Water Stress Vulnerability Assessment of Visakhapatnam District, Andhra Pradesh, India, using AHP and MCDM Methods

Kasiviswanadham P.[1]*, Sanjeet Kumar[1] and Sridevi T.[2]
1. Civil Engg., K L University, Vaddeswaram, Andhra Pradesh, INDIA
2. Geo-Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, INDIA
*kasi.ponnapalli@gmail.com

Abstract
This study seeks to identify water-stressed regions within the study area by evaluating factors including geomorphology, surface runoff, groundwater fluctuations, population density, LuLc, impervious surface, and environmental impacts. Employing the Analytic Hierarchy Process (AHP) and Multi-Criteria Decision-Making (MCDM) techniques, the research aims to develop a comprehensive assessment method that categorizes water vulnerabilities based on geographic and anthropogenic activities.

Utilizing these tools, specific areas for water stress alleviation will be identified, facilitating targeted interventions to enhance water sustainability in urban settings. This study contributes to knowledge in urban water management and offers valuable guidance for policymakers, urban planners, and stakeholders in devising effective strategies to address water stress challenges in densely populated Visakhapatnam City of Andhra Pradesh.

Keywords: MCDM, AHP, Water stress, Water sustainability, Urban water management.

Introduction

Water stress has emerged as a critical global challenge, exacerbated by climate change, population growth, and unsustainable water management practices[12]. The intricate interplay of social, economic, and environmental factors complicates the assessment of water stress vulnerability, necessitating a comprehensive and systematic approach. In recent years, multi-criteria decision-making (MCDM) methods[12] coupled with the Analytical Hierarchy Process (AHP)[9] have gained prominence for their ability to integrate diverse criteria and stakeholder preferences into water resource management decisions and in assessing flood-prone areas[14].

This research study explores the application of AHP and MCDM techniques in assessing water stress vulnerability, providing a structured framework for decision-makers to prioritize interventions and allocate resources effectively. By synthesizing qualitative and quantitative data, this approach enables the evaluation of various stressors such as water scarcity, pollution, and infrastructure inadequacy along with their respective impacts on water resources[14]. The significance of this study lies in its potential to enhance water resource management strategies, particularly in regions facing heightened vulnerability to water stress[8]. By incorporating stakeholder input and expert knowledge, the proposed methodology facilitates a holistic understanding of water stress dynamics, allowing policymakers to identify vulnerable areas, prioritize adaptation measures, and foster resilience in the face of evolving environmental challenges. This research seeks to contribute to the evolving discourse on water stress assessment methodologies. Furthermore, it aims to address existing gaps in current approaches by offering a systematic and adaptable framework that can be tailored to diverse socio-environmental contexts. We delve into the theoretical underpinnings of AHP and MCDM, elucidating their application in water stress vulnerability assessment. Subsequently, we present a case study on Visakhapatnam illustrating the practical implementation of the proposed methodology in a real-world context.

Objectives of the study

In consideration of the Visakhapatnam district's vulnerability to hydric stress and the necessity to alleviate the concomitant risks, the formulation of a detailed water scarcity cartographic representation is recognized as a pivotal undertaking. With the primary aim of bolstering resilience and reducing susceptibility, this research endeavors to establish a Geographic Information System (GIS)-based environmental database, integrating essential variables such as geomorphological characteristics, land use and land cover (LULC), groundwater fluctuation maps corresponding to pre- and post-monsoon periods, impervious surface distribution, demographic density, lineament density, stream hierarchy, topographical slope, and evapotranspiration rates.

By employing the Analytic Hierarchy Process (AHP) and Multi-Criteria Decision Making (MCDM) methodologies, the delineated variables will be methodically ranked and assigned weights to ensure a high degree of precision in the water vulnerability mapping procedure.

- To study pre requisites to adopt AHP and MCDM methods.
- To investigate the determinants contributing to the depletion of groundwater resources.
- To assess the groundwater vulnerability of the study area using MCDM and AHP processes, and to provide recommendations to achieve sustainable groundwater management practices.

https://doi.org/10.25303/189da0890101

Review of Literature

The Analytical Hierarchy Process (AHP) and Multi-Criteria Decision-Making (MCDM) techniques have been effectively utilized in various studies related to water stress assessment. A study prioritized water stress areas using AHP and MCDM, highlighting the effectiveness of these methods in managing water risk[5]. Additionally, it improved the AHP method to optimize expert evaluation matrices for water resource carrying capacity evaluation, showcasing the applicability of AHP in water resource assessments. Furthermore, they employed AHP, SAWM, and FBI techniques in determining suitable sites for rainwater harvesting[11], demonstrating the versatility of AHP in water resource management[2]. These studies collectively emphasize the significance of AHP and MCDM in evaluating and managing water stress areas efficiently.

AHP and MIF had a predictive precision of 75% and 71% respectively. The study identified groundwater potential zones in the Ponnaniyaru watershed[8]. The studies on future global water stress noticed that economic growth and population change have a stronger effect on water stress than climate change[3]. By 2050, an increased number of 1.8 billion people will reside in areas facing water stress due to factors like population growth and changes in water availability, emphasizing the need for effective water management[4]. The development of monitoring tools for assessing water stress incorporates the integration of GIS. Indicators for analyzing drought scenarios derived from data obtained through remote sensing techniques.

The literature review has inferred that most of the related work was executed at the country level. For instance, the World Resources Institute, akin to other global entities, primarily concentrates on water stress at the national level, neglecting even the sub-national or state level. Two of the key factors for water stress assessment i.e. impervious surface and population density have not been included in the analysis. Investigations regarding district-level hydric strain evaluation are limited. A comparable inquiry was executed by Subbarayan et al[15], utilizing Geographic Information Systems (GIS) in conjunction with the Fuzzy Analytical Hierarchy Process (AHP) DRASTIC framework for the assessment of groundwater vulnerability within the designated Area of Interest (AOI) that aligns with the historical confines of the Visakhapatnam district. This research incorporated antecedent groundwater level data from the year 2006, preceding the year 2013. In essence, the study employed remote sensing and GIS methodologies, focusing exclusively on six pivotal influencing factors. Most of the observed investigations pertain to minimal hypsographic variations and do not encompass intricate anthropogenic configurations in contrast to the current research location (Visakhapatnam District).

Study Area

Visakhapatnam District is one of the North Eastern Coastal districts of Andhra Pradesh and it lies between 17° - 41' and 17° -59' in northern latitude and 83° - 12' and 83° - 27' in eastern longitude. It is bounded on the North by Vizianagaram district, on the South and West by Anakapalli district, and the East by the Bay of Bengal. The geographical area of the district is 1049 Sq. KM. which is only 0.64% of the area of the State as in figure 1. This city is known as the industrial city or "city of destiny," located along the eastern coastline with rapid economic and infrastructural growth. The present population is 2,331,000 with an average increase of 2.34% per year as stated in the World Population Prospect Report 2024.

