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GROUNDWATER DEPLETION IN QUETTA: SATELLITE BASED CLIMATE IMPACT ANALYSIS

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Abstract
Groundwater resources are increasingly vulnerable in arid and semi-arid areas due to rising water demands, climate uncertainty, and unsustainable exploitation. In this study, long-term groundwater depletion in Quetta Valley, Balochistan, Pakistan, is assessed using satellite-derived data extracted from the GRACE and GLDAS missions from 2002 to 2023. The findings identify a constant and extreme decline in terrestrial water storage and groundwater levels, showing seasonal patterns governed by winter precipitation and summer evapotranspiration. Groundwater anomalies obtained from the analysis identify the lack of recovery trends, which highlights the pervasive nature of aquifer stress in the area. The findings are supported by field observations and highlight the urgency of overextraction, which is further intensified by restricted natural recharge and uncontrolled well development activity. The study illustrates the applicability of remote sensing techniques in monitoring groundwater in data-poor regions and calls for an immediate policy response to guarantee sustainable groundwater management in Quetta and similar dryland urban settings.

INTRODUCTION

The global groundwater forms about 30% of global freshwater, provides drinking water to more than 2 billion people, and is used to promote world agricultural production [1]. It is accumulated in aquifers or underground water-bearing rocks and is very crucial in arid and semi-arid areas where surface water is very limited. Nonetheless, unsustainable methods of extraction have caused massive depletion of the aquifers hence the lowering of the water table leading to the sinking of the land and low water quality issues are being experienced [2]. 70% of global groundwater abstractions are applied in agriculture, and there is a high depletion of groundwater in rainless areas that have large agricultural spreads, adding to the degradation of environmental issues like the rise of the sea level because of overextraction of groundwater resources[3, 4]. There is urgency in the need to manage groundwater on a sustainable basis given the rate at which groundwater is being depleted, which poses threats to ecosystems and human livelihoods all across the earth.

South Asia is the region with the highest population density in the world, with India, Pakistan, and Bangladesh being some of the countries included in this region, all on a territory that comprises 4% of the world's landmass but carries over 25 percent of the world's population [5]. One of the pillars of the agricultural productivity of the region is the natural occurrence of groundwater and the Green Revolution has caused an immense dependence upon this groundwater to be used as a source of irrigation over the geographical region of this country [6]. In the northwest of India and central Pakistan, farming relies heavily on groundwater to irrigate the expansive farmlands, and the over-utilization of the available groundwater has resulted in the serious depletion of aquifers in the main agricultural areas and regions of India and Pakistan [7]. The challenges affecting the region include land subsidence, seawater intrusion in coastal areas, and a worsening water quality caused by anthropogenic activities, and managing them integrally seems quite necessary to accommodate the increase and demand of water and supply of water in the region [8].

Pakistan ranks 3rd in groundwater use in irrigation, and the Indus Basin Irrigation System (IBIS) is the largest artificial groundwater recharge scheme in the world [9]. Approximately 73% of irrigated areas in Pakistan rely on groundwater, with Punjab alone accounting for 85% of the country's 1.2 million private tubewells [10]. However, because of population expansion and climate change, per capita water availability has drastically decreased from 5,000 m^3 in 1951 to 1,100 m^3 in 2005 and is expected to drop to 800 m^3 by 2025. Such practices as over-abstraction, waterlogging, and contamination undermine the sustainability of groundwater, and 83 percent of the accessible groundwater has been utilized in agricultural and other activities, which is an exceptionally high percentage ratio in a water-stressed nation [11]. These difficulties highlight the importance of a strong groundwater management to make water secure in the long term.

Balochistan, Pakistan's largest province, has an arid to semi-arid climate with an average annual rainfall of less than 250 mm; hence, groundwater is the primary source of water for 90% of the province's needs [12]. Groundwater exploitation has increased due to a lack of surface water and the degradation of traditional karez systems caused by the development of tubewells in the region [13]. Such severe overexploitation has resulted in massive water table losses, with some places being exploited at such a rapid speed that it jeopardizes agricultural and household water security [14]. Furthermore, excessive amounts of contaminants that endanger people's lives, such as arsenic and fluoride, degrade groundwater quality [12]. All these are compounded with the absence of regulatory grids and the social institutional vacuum in the management of ground water and the need to address it as soon as possible appears [15].

