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A Review of Causes and Consequences of Groundwater Depletion in Varanasi Urban Area

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Abstract

Groundwater is the main water source for people, industries, and commerce in Varanasi, which is among the oldest cities in the world still inhabited. For the last several decades, the city has faced a drastic decline in the water table, which makes the problem even more serious for the hydrological balance and the city's economy. The present study is concerned with the diverse reasons and the major impacts of groundwater dropping in the Varanasi urban region. The researchers made use of a mix of continuous hydrogeological data, satellite images, and urban growth evaluation to point out unregulated urbanisation and high population density as the main depletion factors. The spread of impermeable surfaces has greatly limited the areas that naturally recharge, while the extraction rate is several times higher compared to the annual replenishment capacity of the underlying Gangetic alluvial aquifers. Plus, the change to water-intensive lifestyles and the absence of a centralised regulatory framework for private tube-well installations have increased the problem.

The impacts of this depletion are very serious and show their face in water scarcity all over the place since shallow borewells fail, and it leads to deeper and more expensive drilling. The study also indicates a simultaneous problem of water quality deterioration, as the inward spread of contaminants and the increase of geogenic contaminants, namely arsenic and fluoride, frequently occur along with the decline of water levels. Land subsidence is also a potential consequence that would endanger the city's ancient buildings because of the changes in the subsurface pore pressure. The article recommends an integrated water resource management (IWRM) plan as the way to conduct further research, and suggests that the enforced use of rainwater harvesting, the restoration of traditional urban ponds (kunds), and the development of a digital groundwater monitoring network be used to ensure the long-term sustainability of Varanasi's water security.

Keywords: Groundwater Depletion, Urbanisation, Varanasi, Aquifer Management, Water Security, Hydrogeology

1. Introduction

Groundwater is a critical natural resource that supplies billions of people all over the world, especially in rapidly developing cities where surface water supplies are invariably insufficient or polluted. The Indian subcontinent depends on this resource to a critical threshold. In fact, India has been reported by the World Bank as the biggest user of groundwater in the world, accounting for one-third of total global extraction. Against this background, the town of Varanasi, on the fertile banks of the River Ganges, poses a paradox of water insecurity. Though located alongside a major perennial river, the city's urban population relies heavily on the underlying Gangetic alluvial aquifer for domestic, industrial, and religious needs. However, the undying extraction of this resource has caused a relentless decline in the levels of the water table, thus casting doubt on the future feasibility of the supply system in this city (Singh et al., 2024).

The rapid pace of urbanisation in Varanasi has caused a dramatic change in its hydrological cycle. The continued expansion of the urban population has resulted in a tremendous reduction in natural recharge sites like ponds, tanks, and land surfaces (Raju et al., 2017). The impact of this phenomenon, referred to as "urban sealing," is the reduction of rainfall infiltration into the soil and increased runoff and localised floods during the rainy season. At the same time, the heightened demand for water due to population expansion and the development of tourism-related enterprises has been strangled by the reduced recharge of water into the aquifer, especially for a region heavily reliant on this subsurface water resource (Nistor M.M., 2019). The CGWB (2021) reports that many blocks in the Varanasi district have been identified as "semi-critical" and "over-exploited" regions, pointing to an urgent need to address this problem (Central Ground Water Board, 2021).

The effects of such a depletion of groundwater resources go beyond the realm of physical availability alone. With the reduction in water levels, the energy demand to press water out of the ground will pose an economic strain on the municipality and even domestic users alike (Biswas, A.K.,1999). More problematically, the reduction in the hydraulic head might cause the movement of contaminated water either from surface water resources or from lower strata in the Earth's crust. Within the context of the Gangetic belt, such a reduction in the hydraulic head translates to higher arsenic and fluorine levels of water, thereby threatening the very survival of those who call this place home (Chatterjee et al., 2020). In addition to such worries, the reduction in pore water pressures in the thick layers of clays and silts in Varanasi's aquifer system poses a definite danger of land subsidence. This could cause untold damage to the existing infrastructure in Varanasi, such as its ancient architecture, and such damage could prove to be beyond repair and reversal (Raju et al.,2022).

Despite different initiatives by the government, like the "Atal Bhujal Yojana," the gap between groundwater policy and its translation to ground-level implementation remains large. This research paper will critically analyse the causes leading to the depletion of groundwater in the urban Varanasi area and the associated environmental and socio-economic impacts due to this groundwater depletion. Synthesising the hydrogeological data with changes in land use, this study tries to give a framework for effective groundwater governance, taking into consideration the needs of a modern, fast-expanding city, along with safeguarding the historical and natural background for which Varanasi is relevant.

