PREDICTING THE IMPACT OF RAPID URBANISATION ON URBAN GROUNDWATER LEVEL VARIATIONS AND ANALYZING CLIMATE DYNAMICS IN PUNJAB'S CITIES, INDIA: AN APPROACH TOWARDS SUSTAINABLE CITIES

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ABSTRACT:

In the past few decades, India has witnessed an unparallel population growth across its urban centres. The significant rise in urban population has led to acute demands for resources to sustain them, contributing to anthropogenic activities that impact urban resources and climate. This study was carried out to analyse the impact of rapid urbanisation on the groundwater level variation and climate dynamics. Focus was laid on Ludhiana and Patiala urban centres of Punjab state, India. Multi-temporal analysis of LULC was computed using Landsat-4, 5, 7 & 8 datasets to analyse urban sprawl during 1990-2023 for both the cities. A significant increase of 30% urban area was observed during 1990-2023. Further, to analyse the impact of urbanisation on ground water levels, the groundwater water storage variation was analysed using the GRACE and GRACE-FO mission datasets. It was found that the groundwater withdrawal was greater than the amount of total groundwater recharge during 1990-2023. Both these cities Ludhiana and Patiala has experienced an extreme decline in groundwater storage levels. Further, the time-series statistical relationships were explored to understand the relation between urban sprawl and annual temperature, rainfall patterns and total water storage for these cities during the years 2000-2022 for analysing the effect of rapid urbanization.

1. INTRODUCTION

In the current context, a substantial proportion of the global population resides in urban centres, and projections suggest that by 2050, two-thirds of the world's population will call urban areas home (Hegazy & Kaloop 2015). Rise of globalisation has improved living conditions of urban regions giving rise to a well deserved word named smart cities, which emphasizes more effective urban management using information and communication technologies (ICT), which has greater implications (Park and Yoo, 2023). Smart cities have attracted population in the urban cities of Punjab state in India therefore it has shown significant increased rate of population in these regions, which resulted to a pressure on the carrying capacity of urban centres resulting in urban sprawl (Correia et al., 2022). Massive influx of people put immense pressure on urban infrastructure, resulting in the diminution of natural resources such as surface water (Sur et al., 2021) and groundwater (Awasthi et al. 2018). Excessive demand for water in the rapidly growing urban centres due to excessive domestic use, industrial use etc led to the over exploitation of groundwater resources (Trivedi et al., 2023, Singh and Singh, 2002). Inflow of population stress rapidly leads to urbanization, which often results in urban sprawl which is a phenomenon of uncontrolled development along the periphery of the core urban region, where cities expand without proper planning, infrastructure, or zoning regulations (Awasthi, Varade, et al. 2022; Varade et al. 2023, Kumari et al., 2022). Consequently, a range of challenges emerges, including heightened traffic congestion, prolonged commuting durations, and a decline in urban green spaces over a long period of time. The surging urban populace exacerbates vehicular numbers, leading to traffic bottleneck situation, extending travel times, and increased air pollution levels (Awasthi et al. 2020, Boogaar d et al., 2022). Moreover, the progression of urban growth links closely to elevated air and noise pollution levels, predominantly emanating from amplified vehicular emissions, industrial enterprises, and densely populated areas (Awasthi et al. 2019). In tandem, the escalating demands of urban residents for essential resources like water, energy, and raw materials exert substantial pressure on local ecosystems, potentially driving excessive resource exploitation and subsequent environmental as well as natural resource degradation.

