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An Analysis of Stormwater Management with the Internet of Things (IoT)

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Abstract:

The study offers a compressive analysis of stormwater management durability in Chandigarh India, primarily focusing on employing the Internet of Things (IoT). Eleven key stormwater management indices were examined and their data sources and methodologies were detailed. The investigation independently evaluates the urban areas' durability, emphasizing the singular indicators' worth, and their consequences. Moreover, a consolidated comprehensive system durability indicator was computed utilizing the Analytical Hierarchy Method (AHM), offering a holistic viewpoint on stormwater administration. Chandigarh's stormwater management uses a 100% weighted approach, this 100% weighted approach allows stakeholders to make informed decisions about stormwater management sustainability, ensuring the city's water quality and effectiveness in mitigating flooding. Their findings showed a moderate overall sustainability index of 0.761, indicating challenges like waterlogging and limited drainage coverage. The outcomes provide perspectives into Chandigarh's tenacity and durability in metropolitan water administration over a decade highlighting the ever-changing character of urban growth, and the requirement for flexible resolutions.

Key Words	Stormwater Management, Internet of Things (IoT), Analytic Hierarchy Process (AHP), Urban Water Management
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1. INTRODUCTION

Stormwater control is a key element of urban design, and ecological durability as urbanization persists to expand swiftly globally. Along with it is the intricacy of overseeing stormwater drainage. Conventional stormwater management systems frequently face challenges, in managing the growing magnitude and force of storm occurrences resulting in inundation attrition and water purity concerns. Traditional stormwater management systems often struggle with issues such as overflow, pollution, and inefficient resource use. This study addresses these challenges by demonstrating the effectiveness of IoT in real-time data collection, predictive analytics, and remote control of infrastructure, leading to more efficient and cost-effective operations. This research contributes to the existing body of knowledge by providing a comprehensive analysis of how IoT can revolutionize stormwater management. The study highlights the practical implications and advantages of integrating IoT into urban water management systems by focusing on real-world applications and empirical data. Additionally, it emphasizes the need for flexible solutions to cope with the dynamic nature of urban growth and environmental challenges. To tackle these obstacles cities, and municipalities are embracing cutting-edge technologies. One of the most encouraging resolutions is the Internet of Things (IoT) (Ress et al., 2020, Ramovha et al 2024).

The World Wide Web of Things frequently mentioned as IoT is a revolutionary technology, that links everyday objects and devices to the internet enabling them to gather, and interchange data. IoT has acquired substantial momentum in diverse sectors encompassing healthcare transportation and fabrication. In the milieu of stormwater management IoT presents a groundbreaking approach to oversee regulate and enhance how urban areas manage precipitation (Sheng R. & Nawari 2016, Teshome 2020, Sharma 2008).

This examination plunges into the convergence of stormwater administration, and IoT investigating how IoT technologies are transforming the way we tackle this crucial facet of urban planning. It explores the difficulties of conventional stormwater management the advantages and possibilities of IoT in tackling these difficulties and offers practical instances of IoT implementations in stormwater management (Benzerra et al 2012, Andimuthu et al 2019). Traditional stormwater management systems face challenges like overflow pollution and lack of data leading to inefficient resource use, and environmental damage. IoT revolutionizes stormwater management by providing real-time data collection predictive analytics for better planning remote control for infrastructure and cost-efficient operations. Real-world applications show how cities leverage IoT, to enhance urban resilience sustainability, and quality of life promising a smarter eco-friendly future for urban water management (Channi et al 2022, Emama et al 2022).

Smart Urban Water Management uses modern technologies and uniform methods to make effective use of water in urban areas resources. Smart water management ensures equitable access to water, safeguards the environment, and facilitates adaptation to climate change. This facilitates sustained urban expansion. The current study evaluates various sustainability indicators for stormwater management in Chandigarh. The results indicate that Chandigarh has a relatively strong sustainability status with high scores in several indices such as EDSI, DSI, and PI. This study on stormwater management can help urban planners design more effective and sustainable systems. Sustainable Urban Drainage Systems (SUDS) mimic natural processes, improving water quality and aesthetics. Artificial Intelligence modeling tools can predict stormwater behavior and optimize system design. Understanding conduit geometry and physical parameters in karst systems can also improve stormwater management models.