Quetta, the center of Balochistan, depends on the Quetta Valley aquifer, which is pushed under the advancement of a gross population of 0.26 million in 1975 to around 1.6 million by 2024 [16]. The current water demand in the city is estimated to be 61 million gallons per day and the supply capacity of the Water and Sanitation Agency (WASA) is only 34.8 million gallons per day [17]. Overexploitation of the groundwater resources through exorbitant illegal tubewells and weak recharge rates induced by lower natural precipitation rate (150-200 mm annually) and climate fluctuation is causing the ground water level to drop at a harrowing rate of 1.5-5 meters per year [18]. Despite this depletion, land subsidence has occurred due to vertical movement of up to 120 mm a year in parts of central Quetta, which threatens infrastructure and water security [16].

A number of earlier research papers have estimated groundwater depletion in Quetta. Modeling based on MODFLOW has estimated depletion rates per annum and strained imbalance between abstraction and recharge [19]. Geospatial mapping has estimated aquifer vulnerability areas, and hydrochemical analysis has tracked overexploitation and saltwater intrusion contamination [18]. These analyses have been either ground observation-based or localized hydrogeological surveys without taking into account recent satellite-based hydrological modeling advancements. In addition, although GRACE and GLDAS data have been applied globally, their systematic use in estimating Quetta's groundwater trends is rare and not validated with long-term ground observations.

In spite of increasing alarm regarding overexploitation of groundwater in Quetta, earlier there has not been a comprehensive study involving satellite-derived terrestrial water storage data combined with GLDAS-based hydrological variables like soil moisture and surface water to identify and quantify long-term groundwater trends in the region. There is no statistical trend analysis of GRACE data for a few decades, especially with regard to urban water stress in semi-arid highland regions like Quetta. This offers a unique opportunity to adopt remote sensing-based groundwater accounting schemes for enhanced monitoring and policy-making. The objective of this study is to conduct a focused, high-resolution assessment of groundwater depletion in

Quetta using GRACE and GLDAS datasets. The specific aims are to:

1. Quantify long-term groundwater storage anomalies from 2002 to 2023 using GRACE data.
2. Extract and subtract soil moisture and surface water components from GLDAS to isolate groundwater changes.
3. Perform statistical trend analysis to determine the direction and magnitude of depletion.

2. Methodology:

The research approach used in this case is depicted in Figure 1.