The expansion of urban populations carries significant environmental implications, as urban residents both influence and are affected by their surroundings' altered conditions due to increased resource consumption (Awasthi et al. 2019; Varade et al. 2023). Urban regions exhibit distinct consumption patterns compared to rural areas, characterized by heightened energy usage for various purposes. This escalated energy consumption contributes to the formation of heat islands that impact local and downstream weather patterns. These heat islands, arising from cities' reduce heat radiation efficiency compared to rural spaces, giving rise to warmer urban climates and the entrapment of pollutants like Nitrogen Dioxide which is extremely injurious to health (Sur et al. 2021). Consequently, altered cloud patterns, resulting into fog and smog occurrence, augmented precipitation patterns, and more frequent occurrences of thunderstorms and hailstorms in the urban designated areas disturb or cause disruption in the entire urban ecosystem. Consequently, urbanization exerts influence on micro and macro environmental condition by extending its influence on broader regional environmental activities, inducing escalated air pollution, amplified precipitation, and increased thunderstorm frequency in regions located downwind from industrial complexes (Sahoo et al. 2023, Das et al., 2022). Urban expansion also disrupts natural water runoff patterns by intensifying rainfall but diminishing water infiltration, leading to swifter runoff, heightened flood volumes, and water contamination downstream. In these urban regions mostly, groundwater serves as a significant freshwater resource for urban populations. However, the unregulated proliferation of deep well infrastructure in urban areas in the recent past has led to the over exploitation of groundwater resources in the region. Consequently, this has imposed considerable strain on subterranean aquifer systems, culminating in a depletion of groundwater levels (Kumar et al., 2023).

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As a result, the water table in many areas fall, causing significant environmental and social problems (Awasthi, Jain, et al. 2022). Further, anthropogenic activities exaggerated by mega industrialization plans and development of infrastructural projects like building of highways, local roads etc put additive effects on the climatic scenarios in these cities by increasing atmospheric temperature over the decades because concrete area usually traps heat in the atmosphere. Urbanization is a clear representation of increase in impervious area over selected baseline time frame, which when related to changes in ground water availability and can consequently help us to predict the future water and environmental stress in the region. Thus, to marginalize the gap between the demand and supply of groundwater resource in the era of climate change it is need of the hour to understand 3D, urban dynamics, climate dynamics and groundwater dynamics at regional scale. A consistent monitoring of urban sprawl and a comprehensive analysis of its implications on climate patterns and groundwater levels fluctuations remain imperative. In the past, satellite remote sensing has been extensively utilized for continuous monitoring of urban dynamics and analysing it effect on climate change and diminishing groundwater resources (Roy et al., 2022). Awasthi et. al. (2022) analysed the Urban land deformation resulting from over-extraction of groundwater in the urban city (Awasthi, Varade, et al. 2022). Further, Varade et. al. (2023) worked on analysing the effect of urban sprawls on urban climate scenarios by relating the effect of urban sprawls on Land surface temperature and optical depth. Further, another study analysed land surface temperature (LST) variation with the change in urban land use/land cover patterns (Sridhar et al. 2020). Later, in another research multi-decadal changes in the groundwater level in various parts of Malwa region in Punjab was analysed utilizing GRACE datasets (Sahoo et al. 2021, Ali et al., 2022, Awasthi et al., 2023).

But the challenge lies that Landuse, Climate and groundwater has rarely been co related together. This study is focused to analyse the impact of urban land-use change on selected cities mainly (High density urban areas and low density urban areas) of Punjab, India and its impact on ground water resources and environmental condition (rainfall and temperature) during the period 1990-2023 for addressing the Sustainable Development Goals (SDG) outlined by United Nations.

2. STUDY AREA AND DATASETS DETAILS

2.1 Study Area Details

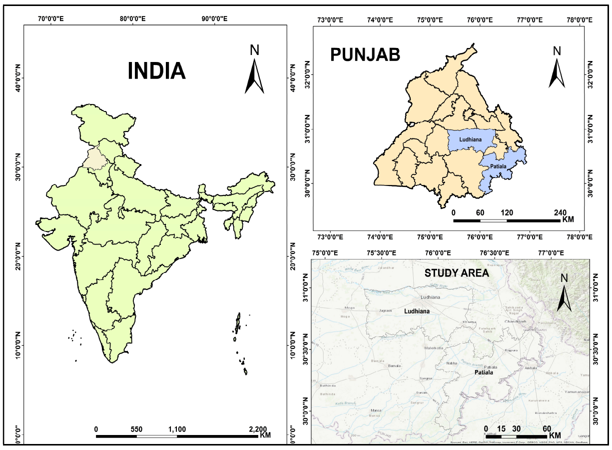

Figure 1. Figure placement and numbering.