The Author (Sheng & Nawari 2016) analyzed stormwater management systems in Wuhan, China, emphasizing sustainable approaches similar to those evaluated in Chandigarh. However, Wuhan's strategies focus more on green infrastructure and permeable surfaces, which might address the pooling issues identified in Chandigarh. The study done by (Swathi et al 2018) applied a stormwater management model to an urban catchment, highlighting the importance of predictive models in managing urban stormwater. The use of such models could potentially help Chandigarh better predict and manage pooling issues. The author (Teshome 2020) presented a review of urban stormwater drainage systems for flood management underscoring the importance of integrating smart technologies with traditional drainage systems. This integration could enhance Chandigarh's stormwater management by reducing water stagnation and improving overall system efficiency. The review done by (Webber et al 2022) on future perspectives of smart stormwater management suggests incorporating real-time data analytics and AI tools to optimize drainage systems. Implementing such technologies in Chandigarh could address the identified shortcomings in pooling and improve adaptive responses to varying precipitation patterns.

2. MATERIALS AND METHODS

2.1. Description of Cities

Chandigarh, located near the Shivalik Hills at 30°43′ N latitude and 76°46′ E longitude, saw its population increase from 1,055,450 in 2011 to 1,169,000 in 2021, marking a 19.65% rise. Urban drainage systems can have significant impacts on stormwater hydrology. In recent years, managing urban stormwater has become a major issue around the world. Climate change and increased urbanization have adversely impacted water flow in metropolitan areas (H. Lee & J. Romero, IPCC 2023).

Traditional solutions like installing additional stormwater pipelines would be costly and only move the flooding downstream (Broekhuizen I et al 2019).

SUDS are technological and policy interventions designed to combat diffuse pollution and manage stormwater sustainably. That's why blue-green infrastructure (BGI), which is also called nature-based solutions (NBS), best management practices (BMP), sustainable urban drainage systems (SuDS), and low-impact development (LID), is important. That's why it has become a more popular way to handle rainwater over the last few decades Moving towards smart stormwater management involves integrating advanced technologies and frameworks for better control and management of urban runoff. By focusing on these hydrological and urban characteristics, the study can provide a comprehensive understanding of the factors influencing stormwater management and potential mitigation strategies (Fletcher T. D et al 2013).

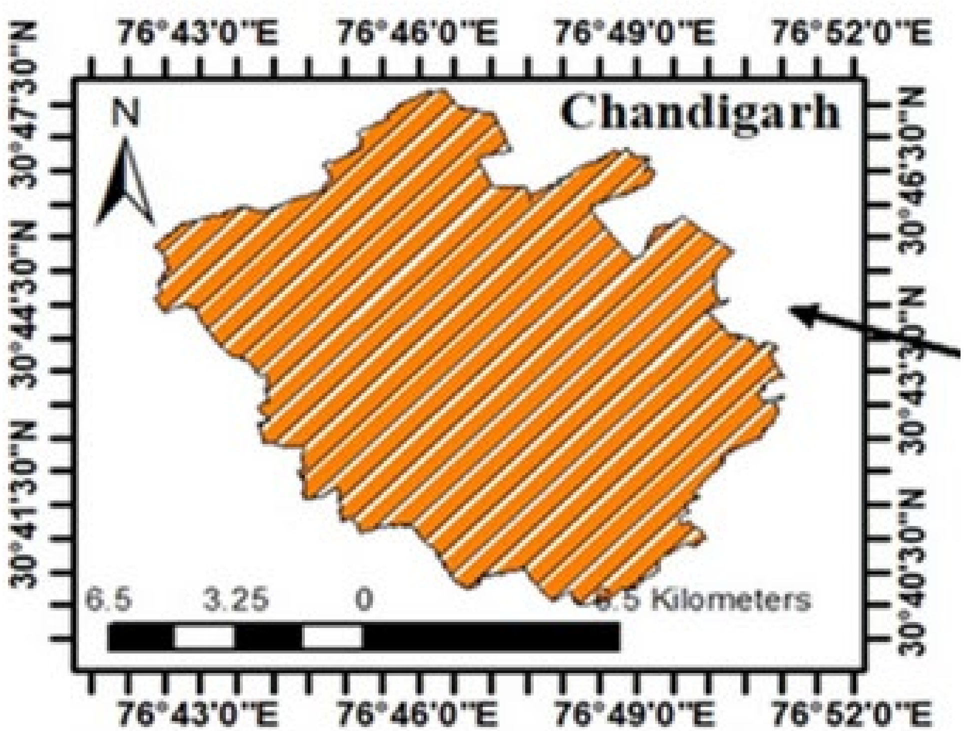

Fig. 1: Map of the study area (Chandigarh).