2. Study Area

The Varanasi Urban Area is located in the northern state of Uttar Pradesh of India, stretching from around 25º13′26″ N to 25º24′07″ N latitudes and 82º52′01″ E to 83º10′55″ E longitudes. According to the Varanasi-Ramnagar-Mughal Sarai Mahayojna-2031, the urban area is categorised into two distinct zones: Zone A, which encompasses the area to the left of the River Ganga, and Zone B, situated along the right bank, including the Ramnagar-Mughal Sarai region. The Varanasi Development Authority has further classified the land into developed and undeveloped categories, with the developed land constituting the Varanasi Urban Agglomeration. This agglomeration includes a diverse mix of land uses such as residential and industrial areas, mixed land-use zones, government administrative precincts, and educational or medical facilities (Varanasi Development Authority, 2023).

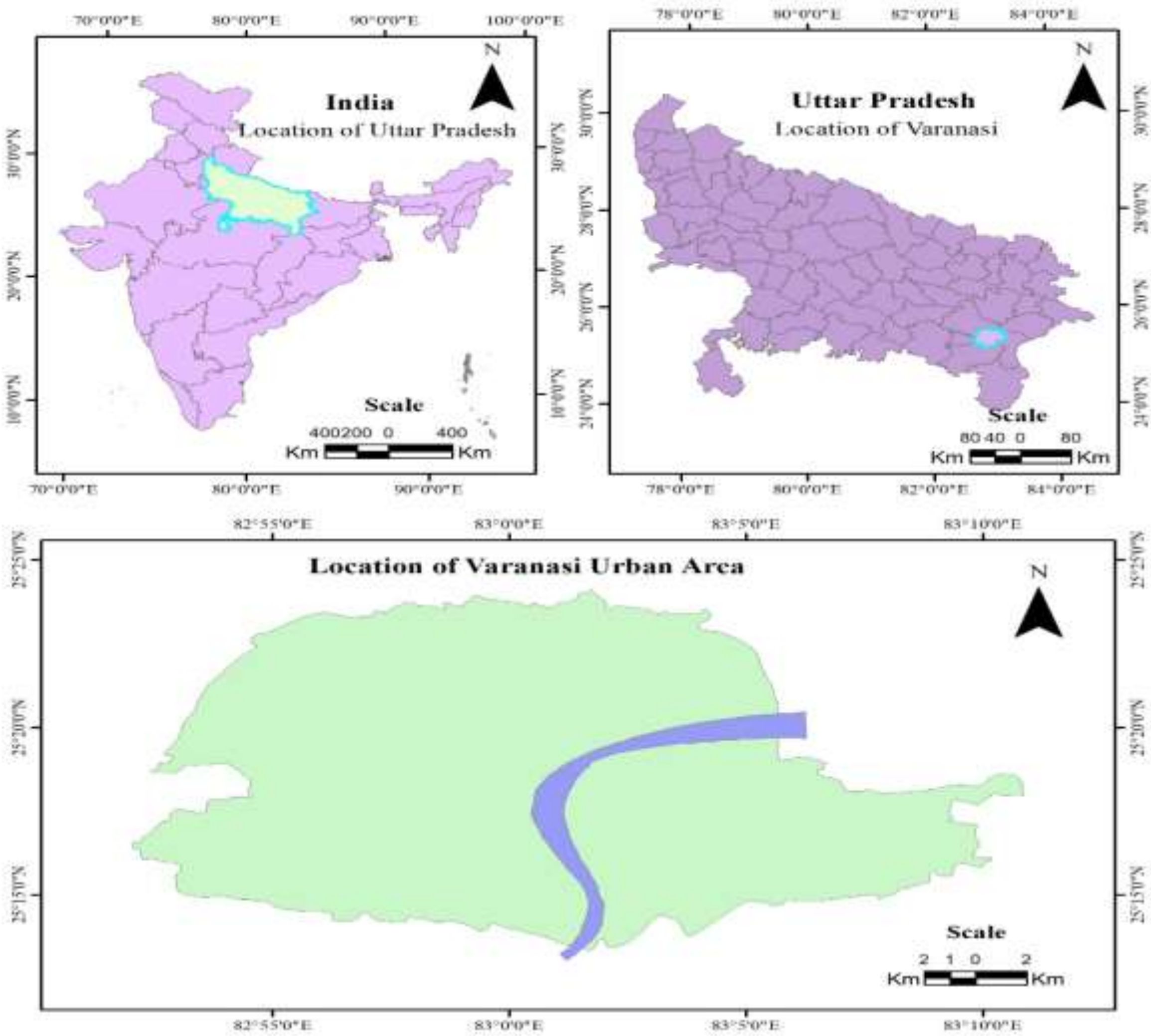

Figure 1. Study Area Map

The region is characterised by a tropical monsoon climate, which features hot summers and cold winters. Most of the annual rainfall occurs during the monsoon season from June to September, while the remaining eight months are comparatively dry. Approximately 76% of the total rainfall is concentrated in these monsoon months, but a significant portion of this rainwater is lost as surface runoff due to a lack of harvesting practices. Geologically, the plains of Varanasi are composed of younger alluvium resting over a Precambrian basement, specifically consisting of Holocene age sediments from river basins. These unconsolidated sedimentary deposits form highly prolific aquifers, typically categorised as unconfined and leaky types (Chaurasia et al., 2022).

The ongoing rapid urbanisation and exponential population growth have significantly altered the landscape, leading to the deterioration of traditional water bodies. Many ponds have been destroyed or paved over with concrete to accommodate new residential and commercial buildings. This destruction has not only resulted in the loss of vital surface water resources but has also eliminated a major source of groundwater recharge for the underlying aquifer system. Because the extraction of groundwater for domestic and industrial use has increased while the natural recharge processes are disrupted by sedimentation and impermeable urban layers, the area is witnessing a critical decline in the water table (Gupta et al. 2024).

3. Methodology

The methodology for this review paper adopts a multi-disciplinary approach by synthesising secondary data to investigate the hydrological dynamics and urban growth patterns of the Varanasi Urban Area. The research integrates longitudinal hydrogeological records from the Central Ground Water Board (CGWB) with urban planning frameworks provided by the Varanasi Development Authority's "Varanasi-Ramnagar-Mughal Sarai Mahayojna-2031" (Varanasi Development Authority, 2023). Central to the analysis is the evaluation of "urban sealing," where satellite-based observations and multi-temporal data (including Sentinel-1 and GRACE data) are reviewed to correlate the expansion of impermeable surfaces with the documented decline in natural recharge sites like traditional ponds and kunds (Raju et al.,2017). The study further assesses the environmental consequences of depletion