The study area of this research is selected as Ludhiana and Patiala districts located in the Punjab state of India. These districts have undergone significant population expansion in recent years with rise in designation of smart cities. They are characterized by a semi-arid climate with subtropical conditions. The prevailing weather pattern includes south easterly summer rains and winter rains caused by westerly atmospheric depressions (Sahoo et al. 2021). Notably, both Ludhiana and Patiala experience winter rains due to westerly depression in the northern zone of India therefore due to these atmospheric conditions gets worst (Larka and Abhishek, 2022). Positioned in the central and eastern parts of the Punjab plain region, Ludhiana and Patiala are situated within a topographically remarkable landscape that is notably flat terrain (Singh et al., 2022). These areas are bordered by alluvial plains and lower shiwalik hills on both side (Sridhar et al. 2020).The climate of these cities manifests five distinct seasons: spring, summer, monsoon, autumn, and winter (Sridhar et al. 2020). Throughout the summer, temperatures commonly fluctuate between 40°C and 42°C, occasionally spiking to a maximum of 44°C. In contrast, winter temperatures typically range from −1°C to 14°C.

2.2 Datasets Used

For this study Landsat-4,5,7 & 8 series datasets are used for the years 1990,2000, 2010 and 2023 respectively. Landsat datasets were chosen because it provides a long term archival with standard projection system. The spatial resolution of Landsat is 30 metre which is very good for distinctly classifying Core and Peri urban region. This study uses optical band of Green, Red and Near Infrared bands to classify the above regions. Corresponding GRACE and GRACE-FO CSR-Mascon mission datasets at a resolution of 25 km are used for the period 2002-2022 to analyse Total Water Storage (TWS) variation in the ground. Further, for climatic exploration TRMM and MODIS LST datasets were used for understanding annual variation of these parameter. Google Earth Engine (GEE) was used to collect the monthly rainfall and LST datasets for the time period 2000-2022.

3. METHODOLOGY

This work involves analysis in three stages (a)Data Mining (b) Classification using Machine learning (c) Geostatistical analysis of the major variable take in the study (i) Landuse (ii) Climate variable (iii) Ground water variables. First the Landsat data collection from 1990 to 2023 was subjected to Support Vector Machine (SVM) algorithm at an interval of 10 years (3 decades) to extract the urban features namely the High Density Urban and Low Density Urban. Further MODIS LST and Rainfall from TRMM was extracted for 20 year from 2000 to 2022 to understand the pattern of temperature in the region at local level over Ludhiana and Patiala two selected district in which the study was conducted. In addition to the above Groundwater variation was calculated from GRACE and GRACE-FO Datasets. These datasets provide Terrestrial Water Storage Information from which other variables like Subtraction of Soil Moisture, Canopy Water Amount, Surface Runoff and Sub-Surface Runoff derived from GLDAS datasets were used to derive the groundwater dynamics for the year 2000 to 2020.The analysis of the above were used to show spatial and temporal variation in the study area. The entire handling of the datasets was done in GIS environments like ARCGIS and GEE which critically takes care of the geospatial synchronisation of multiple datasets over a region with multiple spatial resolutions.