The Visakhapatnam basin is distinguished by elevations varying between 350 and 550 feet above sea level. In the area under investigation, intriguing hypsographic gradients display a variety of vegetation types impacted by industrial, anthropogenic, and naval installations.

Ground Water Scenario in the Study Area: The North coastal region of Andhra Pradesh possesses significant water resources, primarily from groundwater, which is a vital yet over-exploited common property resource. This concealed resource is readily extracted for diverse applications[13], yet its dependable supply and low development cost have fuelled over-exploitation globally[6]. In India, groundwater demand escalates due to demographic and economic pressures, concomitantly with diminishing availability.

Since the 1970 Green Revolution, groundwater irrigation in India has increased, but shallow aquifers have faced significant depletion. Data deficiencies in poorly regulated areas impede accurate evaluations of groundwater dynamics. As a result, stakeholders in over-exploited aquifer regions have adopted remedial measures such as artificial recharge and usage limitations, but these often prove ineffective due to insufficient local participation and neglect of socio-political implications[10].

The area encompasses rivulets and canals that eventually flow into the Bay of Bengal. Groundwater primarily supports the domestic requirements of rural and semi-urban populations, in addition to agricultural and industrial uses.

Material and Methods

Primary Data: Topographic data was sourced from the USGS as SRTM(DEM) and processed in ArcGIS to generate various maps. Population data from the 2011 and 2024 census was utilized to create a population density map with a five-class reclassification for overlay analysis. Impervious surface data underwent supervised classification and was subsequently reclassified into five classes for multicriteria analysis. Precipitation data was obtained from the Andhra Pradesh Water Resources Information and Management System (APWRIMS). Utilize groundwater levels act as a pivotal metric for evaluating the availability of both surface and groundwater resources. Synthesize non-spatial secondary data including District Statistical Data, construct a thorough district profile.

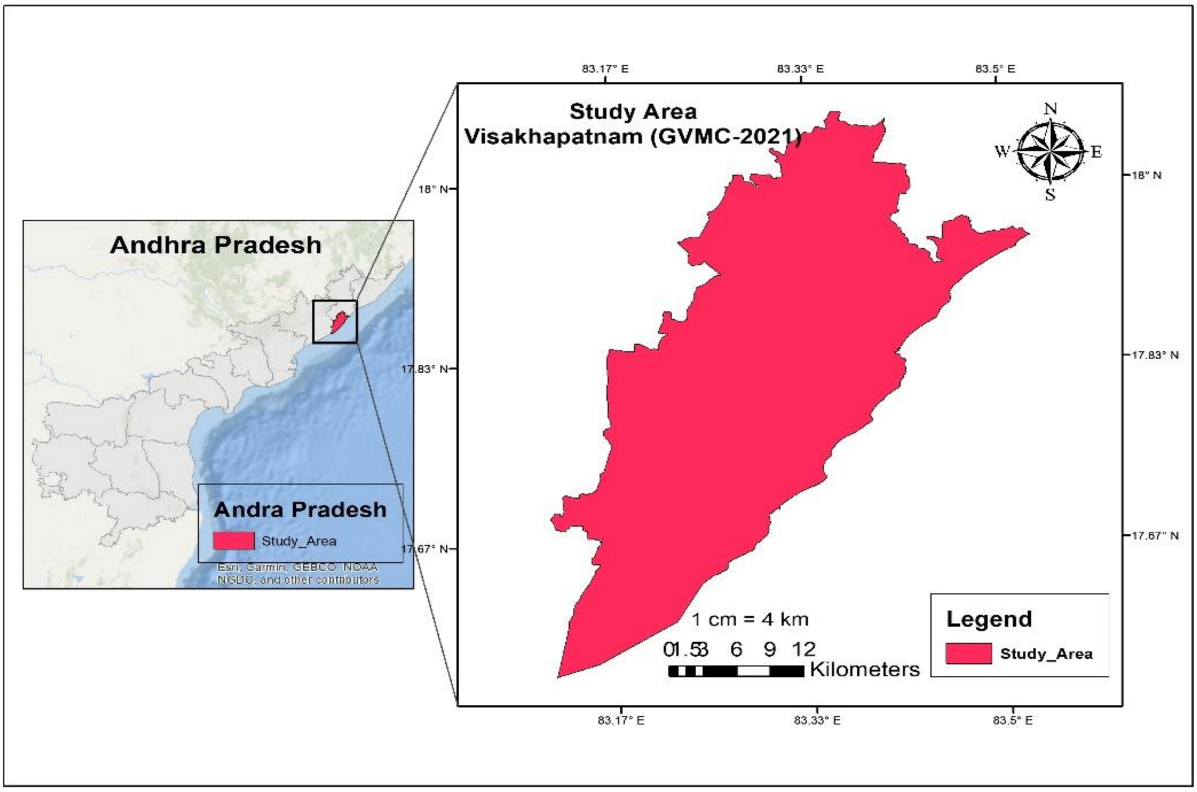

Fig. 1: Study Area, Newly Formed (2021) Visakhapatnam District

Table 1
Input data and sources

DEM	**USGS**
Rainfall	IMD
Groundwater Levels	CGWB
Population	visakhapatnam.ap.gov.in/
Demography profile	visakhapatnam.ap.gov.in/
Physiography	visakhapatnamonline.in/city-guide

This extensive analysis integrates agricultural statistics, demographic data, and physiographic characteristics. Synthesizing spatial and non-spatial data attained a more sophisticated understanding, facilitating a comprehensive assessment of water resources. Groundwater data was collected from the CGWD department of Visakhapatnam and processed using IDW based on measurements from 30 piezometric wells across the study area.

Secondary Data: Utilize groundwater Levels as a fundamental metric for evaluating the availability of both surface water and groundwater resources. Strategically situate observation wells to collect non-spatial data regarding Ground and Surface Water Draft (GVMC). Incorporate non-spatial secondary sources such as District Statistical Data, to construct a comprehensive profile of the district.

This extensive analysis integrates agricultural statistics, demographic data, and physiographic characteristics. By synthesizing both spatial and non-spatial data, a more intricate understanding is developed, facilitating a holistic assessment of water resource availability. The source of the data and the types of data utilized are enumerated in table 1.

The AHP method introduced by Saaty in 1980 is elaborated here. Groundwater potential zones are delineated through the utilization of geographical data in the analysis of water stress in the Visakhapatnam region. The Central Groundwater Board supplied secondary, non-spatial data, which is integrated with water level below-ground information for a comprehensive assessment. These data points are subsequently employed in the context of Multiple Criteria Decision Making (MCDM) and Analytic Hierarchy Process (AHP) to determine specific priority values.

AHP employs numerical inputs necessitating domain expertise to evaluate factors influencing water stress within a structured hierarchy, facilitating decision-making through the quantification of criteria and alternatives about the overarching objective. The concluding phase involves the calculation of numerical priorities for each alternative, highlighting the preferred solutions based on the aggregated values of all factors.