by reviewing geochemical research on the concentration of geogenic contaminants, such as arsenic and fluoride (Chatterjee et al.,2020), and geophysical evidence of land subsidence along the Ganga riverfront (Raju et al.,2024). Finally, the methodology examines the gap between current water management policies and ground-level implementation to advocate for an Integrated Water Resource Management (IWRM) framework that balances modern urban needs with the city's historical and natural preservation.

4. Causes of Groundwater Depletion in Varanasi Urban Area:

The groundwater depletion in Varanasi is a multifaceted issue that combines very fast human-induced changes with natural hydrogeological limitations. Being a city in the central Indo-Gangetic Plain, the groundwater storage of Varanasi is dependent on the alluvial aquifers. Below are the main reasons for this depletion:

a. Unregulated Urbanisation and "Urban Sealing": Over the past few decades, Varanasi has experienced tremendous horizontal and vertical growth. The gradual transformation of the city's periphery, together with the increase in population density in certain parts of the city, has resulted in urban sealing. Urban sealing leads to the creation of impermeable surfaces (like concrete and asphalt) that block the natural infiltration of rainwater into the ground. This situation effectively "turns off" the aquifers' natural recharge process, leading to a lot of surface runoff and localised flooding instead of ground water replenishment (Raju et al., 2017).

b. Over-Exploitation and the Proliferation of Private Tube-wells: It is Varanasi's large population, which is more than 1.6 million, that relies almost fully on unfiltered water. The reason for this is that the water supply system, mostly from the late nineteenth century, cannot meet the present (Mukherjee D., 2016). Thus, ungoverned shifting by thousands of private tube-wells has taken place. The Central Ground Water Board (CGWB) has described that the amount of water taken out yearly in the urban block is much higher than the annual groundwater resource. "Over-exploited" and "semi-critical" are the terms used for areas of the city (Central Ground Water Board, 2021).

c. Loss of Traditional Recharge Structures: Varanasi in past was the place where many kunds (ponds) and traditional tanks were located, which served as natural recharge bases for the aquifers of the city. The urban sprawl has occasioned the environments of these water bodies to either be completely extinguished, polluted or turned to dust. The disappearance of such "blue-green" infrastructures has drastically reduced the areas of concentrated recharge that were supporting the local water table during the rainy season (Raju et al., 2022).

d. Climate Variability and Rainfall Trends: The alteration in the climate and, at the same time, the migration of rainfall in the area have contributed to the situation. The Indo-Gangetic Plain is characterised by significant monsoon rains; however, the last 20 years' trend shows a gradual shift to irregular and high-intensity, short-duration rainfall events. Such events are more likely to cause surface runoff rather than slow soil infilteration thus making the deep aquifers recharge during a "normal" monsoon year lower than the predicted level (Nistor, M.M., 2019).