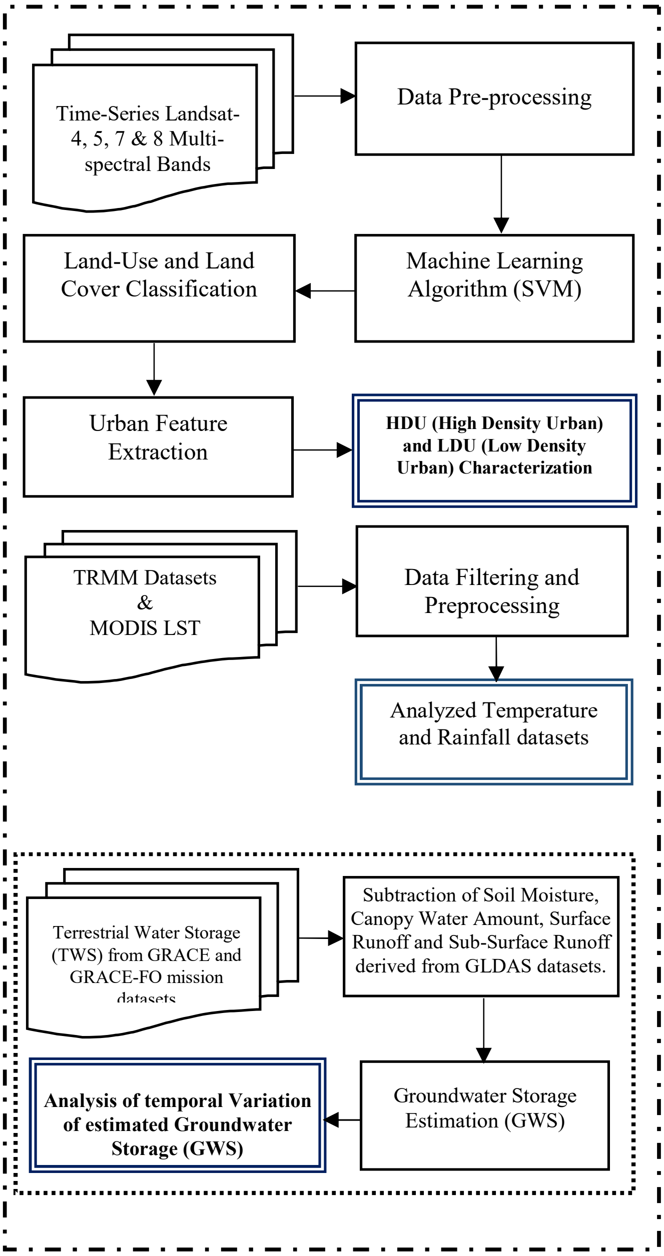

Figure 2. Methodology Flow Diagram

The above methodology flow diagram shown in Figure 2 explains the workflow. This research utilized time series Landsat 5 and 8 datasets, subjected to data pre-processing, followed by the implementation of the Support Vector Machine algorithm to perform Land Use Land Cover Classification, distinguishing between High Density Urban (HDU) and Low Density Urban (LDU) areas. The resulting classification map underwent validation against ground truth data, revealing a notably high accuracy in classification. Additionally, Multi-Temporal datasets of TRMM and MODIS LST spanning 2000 to 2022 were acquired, subjected to data filtering and preprocessing. The ensuing temperature and rainfall datasets were analysed to assess temporal variations between 2000 and 2022. To gauge groundwater fluctuations, the Total Water Storage (TWS) datasets from the GRACE and GRACE-FO missions were employed. Through the utilization of modeled datasets encompassing Soil Moisture, Canopy Water Content, Surface Runoff, and Sub-Surface Runoff from GLDAS, the surface water component was subtracted to estimate Groundwater Storage Estimation (GWS), subsequently permitting an investigation into the temporal fluctuations of the estimated Groundwater Storage (GWS).

3. RESULTS AND DISCUSSION

3.1 Analysis of Urban Sprawl in the Urban Regions

3.1.1 Urban Sprawl in Ludhiana

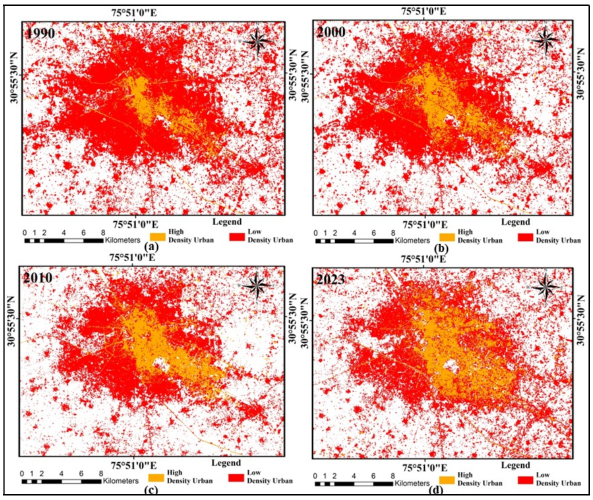

Figure 3. Temporal Variation of Urban Sprawl in Ludhiana

Figure 3 presents the spatial and temporal variation of Urban Sprawl in the Ludhiana area. The analysis involves classifying urban areas into two categories: high-density urban (HDU) and low-density urban (LDU). The classification helped to determine density of urban class pixels per square kilometre. As illustrated in Figure 3, there is a notable expansion of the urbanized region from 1990 to 2023. Specifically, the regions classified as high-density urban (HDU), primarily originating from the central Ludhiana or the nuclei of the city, have experienced substantial growth over the years between 1990 to 2023. Ludhiana has experienced lateral growth on all sides of the core with a major thrust on the eastern part of the city because the eastern part has show significant growth of the industries.