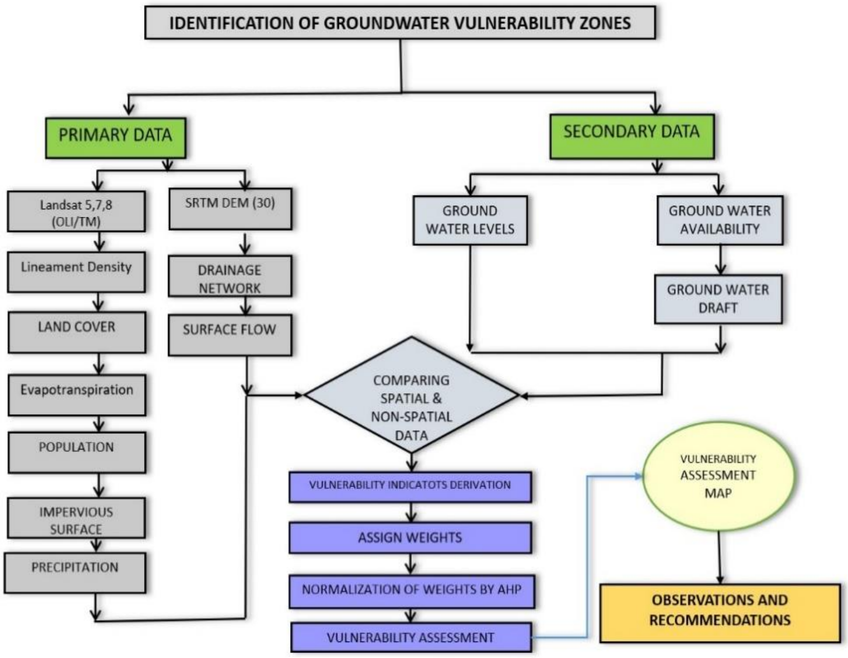

Fig. 2: Methodology chart for water vulnerability assessment in Visakhapatnam district

Figure 2 illustrates the flow of the analysis process. Water stress in the Visakhapatnam district has diverse geological conditions such as hilly terrains, areas with metamorphic rocks, asphalt surfaces, sloping grounds, and coastal regions varying due to distinct environmental and geological characteristics.

Metamorphic Rocks: The geological formations of Visakhapatnam are characterized by the presence of Khondalite, Charnokite, and sporadic dykes of Quartzites and Leptinyte rocks, which are generally associated with low porosity and permeability, thereby constraining the storage and movement of groundwater. Consequently, this phenomenon results in limited groundwater availability, rendering areas predominantly composed of these geological materials more susceptible to hydric stress during arid intervals.

Hilly Terrain: The Visakhapatnam region under investigation is characterized by multiple elevations reaching 550 feet above mean sea level and is significantly affected by precipitous inclines and swift surface runoff, which diminishes the capacity for water retention within the soil matrix. These areas frequently encounter difficulties in the replenishment of groundwater resources owing to inadequate infiltration rates and heightened erosion processes, thereby intensifying the prevailing conditions of water scarcity.

Asphalt Surfaces: The study area experiencing rapid urbanization exhibits asphalt surfaces that exacerbate hydric stress by augmenting surface runoff and diminishing infiltration. These non-permeable surfaces obstruct groundwater replenishment and may precipitate urban flooding, thereby exerting pressure on water resources during arid periods.

Sloping Ground Surfaces: Regions undergoing swift urbanization display sealed asphalt surfaces that intensify hydric stress by increasing surface runoff and reducing infiltration. These impermeable surfaces hinder the replenishment of groundwater and may lead to urban flooding, consequently placing strain on water resources during periods of aridity.

Adjacent to the Coast: Individuals residing in proximity to Pandurangapuram are experiencing the ramifications of seawater encroachment and encounter difficulties associated with saline intrusion during pre-monsoon intervals, particularly within over-exploited aquifers. The elevation of sea levels coupled with the depletion of groundwater results in the contamination of freshwater reserves with saline water, thereby exacerbating water stress in these regions.

Analytical Hierarchy Process (AHP): AHP offers a systematic framework for making necessary decisions by quantifying the criteria and alternative options and establishing their connection to the overall goal[11]. In the final phase of the process, numerical priorities are computed for each alternative option, indicating the most favoured solutions based on the collective values of all the influencing factors.

The information obtained from online sources such as USGS, Eofactory, NOVA, CGWB, and GSI is processed using ArcGIS, and other software. This process involves determining the relative significance of spatial data that influences water yield through percolation and surface runoff. Each factor is assigned a numerical value ranging from 1 to 9, facilitating the construction of a pairwise comparison matrix. Equal weighting is attributed to each factor in this assessment process. Weightages and significance factors suggested are listed in table 2.

Table 2
Weightages suggested

Weightage	Significance
1	Equal Importance
3	Moderate importance of one over the other
5	Strong or Essential Importance
7	Very strong Importance
9	Extreme Importance

Intermediate values (2, 4, 6, 8) represent gradations between two adjacent judgments. The process of constructing a normalized pairwise comparison matrix entails dividing each value within a column of the pairwise comparison matrix by the sum of that respective column. Subsequently, in the third stage, the weight assigned to each criterion or factor is determined by dividing the sum of each row in the normalized pairwise comparison matrix (Table 4) by the total number of criteria or factors under consideration.

A consistency check may be conducted utilizing the equation provided below to assess the accuracy and consistency of the comparisons made. The Consistency Index (CI) can be computed using the formula:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

where CI denotes the consistency index with n representing the number of factors subject to comparison within the matrix while λ_{Max} signifies the maximum eigenvalue of the pairwise comparison metrics. The determination of the maximum eigenvalue (λ Max) of the comparison matrix (Table 5) is achieved through the outlined procedure.

Step 1: Multiply each value in the column (from the non-normalized matrix table) by the criteria weight.

Step 2: Compute the weighted sum by adding the values in the rows.

Step 3: Calculate the ratio of each weighted sum value concerning the criteria weight.

Step 4: Average the ratios of the weighted sum values to the criteria weight.

Lastly, to evaluate the consistency of the comparison, the consistency ratio (CR) can be computed utilizing the equation:

$$CR = \frac{CI}{RI} \quad (2)$$

Factors and their influence processed through AHP are listed in the table 4. These are the critical components in the processing to achieve the final vulnerability map. Water stress analysis was performed through an assessment of 11 factors that play a crucial role in influencing the criteria utilized for making decisions in this context. The key factors that have been specifically utilized in the present study encompass Groundwater recharge, Geomorphology, Slope, Groundwater level-pre, Groundwater level-post, Land Use Land Cover (LULC), Evapotranspiration, Impervious surface, Population, Lineament Density, and Stream order.