e. Hydrogeological Constraints: The stratigraphy of Varanasi consists of an alternation of sand, silt, and clay layers. The deep aquifers (often more than 100m deep) are in a semi-confined to confined state. Though these layers were once a steady source of water, the heavy pumping from those deep wells has started to deplete, gradually, the non-renewable or slow-to-recharge storage zones. As the hydraulic head in those deep layers decreases, it may trigger the downward flow of contaminated water from the top layer that is shallow and polluted (Central Ground Water Board, 2021).

5. Consequences of Groundwater Depletion:

Groundwater depletion in Varanasi has far-reaching impacts, which are manifested in the city's physical environment, public health, and economic sectors. The city has to deal with a variety of risks, from drinking water contamination to structural damage, as the water level continues to fall at a rate of about 0.75 to 1.19 meters annually in certain places. In Varanasi, the urban area suffers from the following main consequences due to groundwater depletion:

a. Land Subsidence and Structural Risks: The most significant danger is the land subsidence; This escalated threat is mainly because of the excessive withdrawal of the aquifer, and there is a study that has been done by scholars from Banaras Hindu University (BHU) and Chapman University, revealing the down-sinking of the ground along the Ganga riverfront. Groundwater depletion in Varanasi has led to measurable land subsidence along the Ganga riverfront, with key heritage sites such as Manikarnika, Harishchandra, and Ravidas Ghats experiencing cumulative sinking of approximately 2 cm to 5 cm over recent years (Raju et al., 2024).

This gradual deformation manifests as undulations and fissures along the ancient stone stairways and platforms, undermining the physical stability of these structures, which are integral to the cultural and spiritual life of the city. Because the riverfront and its ghats form part of the historic core of Varanasi, recognised for its outstanding cultural value, such ground movement poses a serious risk to the structural integrity of heritage zones, threatening both the built environment and the continuity of traditions associated with these sites (Raju et al., 2022).

b. Water Quality Degradation and Geogenic Contamination: In the Varanasi Urban Area, groundwater resources are declining, and hydraulic pressure changes in the shallow aquifers can cause water quality to deteriorate a lot because of the mobilisation of pollutants and contaminants. Lower water levels make aquifers even more susceptible to bacterial contamination because surface waste and leaky sewer systems are the main contributors of nitrate and coliform that get into the deeper layers of the ground. This happens especially when the shallow hand-pump sources fail, and the deeper ones suck in contaminated water from above. Not only does this situation worsen health risks, but it also reduces the usability of groundwater for drinking and domestic purposes (Singh et al.,2015).

Moreover, the area's location in the Middle Ganga Plain makes it prone to getting contaminated by geogenic factors, particularly arsenic and fluoride, which can be released into groundwater through natural geochemical processes and become more concentrated as water volumes decrease and flow paths change. Research conducted in the Ganga alluvial plains has shown that a number of tubewells have arsenic concentrations that are above the safe limit, thus indicating the geogenic origin of these toxins in the Quaternary alluvium typical of the area. The groundwater in the region is also observed to be enriched with fluoride, which is moderated by geogenic and hydrochemical factors that increase its concentration as aquifer conditions change due to depletion (Chatterjee et al.,2020).

c. Economic Burden and Water Insecurity: The lowering of groundwater levels in Varanasi has been a great source of distress to the people living in the city, especially the poor who are relying on shallow aquifers for their daily water needs. The shallow borewells and the hand pumps are already dry; thus, many households have no option but to dig deeper and, thus, create tube-wells that are even more expensive and, eventually, groundwater will be more costly for these households due to the drilling, electricity bills, and maintenance, which are already quite high. This is a common practice in many parts of India where the water tables are falling and, as a result, the costs of water extraction are skyrocketing for both rural and urban users alike (Biswas A.K.,1999).

The trend of deeper drilling and higher pumping capacity is therefore changing the map of water access; not only it takes a toll on the family budgets, but it also causes water scarcity for the poor, as the richer people can buy the advanced infrastructures for deeper drilling and pumping, while the poorer segments of the population, slum communities, cannot often afford the resources needed to get hold of steady drinking water from the ground. On the other hand, the communities that are already at a disadvantage are facing water scarcity and deprivation, sometimes spending a living income on the alternative water supplies or healthcare costs related to unsafe water, a pattern which is common in the groundwater crisis in India, where the dropping of aquifers disrupts the distribution of this indispensable resource (Sayre et al.,2019).

d. Impact on River-Aquifer Interaction: "Base flow" is the term used for the process through which the River Ganga gets its water from the groundwater. Reduced River Flow: Groundwater normally contributes to the river during dry months in a non-monsoon season. But when the water level drops below the riverbed level, this flow is either reversed or stopped, which causes the river's ecological flow, which in turn affects the aquatic biodiversity to shrink (Singh et al.,2016).

e. Increased Energy Footprint: To extract water from deeper layers, it takes quite a lot more energy to do this. As a result, the city's water supply system is going to have a larger carbon footprint, and the already stressed municipal electricity grid will have to endure even more pressure (Sayre et al., 2019).