Chandigarh is encompassed on the northern, western, eastern, and southern sides by the states of Punjab and Haryana, correspondingly. The customary yearly precipitation is approximately 105 millimeters, and the mean temperature fluctuates between 0 to 44 degrees Celsius. Furthermore, there is intermittent snowfall in the winter due to the western disturbance. Based on the 24-hour data, Chandigarh experienced an unprecedented torrential downpour of 302.2 mm within the timeframe leading up to 8:30 a.m. on October 20, 2023.

2.2. Choice of Indicators for the Investigation

Eleven of the twenty plausible indices were contemplated for this investigation (Table 1) as they were intimately connected to our study paramount aim of executing comprehensive technical scrutiny of stormwater systems with an emphasis on their utmost pivotal components (Dos Santos et al 2017). The justifications for obliterating indicators from this investigation may be classified as follows, even though all indicators provide valuable insights into numerous interconnected facets of sustainability. a dearth of data/information, b the intricacy of enumerating all of the variables, and c a concentration on management and administration rather than technical status evaluation (Masaki et al 2014, Zafar et al 2024). The inclusionary status of indicators and the rationale for their exclusion are both displayed in Table 1.

Table 1: Catalog of diverse stormwater control measures.

“Sr. No.	Indicator	Ideal/Minimum Desirable	Definition	Included/Excluded with Reason
1	Index for Drainage Cleaning	1.0/0.65	Important drain maintenance and cleaning parameters.	Eliminated. Intricacy and data deficiency; Management of technical status evaluation
2	Index of Water Logging	0	Waterlogging occurs in four-hour-plus, six-inch-deep floods.	Incorporated
3	Vulnerability Index for Water Bodies	1.0/0.8	Current encroachment to total water body area at datum.	Incorporated
4	Index of Complainments Redressal	1.0/0.7	The ratio of effectively resolved drainage complaints to total complaints.	Excluded. Complexity/data lack; Management over technical status assessment
5	Drainage Coverage (Construct) Index	1.0/0.8	Effectively resolved drainage complaints/total complaints.	Incorporated
6	Index for the Recharge of Artificial Ground Water and Rainwater Harvesting	0.3	Relative rainfall volume stored/harvested/measured.	Eliminated. Lacking of data/information
7	Sewage Mixing Index	0	Stormwater drainage receives a percentage of sewage flows.	Eliminated. Lacking of data/information
8	Water Bodies Rejuvenation Index	1.0/0.6	Comparing planned water body rejuvenation to total water body area, including encroached areas.	Incorporated
9	System Robustness Index	<1	Storm inflow/pumping rate ratio.	Eliminated. Lacking of data/information

10	Natural Drainage System Index	1.0/0.7	The percentage of operational natural drainage systems as of a certain date.	Incorporated
11	Area Vulnerability Index	0	Area prone to floods now both inside cities	Incorporated
12	Vulnerability Index of People	0	The residents of vulnerable areas, whether they have drainage or not, are divided.	Incorporated
13	Flood Moderation Index	1.0/0.6	Moderated versus unmoderated areas prevented flooding.	Incorporated
14	Permeability Index	0.4/0.7	The percentage of the catchment that is impermeable.	Incorporated
15	Index of Master Plans	1.0/0.6	If a city lacks a basic master drainage plan, one will be created and indices included.	Eliminated. Absence of data/information
16	Tidal Index	<1.0	The city's maximum water level for current protection.	Excluded. Data and information are unavailable; there is a lack of relevance for multiple cities.
17	Meteorological Index for Rainfall	Variable	Proportion of measured rainfall intensity to flooding-causing rainfall in that region	Incorporated
18	Index for Early Warning and Readiness	1	Point-specific lead time-flow duration ratio.	Excluded. No data or information is available.
19	Stormwater Discharge Quality Index	1	Calculate the storm drain water's TSS/BOD ratio to the recommended ranges.	Incorporated
20	Index of Climate Change Stress	1.4	The ratio of a city's expected rainfall intensity to its designed rainfall intensity.	Eliminated. Challenges in enumeration complexity; Lack of data availability