It is essential to recognize that these factors collectively contribute to determining not only the availability of water but also its distribution and quality within a given region, thereby directly impacting the level of water stress experienced by the inhabitants living within Visakhapatnam district. By assigning a certain weightage to each factor in a 100% weight allocation scenario, it becomes possible to compare these factors effectively, to utilize methodologies like the Analytic Hierarchy Process (AHP) to facilitate a systematic and consistent approach to decision-making in the realm of water resource management.

Factors influencing Water Stress

Groundwater recharge: Groundwater recharge constitutes a fundamental element that significantly affects the depletion of groundwater resources as in figure 3. It carries a weight of 18% in relation to other influencing factors.

Table 3
Factors and their influence processed through AHP

Factors	Criteria Weights	Criteria weight (%)
Groundwater recharge	0.1761	18
Geomorphology	0.1516	15
Slope	0.1486	15
Groundwater level-pre	0.1136	10
Groundwater level-post	0.1104	12
LULC	0.0813	8
Evapotranspiration	0.0569	6
Impervious surface	0.0721	7
Population	0.0397	4
Lineament Density	0.0282	3
Stream order	0.0215	2

Geomorphology: The topographical characteristics are instrumental in modulating the hydrological cycle and may yield considerable repercussions regarding the availability of terrestrial and aquatic resources. It accounts for a relative significance of 15% in conjunction with other contributing variables.

Slope: The terrain's incline significantly affects groundwater storage through various interconnected factors.

The land surface gradient: Influences water movement and retention in soil, impacting aquifer recharge. It represents a relative significance of 15% alongside other contributing variables.

Pre and Post Monsoon groundwater levels: Groundwater levels exert a direct impact on the water demand, although they are also affected by various additional factors. This phenomenon signifies a relative importance of 11% in conjunction with other contributing variables.

LULC: It exerts a considerable influence on the storage of groundwater via numerous mechanisms, signifying a relative importance of 8%.

Population: The interconnection between population expansion and groundwater levels is vital for effective water resource management in densely populated regions. Grasping this connection is crucial for sustainable development and groundwater resource availability. The subsequent points delineate the principal factors by which population dynamics affects groundwater levels: the most recent official census data available is from 2011, and future projections utilize data from macro trends, indicating a relative significance of 4%.

Other determinants, namely evapotranspiration contributes 6%, impervious surfaces contribute 7%, lineament density contributes 3%, and stream order contributes 2%. Cumulatively, these factors amount to a total of 100%. The Analytical Hierarchy Process (AHP) methodology exclusively engages in the quantitative assessment of weightings, whereby all eleven factors are systematically reclassified according to their impact on water stress, shown in figure 4.

In the context of Analytic Hierarchy Process (AHP) and Multi-Criteria Decision Making (MCDM) analysis, the examination encompassed a total of 11 factors (n). The principal Eigen value derived from pairwise comparisons denoted as λ Max, was determined to be 11.72. Subsequent computation yielded a Consistency Ratio (CR) of 0.05, a Consistency Index (CI) of 0.07, and a Random Consistency Index (RI) for a matrix of more than 5 factors is 1.51. Following the analytical procedures, a water stress/vulnerability map was generated in figure 4 and subsequently validated through on-site verification as in figure 5. The verification process affirmed the congruence and applicability of the analysis to real-world scenarios.

Pairwise Comparison Matrix: In the Analytical Hierarchy Process (AHP), a matrix facilitates the pairwise evaluation of criteria or alternatives. Each criterion is assessed on a scale from 1 to 9, indicating varying levels of importance. The matrix's reciprocal nature ensures that if one criterion is favoured, the other is rated accordingly. This matrix enables the determination of relative criterion weights via Eigen vector methods, thereby ensuring logical consistency and furnishing a quantitative foundation for decision-making in water stress analysis. Analytic Hierarchy Process (AHP) and Multi-Criteria Decision Making (MCDM) are methodologies that exclusively operate with numerical data. Consequently, in these frameworks, the evaluation of various factors relies on quantitative assessments, devoid of any qualitative input. The process involves assigning weightages to each factor based on human intelligence, facilitating pairwise comparisons to determine the relative importance of each factor in the decision-making process.

Normalized Pairwise Comparison Matrix: Normalized pairwise comparison within the Analytic Hierarchy Process (AHP) involves the division of each element within the matrix by the total sum of its respective column, thereby achieving the standardization of the raw values. This approach ensures that the cumulative weight of all criteria sums to 1, thereby enabling a systematic and proportional assessment of the relative importance of the criteria. In a normalized pairwise comparison matrix, the evaluation of criteria is conducted through the analysis of their comparative significance. Initially, a matrix is constructed wherein each individual element represents the extent of relative importance among various criteria.

The subsequent phase consists of calculating the total for each column in the matrix, followed by the normalization process, which involves dividing each element by the total of its corresponding column. Following this, the priority vector is established by computing the average of the rows within the normalized matrix, leading to the allocation of weights to each criterion by their relative significance. This systematic methodology guarantees a consistent and comprehensive analysis of factors during the decision-making processes employed in the current investigation concerning the Visakhapatnam district.

Calculating Consistency: The calculation of consistency within the Analytic Hierarchy Process (AHP) plays a crucial role in guaranteeing the dependability and trustworthiness of the pairwise comparisons that are utilized within the realm of multi-criteria decision-making (MCDM). Specifically, the determination of the consistency ratio (CR) involves the division of the consistency index (CI) by the random index (RI). When the resulting CR value is less than 0.1, it signifies that the level of consistency is deemed acceptable. This method holds significant importance in the realm of assessing factors associated with water stress, ultimately serving as a pivotal component in facilitating the execution of precise and dependable decision-making processes.