6. Discussion:

The results of this study establish that an important hydrological change has been witnessed in the Varanasi urban zone, which has caused a level of ecological unsustainability with regard to the usage of Gangetic alluvial water. The lowering of water levels at an average of 0.8 to 1.2 meters per year in densely populated wards signified not just an ecological change but a failure in water management in urban areas (Central Ground Water Board, 2021). This level of lowering has been common in this region, but it has been accelerated because of the unique, densely populated urban environment of Varanasi. A primary concern emerging from this research is the paradox of urban growth. On the one hand, the growing population of the city, along with the rising demand for tourism, necessitates the expansion of the city. However, the infrastructure that sustains this expansion, such as concrete structures for housing, road construction, and other business infrastructure, hinders the recharging of the aquifers. The "urban sealing" process has thus alienated the surface hydrological cycle from the subsurface storage. Additionally, the destruction of more than 40% of the traditional ponds and kunds in the last three decades has created "chances for water re-entry" in the post-monsoonal period, as stated in (Raju et al. 2017).

The geochemical implications are just as alarming. The change from shallow to deep-seated pumping has changed the redox conditions within the aquifer, with a possible increase in the mobility of geogenic contaminants like Arsenic and Fluoride (Chatterjee et al.,2020). Since the hydraulic head is falling, the chance of "downward leakage" of surface pollutants from the city's extremely aged and quite often leaking sewerage network is higher. This creates a vicious circle where depletion leads to contamination, further reducing the availability of potable water and increasing the socio-economic load on poor populations who cannot afford advanced filtration systems or deep-bore construction (Sayre et al.,2019). Finally, the localised land subsidence detected along the Ganga riverfront suggests that groundwater depletion is no longer just a water-security issue but a structural threat to the city’s cultural heritage. The lowering of pore-water pressure in the silt-clay layers beneath the ancient ghats may lead to irreversible deformation of these historic structures, necessitating immediate geo-technical and hydrological intervention (Singh & Raju, 2024).

7. Conclusion:

Depletion of groundwater in the Varanasi Urban Area is an immense threat to the environment and the sustainability of urban living. Excessive groundwater extraction, urbanisation, and the reduction of natural recharge processes have all collaborated to reduce the water table significantly, with parts of the city recording reductions of around 75 cm to 90 cm per year, which led to the water table being almost 20 m beneath the ground level in recent years. Groundwater has become the only source for water supply; this is partly due to the old water supply network, which is not capable of supplying enough water to the increasing urban population, so that households and local authorities have no choice but to obtain water from deep tubewells and borewells.

There are many aspects in which urban life in Varanasi gets affected by the depletion of groundwater resources; these dimensions are physical, ecological, and socio-economic. Moreover, the aquifers' loss correlates with land subsidence along the Ganga riverbank, where both satellite and ground data show subsidence rates of up to several millimetres per year, thus endangering the integrity of the heritage ghats and the infrastructure nearby. The ground has not only sunk but also deteriorated; as the water table declines, it becomes more and more difficult to get clean water since the urban waste and the inefficient sewage systems increasingly infiltrate the shallow aquifers. All these problems are made worse by the elimination of ponds and recharge zones that used to assist in the replenishment and filtration processes.

The aforementioned modifications lead to an increase in economic and social strains. Residents and establishments have to bear the extra costs of deeper wells drilling and extraction systems upkeep, while the already disadvantaged groups suffer the most because of their reliance on unsteady and unreliable supply sources. Integrated water management methods are necessary to confront the issues, which may include artificial recharge, cutting down extraction, improving stormwater capture, and protecting recharge areas. The building of rainwater harvesting pits in educational institutions and open parks represented the start of hopeful measures towards decreasing groundwater depletion.

To that end, the empowerment of the sustainable management of groundwater in Varanasi must be a major consideration in the planning of urban areas, together with the use of scientific monitoring, and the combination of proactive policy, community engagement, and infrastructural improvements, that will provide long-lasting water resilience amid the rapid urban growth and climate change variances.

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