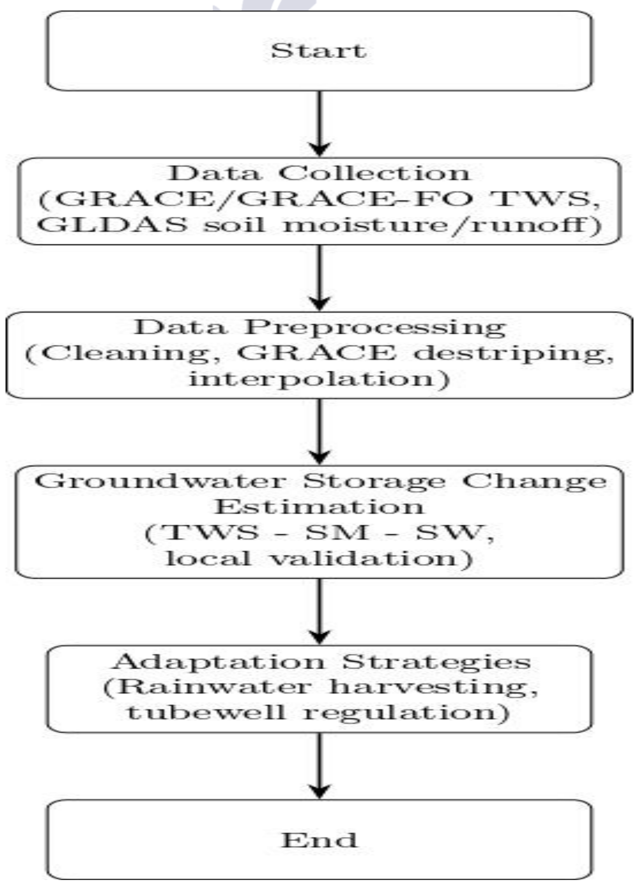

Figure 1|Methodology flowchart for groundwater depletion assessment in Quetta Valley using GRACE/GRACE-FO and GLDAS.

2.1 Study area:

Quetta District is surrounded by Pishīn District to the north; its western side is Afghanistan; it is bounded by Ziārat and Harnāi Districts to the east and Mastung and Nūshki Districts to the south. This study focuses on Quetta, Pakistan's Balochistan provincial capital, which is located in a semi-arid to arid climatic belt with an approximate population of 1.6 million as of 2024 [16]. The city is practically solely dependent on the Quetta Valley aquifer, which is under extreme pressure as a result of rapid demographic growth, intensive groundwater use through numerous tubewells, and limited natural replenishment due to minimal rainfall amounts. The study area is the broader Quetta region, where groundwater is the major water supply for household, agricultural, and commercial uses. Therefore, assessing the fluctuations in groundwater reserves is vital to ensuring sustainable water supply and efficient resource management [20].

2.2 Data collection:

This study uses two primary datasets derived from satellite data to investigate and distinguish differences in groundwater storage in the Quetta region.

The first dataset in question is Terrestrial Water Storage (TWS), which is obtained using the Gravity Recovery and Climate Experiment (GRACE) and its sequel, the GRACE Follow-On (GRACE-FO). The mission is a collaboration between NASA and the German Aerospace Center (DLR). These missions provide monthly averages of total water storage anomalies since the year 2002 by measuring changes in the gravitational field of Earth. The GRACE dataset has an effective spatial resolution of the order of 1° × 1° (which is approximately equivalent to about 150,000 km^2) and includes integrated water storage in all forms, including groundwater, soil moisture, surface water, and snow [21]. This dataset is of the highest importance in characterizing hydrological regional water balances and long-term hydrological trends.

The secondary data consist of Soil Moisture (SM) and Surface Water (SW) storage estimates from the Global Land Data Assimilation System (GLDAS). GLDAS combines satellite data and terrestrial meteorological data with land surface models to model hydrological parameters at a higher spatial resolution of 0.25° × 0.25° [22]. The data are important in the measurement and subtraction of the effect of the soil moisture and surface water from total water storage, thereby making it possible to assess groundwater storage anomalies at a more specific level.

2.3 Data processing:

All analysis and processing steps are carried out with the assistance of Google Earth Engine, a cloud platform that is specifically tailored for large-scale geospatial analysis [23]. Google Earth Engine enables the merging of GRACE and GLDAS data, thus enabling the effective computation of groundwater storage changes over the study period. The functionality of the platform enables synchronization of data to consistent spatial and temporal resolutions, which is pivotal in ensuring that analysis is scalable and accurate. This step is crucial towards processing large amounts of satellite data and performing sophisticated computations within a cloud environment, thus making the study more reproducible and feasible.

