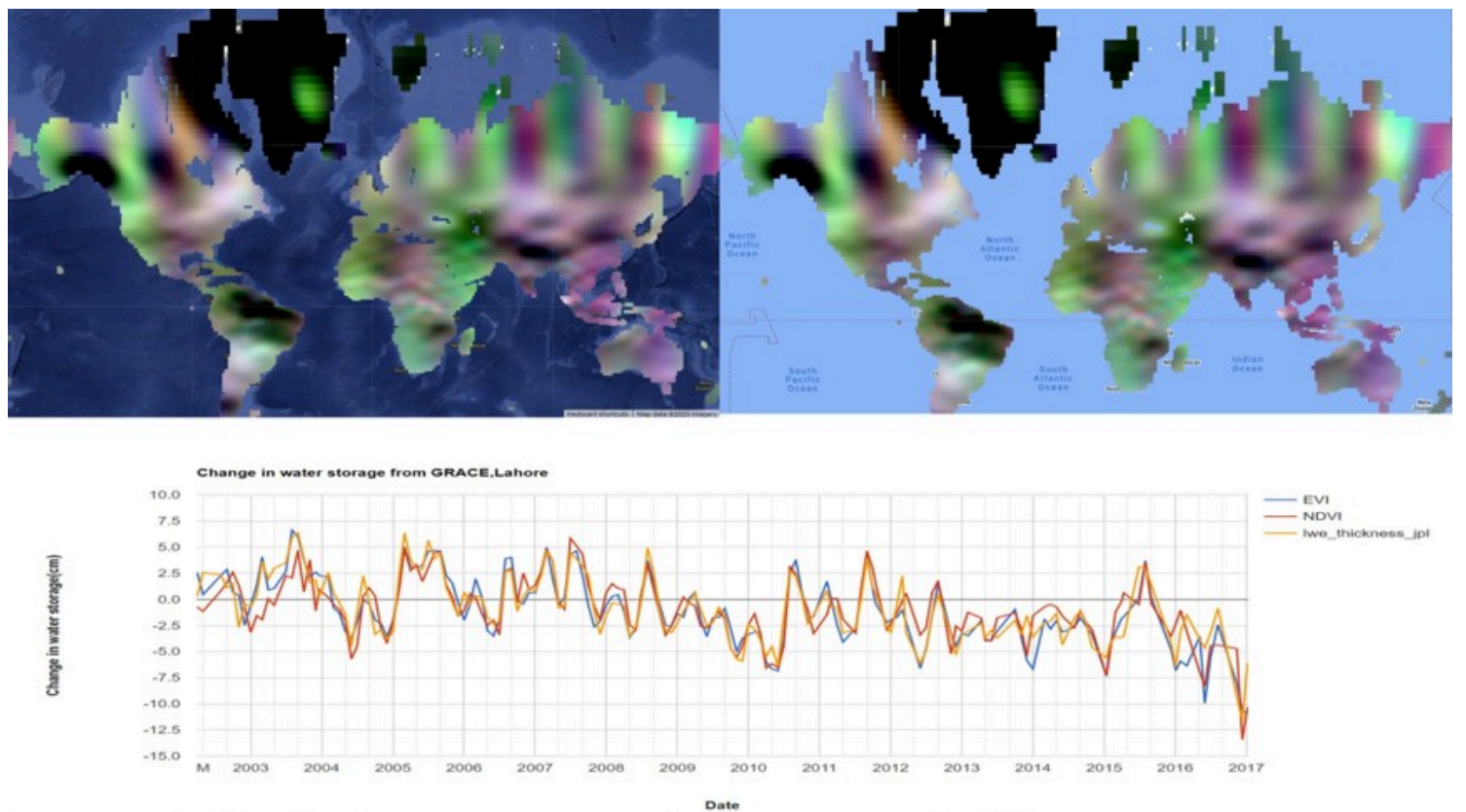


Figure 4

NASA-GRACE satellite view of Lahore (2000–2019): map view of Lahore showing water storage, and variation in water storage as measured by GRACE

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