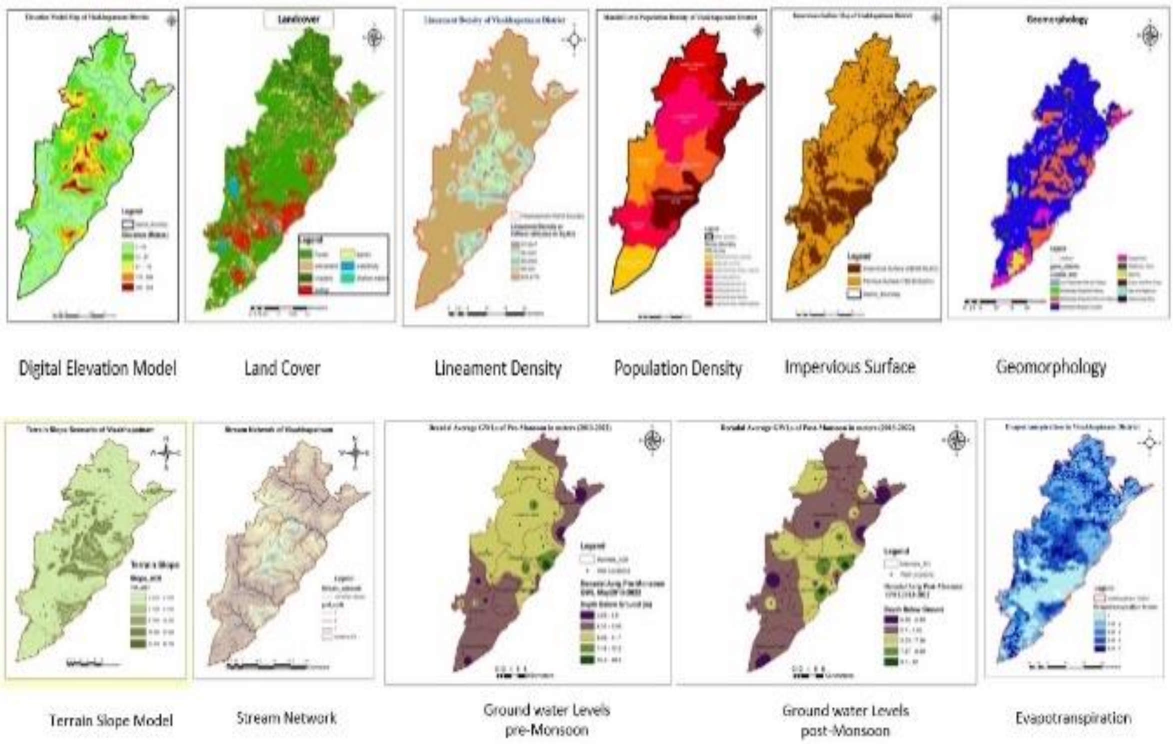

Fig. 3: Factors influencing Groundwater Availability

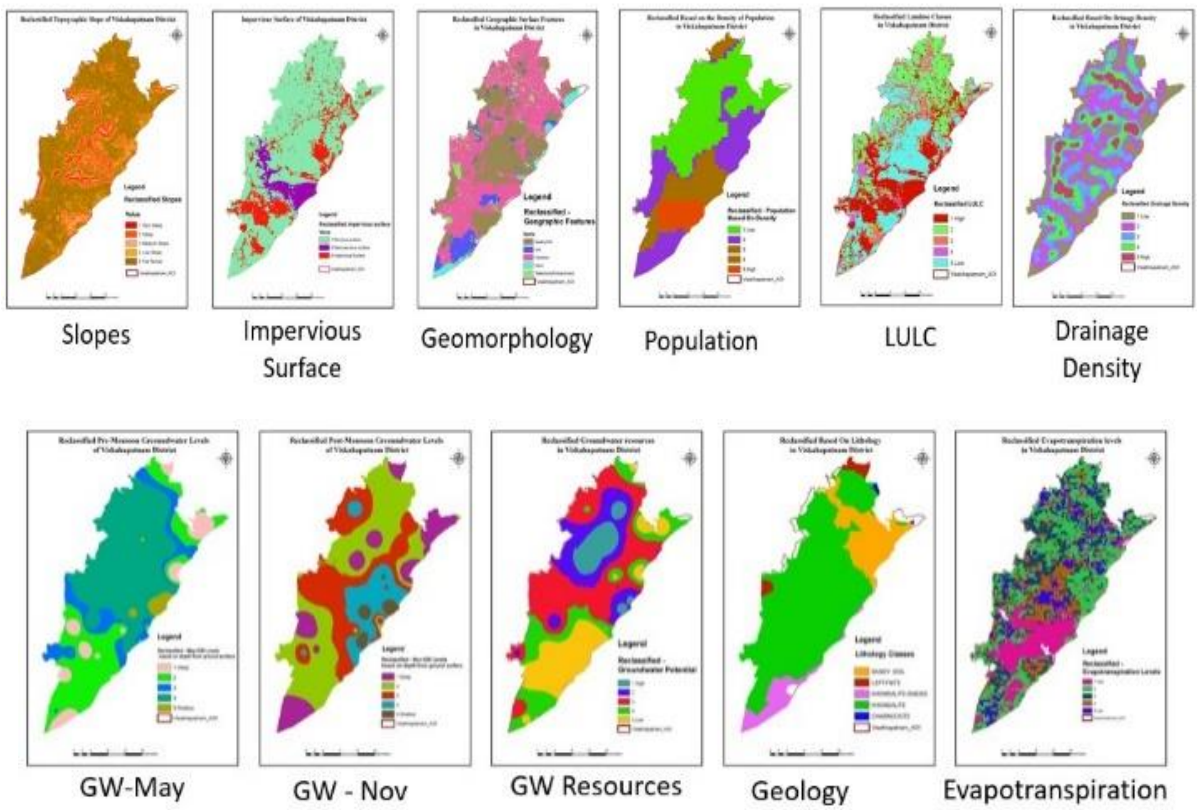

Fig. 4: Reclassified Factors influencing Groundwater Availability

Weighted Overlay Analysis for Water Vulnerability Estimation: The weights assigned to the criteria, derived from a rigorous comparative analysis of each of the 11 factors, have been normalized and computed to reflect their respective influence weights totalling 100 percent, as shown in table 6.

$$GWPI = \sum_{w=1}^{m} \sum_{j=1}^{n} (W_j \times X_i) \quad (3)$$

where Wj represents the normalized weight of the j parameter, Xi refers to the weight of the I class of the parameter, m denotes the number of the parameters and n denotes the number of classes within a specific parameter. For each grid, water stress was computed.

Results and Discussion

The present study on Visakhapatnam district highlights challenges conducting data analysis in this hilly and geologically rocky area may yield inaccurate results. While the AHP and MCDM process proved effective on a broader scale, its applicability at finer levels requires careful consideration of data suitability, especially in diverse terrains such as city environments with unique geographical characteristics like Visakhapatnam. Results from the analysis are shown in figure 5. The spatial extents of each stressed area are shown in table 8.

The recently established Visakhapatnam district encompasses an expanse of 1049 square kilometers. Merely 12.58% of this area experiences significantly high stress levels, particularly at location 4, namely Gajuwaka and Peda Gantyada region. These regions are characterized by high population densities and extensive industrial activities leading to increased water consumption. Areas under moderate to high stress constitute 36.85% of the district, primarily observed near Dwaraka nagar and the MVP colony at location 3. The sloping terrain and impervious surfaces in this area result in higher surface runoff compared to percolation. Moderate stress is prevalent in a substantial portion, accounting for 27.21% of the total area, with locations such as Madhurawada and Pothina Mallayyapalem at location 2.

The areas with low-stress levels and good water potential are situated close to Bhimunipatnam and Mamidipalem at location 1, covering 23.37% of the total district area. These locations are characterized by flat terrain and sandy soil with high permeability. Water stress assessment utilizing AHP, MCDM, and GIS is critically significant for research in various domains:

Effective Resource Management: AHP systematically addresses complex water resource challenges by evaluating diverse criteria, and enhancing decision-making in water-stressed regions.