2.4 Groundwater assessment

In this project Google Earth Engine was used to estimate variations in groundwater storage. Terrestrial Water Storage variations (TWS) were estimated from GRACE, whereas changes in soil moisture and surface water storage were estimated from GLDAS [24]. Surface water and soil moisture were deducted from TWS to obtain variations in groundwater storage. The snow component is not included in this project since Quetta is an arid, dry area. The formula for TWS calculation is as follows:

$$\Delta TWS = \Delta GW + \Delta SM + \Delta SWE + \Delta SW$$

$$\Delta GW = \Delta TWS - \Delta SM - \Delta SWE - \Delta SW$$

ΔTWS = change in terrestrial water storage
ΔGW = change in groundwater storage
ΔSM = change in soil moisture
ΔSWE = change in snow water equivalent
ΔSW = change in surface water storage

3. Result:

3.1 Groundwater assessment

Traditionally, water wells were employed to gauge groundwater depth. Remote sensing lacks a direct groundwater measurement. GRACE and GRACE-FO satellite observations have been employed to make monthly, total surface, and groundwater depth estimates since 2002 with a ~150,000 km² resolution. GRACE and GRACE-FO are collaborative satellite missions of the German Aerospace Center (DLR) and the National Aeronautics and Space Administration (NASA). They provide data to infer large-scale global groundwater distribution with some other hydrological data.

The TWS data was collected from GRACE, and soil moisture and surface water data were collected from GLDAS. Groundwater data was collected by subtracting surface water and soil moisture from TWS. The entire computation was done in Google Earth Engine.

Figure *2* represents variation in TWS, soil moisture, surface water, and groundwater storage. Positive values represent an increase in storage in the above parameters. Negative values represent depletion. Irregular changes were observed in TWS, soil moisture, and groundwater. A heavy decrease is observed in the above parameters in the first five and last seven years. Additionally, the contribution of surface water is negligible because Quetta is a sparsely vegetated region. The snow component is not considered because Quetta is a dry, arid region.

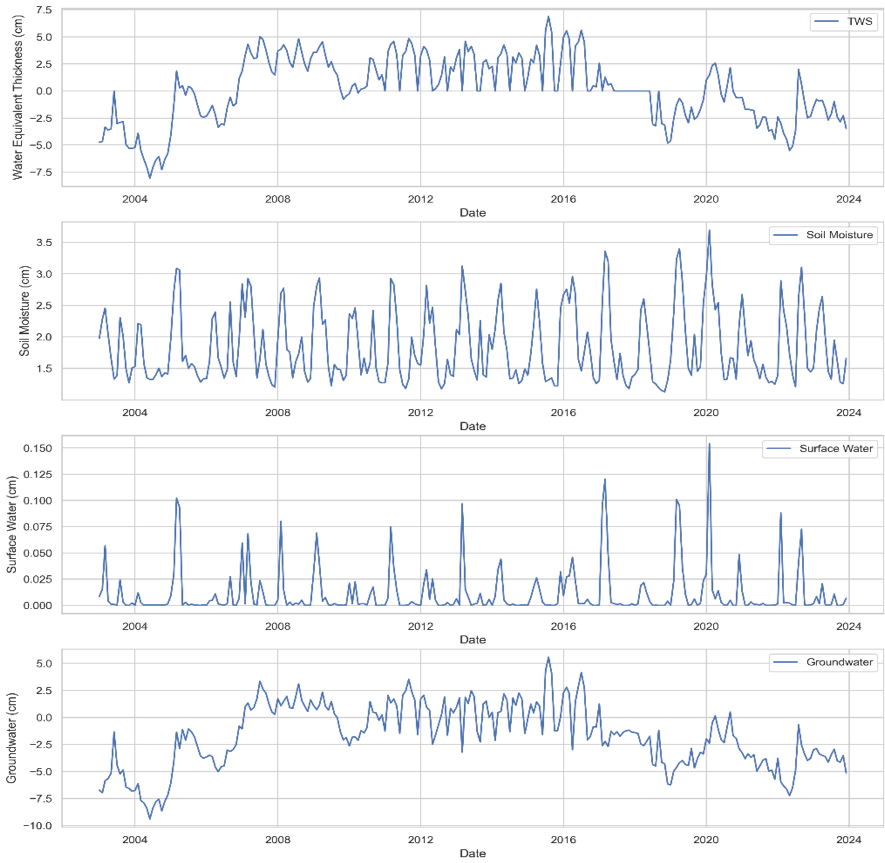

Figure 2|Variation in TWS, soil moisture, surface water and groundwater storage.