3.1.2 Urban Sprawl in Patiala

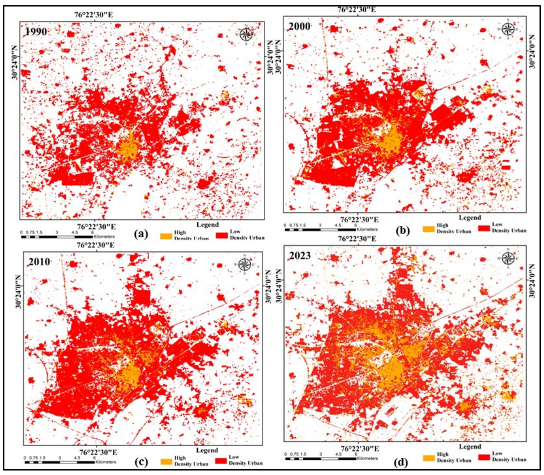

Figure 4. Temporal Variation of Urban Sprawl in Patiala

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Urban Sprawl in Patiala was also explored. Patiala significantly showed an increase in the urban area over the time.

Figure 4 illustrates the spatial and temporal dynamics of urban sprawl in the Patiala region. The growth of the city is evident in 2010 to 2023 more than the previous years. Classified high-density urban (HDU) and low-density urban (LDU) zones based on the density of urban class pixels per square kilometre shows expansion of HDU is very high in 2023. It is quite important to note that LDU zone is expanding towards the western part were as the HDU zone is expanding towards the eastern part of the city. Thus it can be clearly commented that the nuclei is expanding therefore the compactness in the core city area is expanding over the time.

3.1.3 Groundwater Level Variability in Ludhiana

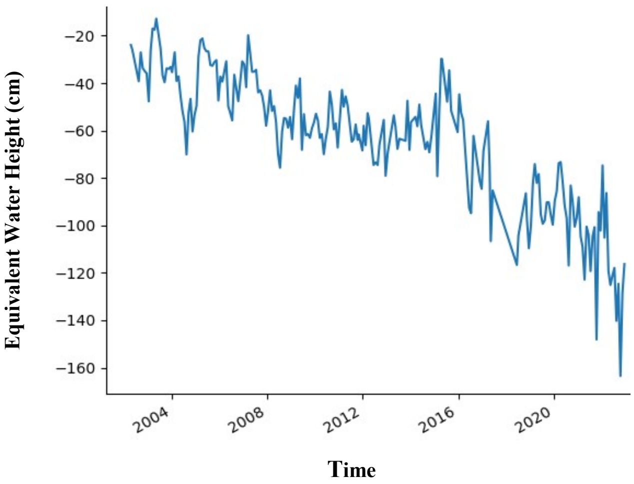

Figure 5. Groundwater storage variability in Ludhiana

Groundwater storage variability in the Ludhiana region has been shown using the GRACE-CSR Masons datasets. A massive downfall in the groundwater was observed during the time period 2015 and 2017 years. The overall variation in the equivalent water height (cm) has been observed to be around 160 cm during the past with respect to 2002-2022 years.