Spatial Analysis Integration: The amalgamation of GIS with MCDM incorporates spatial analysis into decision-making, facilitating the visualization of water scarcity and guiding resource allocation.

Drought Vulnerability Mapping: AHP and GIS collaboratively evaluate drought vulnerability by examining climate, land use, and water availability, essential for sustainable management.

Environmental Sustainability: These methodologies assist policymakers in reconciling economic growth with environmental conservation, promoting efficient water usage for future sustainability.

Analyzed water-stressed locations/areas in the Study area

Location 1- Bhimunipatnam and Mamidipalem area: The spatial extent of regions classified as low water stress encompasses an area of 245.13 square kilometers, representing 23.37% of the overall expanse of 1049 square kilometers.

Table 4
Pairwise Comparison Matrix

Factors	Groundwater recharge	Geomorphology	Slope	Groundwater level-pre	Groundwater level-post	Lulc	Evopo-transpiration	Impervious surface	Population	Elevation	Stream order
Groundwater recharge	1	2	2	2	2	3	3	2	3	4	4
Geo-morphology	½	1	1	3	2	3	3	1	4	5	5
Slope	½	1	1	2	2	3	3	2	4	4	6
Groundwater level-pre	½	1/3	½	1	2	2	3	2	3	4	5
Groundwater level-post	½	½	½	½	1	2	3	3	4	4	4
LULC	1/3	1/3	1/3	½	½	1	2	2	3	4	5
Evapotranspiration	1/3	1/3	1/3	1/3	1/3	½	1	1	2	3	4
Impervious Surface	½	1	½	½	1/3	½	1	1	2	3	4
Population	1/3	¼	¼	1/3	¼	1/3	½	½	1	2	3
Elevation	¼	1/5	¼	¼	¼	¼	1/3	1/3	½	1	2
Stream order	¼	1/5	1/6	1/5	¼	1/5	¼	¼	1/3	½	1
Sum	**5.00**	**7.15**	**6.83**	**10.62**	**10.92**	**15.78**	**20.08**	**15.08**	**26.83**	**34.50**	**43.00**

Table 5
Normalized Pairwise Comparison

Factors	Groundwater Recharge	Geomorphology	Slope	Groundwater level-pre	Groundwater level-post	Lulc	Evapotranspiration	Impervious surface	Population	Elevation	Stream order	Sum	Criteria Weights	Criteria weight (%)
Groundwater Recharge	0.2000	0.2797	0.2927	0.1884	0.1832	0.1901	0.1494	0.1326	0.1118	0.1159	0.0930	1.9368	0.1761	18
Geomorphology	0.1000	0.1399	0.1463	0.2826	0.1832	0.1901	0.1494	0.0663	0.1491	0.1449	0.1163	1.6680	0.1516	15
Slope	0.1000	0.1399	0.1463	0.1884	0.1832	0.1901	0.1494	0.1326	0.1491	0.1159	0.1395	1.6344	0.1486	15
Groundwater level-pre monsoon	0.1000	0.0466	0.0732	0.0942	0.1832	0.1267	0.1494	0.1326	0.1118	0.1159	0.1163	1.2499	0.1136	11
Groundwater level-post monsoon	0.1000	0.0699	0.0732	0.0471	0.0916	0.1267	0.1494	0.1989	0.1491	0.1159	0.0930	1.2148	0.1104	11
LULC	0.0667	0.0466	0.0488	0.0471	0.0458	0.0634	0.0996	0.1326	0.1118	0.1159	0.1163	0.8945	0.0813	8
Evapotranspiration	0.0667	0.0466	0.0488	0.0314	0.0305	0.0317	0.0498	0.0663	0.0745	0.0870	0.0930	0.6263	0.0569	6
Impervious surface	0.1000	0.1399	0.0732	0.0471	0.0305	0.0317	0.0498	0.0663	0.0745	0.0870	0.0930	0.7929	0.0721	7
Population	0.0667	0.0350	0.0366	0.0314	0.0229	0.0211	0.0249	0.0331	0.0373	0.0580	0.0698	0.4367	0.0397	4
Elevation	0.0500	0.0280	0.0366	0.0235	0.0229	0.0158	0.0166	0.0221	0.0186	0.0290	0.0465	0.3097	0.0282	3
Stream order	0.0500	0.0280	0.0244	0.0188	0.0229	0.0127	0.0124	0.0166	0.0124	0.0145	0.0233	0.2360	0.0215	2
												11	1	100

Table 6
Calculating Consistency

Criteria Weights	**0.1761**	**0.1516**	**0.1486**	**0.1136**	**0.1104**	**0.0813**	**0.0569**	**0.0721**	**0.0397**	**0.0282**	**0.0215**			
Factors	Groundwater recharge	Geomorphology	Slope	Groundwater level-pre Monsoon	Groundwater level-post Monsoon	LULC	Evapotranspiration	Impervious surface	Population	Elevation	Stream order	Weighted sum value	Criteria Weight	WSV/CW
Groundwater recharge	0.1761	0.3033	0.2972	0.2273	0.2209	0.2440	0.1708	0.1442	0.1191	0.1126	0.0858	2.1011	0.1761	11.93
Geomorphology	0.0880	0.1516	0.1486	0.3409	0.2209	0.2440	0.1708	0.0721	0.1588	0.1408	0.1073	1.8437	0.1516	12.16
Slope	0.0880	0.1516	0.1486	0.2273	0.2209	0.2440	0.1708	0.1442	0.1588	0.1126	0.1287	1.7954	0.1486	12.08
Groundwater level-pre Monsoon	0.0880	0.0505	0.0743	0.1136	0.2209	0.1626	0.1708	0.1442	0.1191	0.1126	0.1073	1.3640	0.1136	12.00
Groundwater level-post Monsoon	0.0880	0.0758	0.0743	0.0568	0.1104	0.1626	0.1708	0.2163	0.1588	0.1126	0.0858	1.3123	0.1104	11.88
LULC	0.0587	0.0505	0.0495	0.0568	0.0552	0.0813	0.1139	0.1442	0.1191	0.1126	0.1073	0.9491	0.0813	11.67
Evapotranspiration	0.0587	0.0505	0.0495	0.0379	0.0368	0.0407	0.0569	0.0721	0.0794	0.0845	0.0858	0.6528	0.0569	11.47
Impervious surface	0.0880	0.1516	0.0743	0.0568	0.0368	0.0407	0.0569	0.0721	0.0794	0.0845	0.0858	0.8269	0.0721	11.47
Population	0.0587	0.0379	0.0371	0.0379	0.0276	0.0271	0.0285	0.0360	0.0397	0.0563	0.0644	0.4512	0.0397	11.37
Elevation	0.0440	0.0303	0.0371	0.0284	0.0276	0.0203	0.0190	0.0240	0.0198	0.0282	0.0429	0.3217	0.0282	11.43
Stream order	0.0440	0.0303	0.0248	0.0227	0.0276	0.0163	0.0142	0.0180	0.0132	0.0141	0.0215	0.2467	0.0215	11.50
													L.max=	11.72