4 Discussion:

The analysis of groundwater storage variations in Quetta, Balochistan, using satellite-derived data from GRACE and GRACE-FO, complemented by GLDAS, reveals a persistent and alarming decline in groundwater resources, particularly pronounced over the last decade. This study's findings indicate significant reductions in groundwater storage, with notable decreases in the first five and last seven years of the study period, reflecting the unsustainable nature of current extraction practices in this arid region. These findings are consistent with field observations, as reported by [16], documenting groundwater table declines ranging from 1.5 to 5.0 meters per year in areas experiencing intensive groundwater withdrawal. This excessive pumping has also led to observable land subsidence in central Quetta, with vertical displacement rates reaching up to 120 mm annually. Such rapid groundwater depletion poses severe risks to long-term water security, especially under recurring drought conditions.

The regional nature of this phenomenon is supported by [25], who concluded that prolonged over-extraction combined with prolonged drought has reduced the groundwater levels of Balochistan significantly. In addition, our remote sensing-based assessment verifies that the groundwater depletion in Quetta is progressing very fast and is expected to consolidate under future warming conditions. This study advances these earlier findings by employing a satellite-based approach to provide a comprehensive, long-term perspective on spatio-temporal groundwater dynamics, addressing a research gap in integrating climate impact assessments with advanced remote sensing data.

These implications are severe in terms of the environmental and socio-economic consequences of findings. Land subsidence caused by excessive ground water pumping is already being observed and creates serious infrastructure stability risks such as deterioration of buildings and roads and is a symptom of overall environmental degradation in Quetta. This is in agreement with [16], wherein a relationship between subsidence and groundwater overdrawal was identified, but satellite-derived evidence of this present study serves to further necessitate swift action by quantifying the geographic extent of depletion. In addition, the simulated increase in frequency and severity of drought in future climate projections, SSP245 and SSP585, shows that groundwater depletion will increase, hence further compromising water security in a region where population is expected to increase to about 1.6 million by 2024 [16]. This overlap of humankind induced pressure and climate exposes the serious necessity of adaptive water resources management.

In order to overcome these challenges, there are some practical steps suggested. Regulation of groundwater extraction like, licensing of tubewells and persecution is compulsory to prevent illegal drilling and excessive abstraction which is also a major problem according to study[14]. The demand can be lowered through efficient use of water by modern irrigation methods and popularization of water saving among the population. Moreover, it has also been proposed through a study that methods of managed aquifer recharge like artificial recharge and rainwater harvesting would improve the low natural recharge rates [18]. Investments in modern monitoring systems, such as remote sensing and technologies based on the Internet of Things, will allow to monitor the level of groundwater and its quality in real-time, and make the decision-making process based on data. Acting on these recommendations, the idea of sustainable groundwater in Balochistan [26] but emphasize the integration of cutting-edge technologies to address Quetta's unique hydrogeological and climatic challenges.

5. Conclusion:

This study shows good indicators of continued depletion of groundwater in Quetta Valley, a region in Balochistan, over the past twenty years with the help of satellite-based terrestrial water storage and hydrological elements. GRACE and GLDAS datasets analysis shows a long-term negative trend in groundwater storage over the period 2002-2023, which implies an enormous deficiency between constraining natural recharge and increasing pressure of extraction activities. Seasonal variations that occur during winter rains are observable; but these cannot completely match up the continual losses that may be caused by the unconstrained pumping, compacted urban development and even increased consumption of water. These findings are consistent with past studies into field-based and hydrogeological studies that are indicating that the aquifer under Quetta is chronically stressed and the implications are far reaching on water security in urban settings, agricultural productivity, and unstable land. There are no surface water resources in this arid highland area and as such urgent policy interventions are required to regulate ground water pumping, increase artificial recharge and integrate remote sensing technologies in ground water monitoring and policy of governance. This study demonstrates the value of GRACEGLDAS to be a low-cost and scalable tool to facilitate evidence-based water management in the data-poor location like Balochistan.

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