3.1.4 Groundwater Level Variability in Patiala

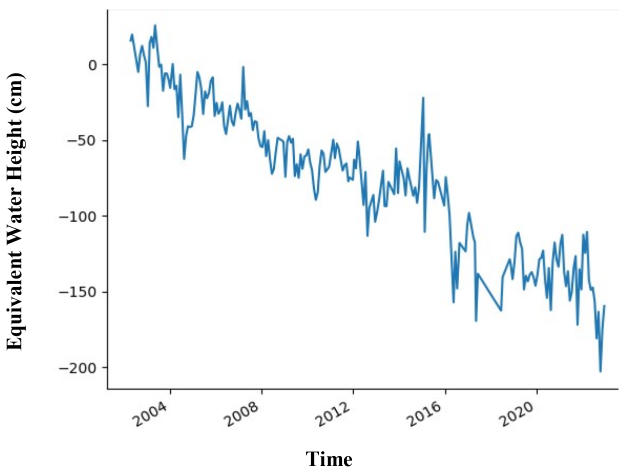

Figure 6. Groundwater storage variability in Patiala

The region of Patiala recorded much more rapid depletion of groundwater level compared to Ludhiana. Therefore it is clear that Patiala is facing more stress that Ludhiana in terms of urban pressure. A very steep decline in the groundwater level was observed between 2002 and 2012. During the year 2012-2015 a nearly steady or slightly increased groundwater level was experienced in the region, which again started depleting during the years 2021 to 2022. During the whole duration of year 2002 to 2022, the Patiala experienced 200 equivalent water height (cm) decline in groundwater level. The depletion in the equivalent water height is highly alarming and therefore needs immediate attention.

3.2 Climate Variability in the Urban Regions

3.2.1 Climate Variability in Ludhiana

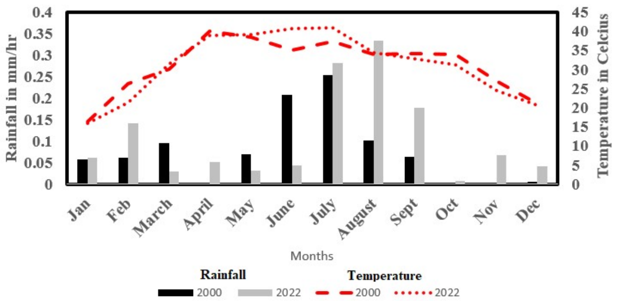

Figure 7. Climate variability in Ludhiana

Climatic pattern of industrialised city Ludhiana has highly changed over time frame 2000-2020 due to increase in the urban landmass, a clear rise in temperature is seen between months of May to July (Summer Months) and fall in temperature is seen between Octobers to February (Winter Months) from Figure 7. This variation in temperature illustrates strong changes in climate pattern at the local level. Contrasting to temperature pattern, rainfall have increased over the years in all the months specially in August and September.

3.2.2 Temperature Variability in Patiala

Patiala exhibits also a similar trend in regard to change in climatic pattern of Ludhiana. During the time frame 2000-2020 expansion of core and peri-urban has led to a clear rise in temperature between months of May to July (Summer Months) and fall in temperature is seen between Octobers to February (Winter Months) from Figure 8. This variation in temperature illustrates strong changes in climate pattern. Climate change also leads to change in rainfall pattern at micro and macro level of Patiala. Even in Patiala rainfall is showing and increasing trend in the post summer period this indicates rise in heat stress over the region. This stress can be connected to the fact that urbanisation has led to increase in the concrete surface therefore solar insolation easily heats the surface and the radiated heat gets trapped in the atmosphere consequently leading to fluctuations in the climate over the years.

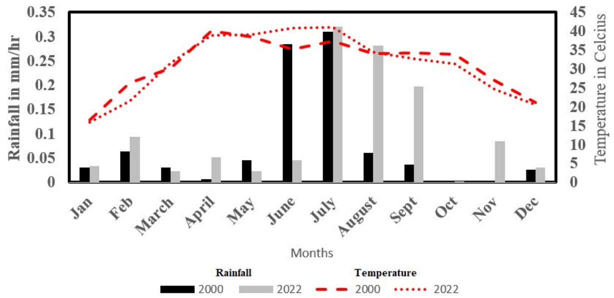

Figure 8. Climate variability in Patiala

4. CONCLUSION

This study indicated an alarming future to the growing urban cities of Punjab, India due to both anthropogenic and climatic stress. Increase in urbanization rate is witnessed in the predicted future of the selected urban hubs and growing stress over natural resources and creating substantial amount of liability over sustainable development in the region. In addition, groundwater level has substantially depleted in the last 20 years in these cities namely Ludhiana and Patiala due to excessive population thrust over the urban centres. Therefore stake holders department need immediate attention to revive the changing dynamics of urbanisation and ground water in a planned way so that sustainable managements of the cities is possible. This study also proposes an outline for interested researchers to explore ground water dynamics in Punjab and its impact on micro climate environment.

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