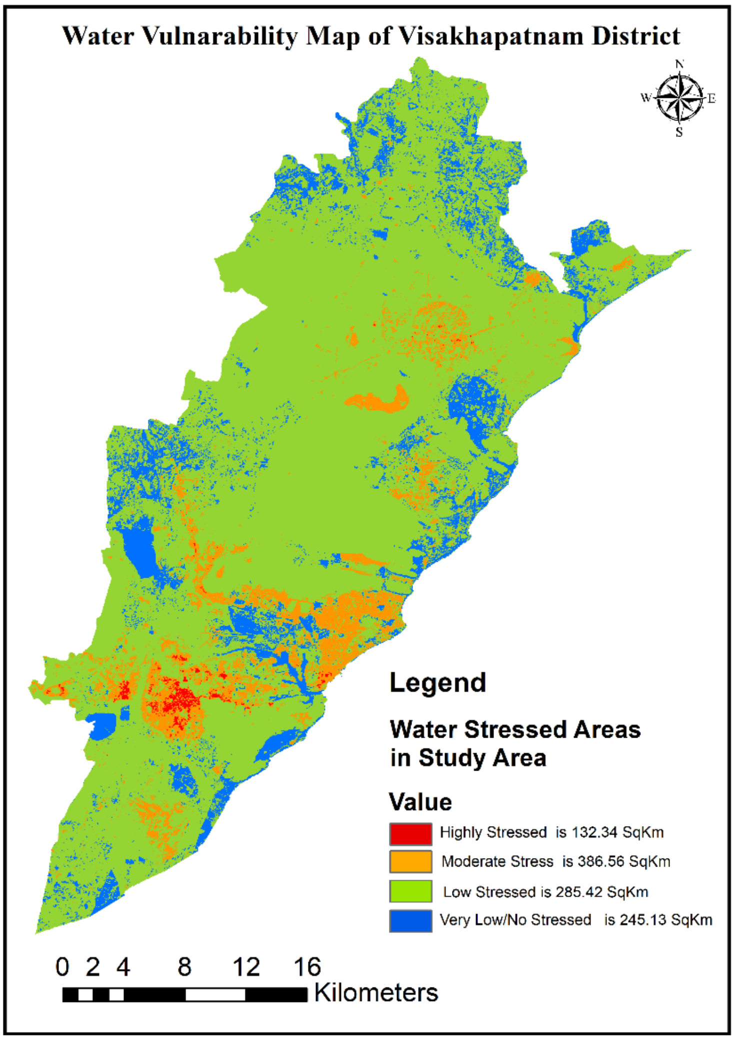

Fig. 5: Analysed water-stressed areas in Visakhapatnam

This region is characterized by a nearly horizontal and extremely gentle slope, coupled with a permeable surface that facilitates significant percolation.

Location 2 - Madhurawada and Pothina Mallayya Palem: The region characterized by low to medium water stress encompasses an area of 285.42 square kilometers, accounting for 27.21 percent of the overall geographical expanse. This zone is characterized by a relatively gentle gradient, coupled with a permeable substrate; the presence of surface runoff, along with a deficient drainage network, renders this area susceptible to water stress during the peak summer months, specifically in May and June.

Location 3 - Dwaraka Nagar, Maharanipeta, Pandurangapuram and Muvvala Vani Palem: The region characterized by moderate to high water stress encompasses an area of 386.56 square kilometers, representing 36.85 percent of the total area of 1049 square kilometers. This region is marked by a substantial population density, a moderate topographical gradient, non-permeable surfaces, significant surface runoff, and deficient drainage infrastructure, the phenomenon of saltwater intrusion, which collectively contributes to the manifestation of moderate water stress during peak periods, not only in the summer months but also throughout intervals of reduced precipitation.

Location 4- Peda Gantyada and Gajuwaka: The region characterized by significant water stress encompasses an area of 132.34 square kilometers, representing 12.58 percent of the total expanse of 1049 square kilometers. This region is composed of low-slope, impermeable aquiclude soil, which in conjunction with its proximity to heavy industrial operations, oil refineries, coal and iron ore dust from the conveyor belt causing surface water pollution, a near-surface water table that coincides with sea level, and deficient drainage infrastructure, renders it susceptible to high levels of water stress throughout the entire year.

Conclusion

In conclusion, this research proposes a significant advancement in urban water stress assessment by focusing on input selection and weighting. The refined framework ensures the inclusion of relevant and reliable criteria, capturing the specificities and complexities of individual urban environments. Additionally, it emphasizes accurate weight assignment, reflecting the true influence of each factor within the specific context. Further upgrading the inputs i.e. primary data using the data captured from the aerial platform will enhance the accuracy and quality of the results[4]. This further helps nuanced, and actionable assessments, empowering researchers, and decision-makers to develop targeted interventions and implement sustainable water management strategies.

This is crucial for mitigating the growing crisis of water stress in urban environments. SDG 6, addressing water, mandates achieving affordable and accessible water for all by 2030. Moreover, it is imperative to consider the topography and demography of the study area, ensuring a thorough understanding of the real-world scenario transformed into data for multiple criteria. The integrated GW stress map, a reverse of the potential map, can aid decision-making processes. This approach supports developing successful groundwater extraction strategies and ensuring long-term sustainability through predictive management strategies.

The amalgamation of AHP, MCDM, and GIS facilitates a holistic, multi-criteria framework for evaluating water stress, yielding enhanced accuracy and objectivity in decision-making processes through a synergistic approach to qualitative and quantitative factors. The incorporation of GIS significantly improves the spatial accuracy of water stress evaluations, allowing for the generation of detailed visual representations that pinpoint regions vulnerable to water scarcity, thus informing targeted resource management strategies.

Employing AHP and MCDM methodologies, the study proposes an advanced framework for assessing vulnerabilities by analyzing diverse factors including climate dynamics, water consumption, and land use, particularly in drought-prone areas, thereby enriching the analysis with socio-economic and environmental dimensions.

Table 8
Spatial Extent of the Water-Stressed Zones

Category	Area (sq. km)	Coverage % in Study Area
High Stress	132.34	12.58
Moderates stress	386.56	36.85
Low stress	285.42	27.21
Very Low/ No stress	245.13	23.37

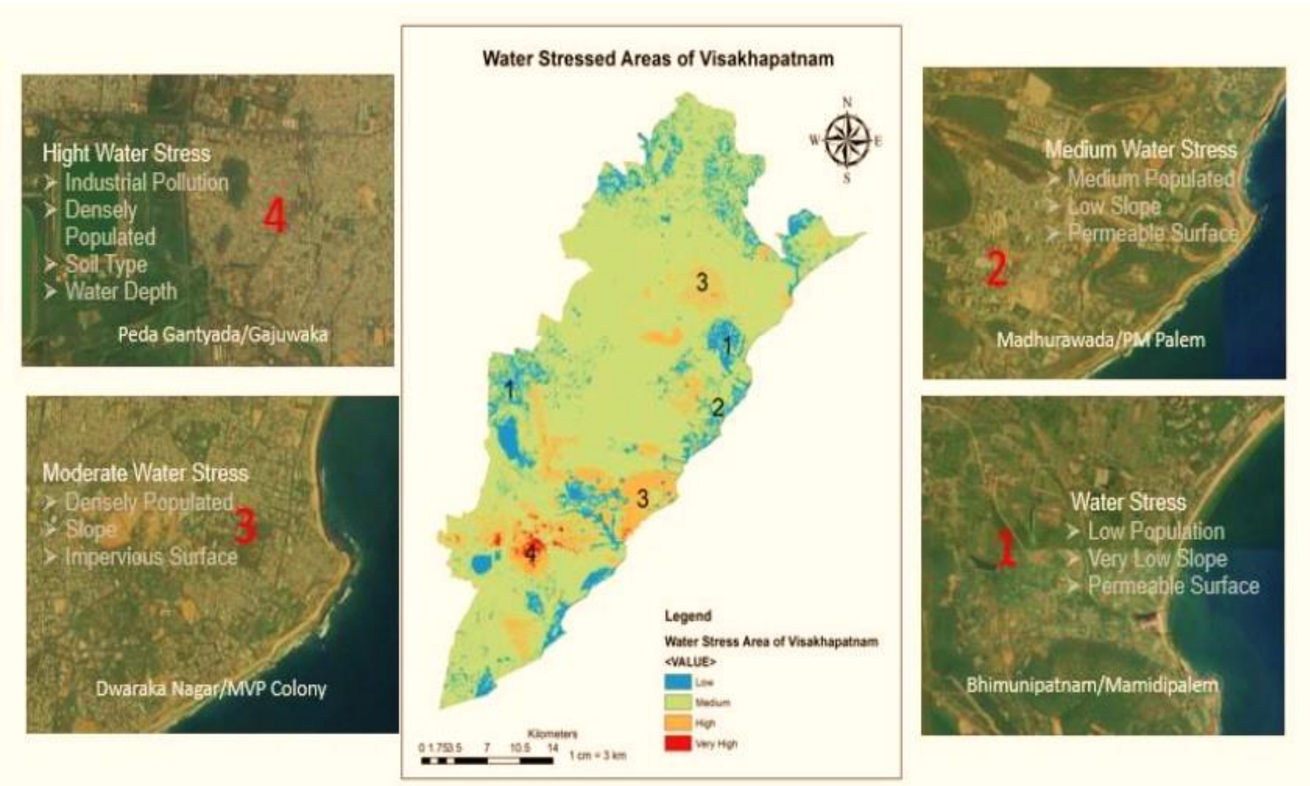

Fig. 6: Analyzed water-stressed area Distribution in Visakhapatnam Shown on Google Earth Images

References

1. Abijith D. et al, GIS-based multi-criteria analysis for identification of potential groundwater recharge zones - a case study from Ponnaniyaru watershed, Tamil Nadu, India, *Hydro Research*, **3**, 1–14 **(2020)**

2. Alkaradaghi K. et al, Geospatial Technique Integrated with MCDM Models for Selecting Potential Sites for Harvesting Rainwater in the Semi-arid Region, *Water Air Soil Pollut*., **233(8)**, Doi: 10.1007/s11270-022-05796-2 **(2022)**

3. Asadabadi M.R., Chang E. and Saberi M., Are MCDM methods useful? A critical review of Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP), *Cogent Eng*., **6(1)**, 1623153 **(2019)**

4. Bouramdane A.A., Optimal Water Management Strategies: Paving the Way for Sustainability in Smart Cities, *Smart Cities*, **6(5)**, 2849–2882 **(2023)**

5. Karanam H.K. et al, Delineation of Groundwater Potential Zones in Greater Visakhapatnam Municipal Corporation, *IJISET-International Journal of Innovative Science, Engineering & Technology*, **1(4)**, 478-492 **(2014)**

6. Kumar M. et al, A GIS-based multi-criteria approach to delineate groundwater prospect zone and its sensitivity analysis, *Appl Water Sci*., **12**, 71 **(2022)**

7. Kuzma S. et al, Using a Deep Learning Framework to Forecast Reservoir Water Availability in India, World Resources Institute, doi:10.46830/writn.21.00088 **(2023)**

8. Nagy G.J. et al, An Assessment of the Relationships between Extreme Weather Events, Vulnerability, and the Impacts on Human Wellbeing in Latin America, *International Journal of Environmental Research and Public Health*, **15**, E1802 **(2018)**

9. Negese A., Worku D., Shitaye A. and Getnet H., Potential flood-prone area identification and mapping using GIS-based multi-criteria decision-making and analytical hierarchy process in Dega Damot district, northwestern Ethiopia, *Appl Water Sci*., **12**, 255 **(2022)**

10. Rajput S. and Arora K., Analytical Study of Green Spaces and Carbon Footprints, Urban Book Series, doi:10.1007/978-3-319-47145-7_23 **(2017)**

11. Rivera Vázquez B.I. et al, Use of Analytic Hierarchy Process Method to Identify Potential Rainwater Harvesting Sites: Design and Financial Strategies in Taxco de Alarcón, Southern Mexico, *Sustainability* (Switzerland), **15(10)**, 8220 **(2023)**

12. Rubio-Aliaga A., García-Cascales M.S., Sánchez-Lozano J.M. and Molina-Garcia A., MCDM-based multidimensional approach for selecting optimal groundwater pumping systems: Design and case example, *Renew Energy*, **163**, 213-224 **(2021)**

13. Sar N., Chatterjee S. and Das Adhikari M., Integrated remote sensing and GIS-based spatial modeling through analytical hierarchy process (AHP) for water logging hazard, vulnerability, and risk assessment in Keleghai river basin, India, *Model Earth Syst Environ.*, **1(4)**, 31 **(2015)**

14. Sivakumar Babu K.V., Achuthan A. and Ahmad S., Hydrological assessment of the Gundlakamma sub-basin through SWAT modeling: land use land cover (LULC) integration and climate changes, *Journal of Water and Climate Change*, **15**, 849–867 **(2024)**

15. Subbarayan S., Thiyagarajan S., Gangolu S., Devanantham A. and Nagireddy Masthan R., Assessment of groundwater vulnerable zones using conventional and Fuzzy-AHP DRASTIC for Visakhapatnam district, India, *Ground Sustain Dev*., **24**, 101054 **(2024)**

16. Troccoli A., Effect of Climate and Geography on Worldwide Fine Resolution Economic Activity **(2018)**.

(Received 06th October 2024, accepted 15th November 2024)