2.3. Data Accessibility

Geospatial data sets taken from many sources helped to derive the necessary spatial inputs. The spatial and other data sets have these specifics:

- ArcGIS 10.4 is used to analyze Landsat 7 OLI satellite images with 1 to 7 bands.
- ArcGIS 10.4 can be used to analyse Landsat 8 OLI satellite images with 1 to 7 bands.
- A digital elevation model (DEM) with a resolution of 30 meters from the Shuttle Radar Topographic Mission (SRTM).
- Information about the population gathered from old census records.

2.4. Processing of Data

Acknowledging and delineating the principal aqueduct network: The initial phase entailed discerning and charting the indigenous watercourses within the designated study zone. The primary innate hydrological network was ascertained utilizing SRTM DEM (30 m x 30 m), and its perimeters were delineated employing ArcGIS 10.1's hydrographic chart. To evaluate the topographical attributes of the investigation area, we employed the state-of-the-art Electronic Altitude Blueprint (EAB).

2.4.1 Quantification of Drainage Profiles

By utilizing the advanced capabilities of ArcGIS 10.1's cutting-edge hydrological mapping, we successfully discerned and quantified the intricate network of conduits within the designated research vicinity, thereby effectively demarcating their extensive longitudinal profiles.

Identification and Demarcation of Aqueous-Saturated Regions

Using the 2020 Digital Elevation Model (DEM) from ASTER and Landsat 7 TM imagery, we analyzed the spatial and temporal dynamics of how individuals interact with their flood-prone environments. Maps were created in Arc GIS 10.1 to detail the region's topography, including elevation variations, gradients, watercourses, and embankment distribution. Further analysis using the GLOVIS ASTER dataset refined the DEM, and ArcGIS 10.1 along with ERDAS Imagine 9.1 was used to convert spectral data into surface brightness values. Finally, the Landsat imagery was used to classify and identify waterlogged areas within the study region.

Establishment of Delineation for the Research Domain

The DEM was precisely delineated with the aid of the cutting-edge Arc GIS 10.1 software.

Cartographic Representation of the Research Region's Terrain Features

A cartographic diagram was generated utilizing Arc GIS 10.1.

Calculation of Despondency Repositories

The customary catchment vicinity water profundity is a cutting-edge indicator of the hollow retention's magnitude, which fluctuates with land cover, innate topography, and incline. Based on extensive research, the typical profundity of despondency harbored by paved surfaces ranges from

1.0 to 3.0 mm, while it can escalate to a maximum of 7.5 mm in sylvan regions. Nevertheless, the storage capacity may be significantly amplified on level, undulating terrain and in areas with concealed drainage, such as colossal hollows. Lawns possess an impressive capacity for moisture retention, with a range of 3.0–5.0 millimeters. Linsley postulated a groundbreaking formula for the volumetric capacity (Vs) of aqueous content in permeable substrates:

$$V_s = S_d \left(1 - e^{-\frac{Pe}{S_d}}\right) \tag{1}$$

where,

V_s = depression storage per unit area, mm;

S_d = depression storage capacity, mm;

P_e = depth of precipitation in excess of interception and infiltration.

Evaporation (Pe) is considered to be zero in the model, and depression storage is taken to be at full capacity. Experiments show that on a 1% gradient, impermeable surfaces retain an average of 3 mm of water, which decreases to 1.3 mm at a 3% gradient. Natural basin storage ranges from 10-50 mm, and grassy surfaces can hold around 5 mm. The rate at which depression storage fills during storms can be further explained by...

$$V_s = e^{-\frac{Pe}{S_d}} (I - f) \tag{2}$$

where,

I = rainfall intensity, mm/h;

f = infiltration rate, mm/h."

2.5. Listing of Singular Indicators in Independent Mode

2.5.1. Natural Drainage System Indicator

Delineating the research area and identifying the natural waterways within it allowed us to calculate the index shown in Fig.2

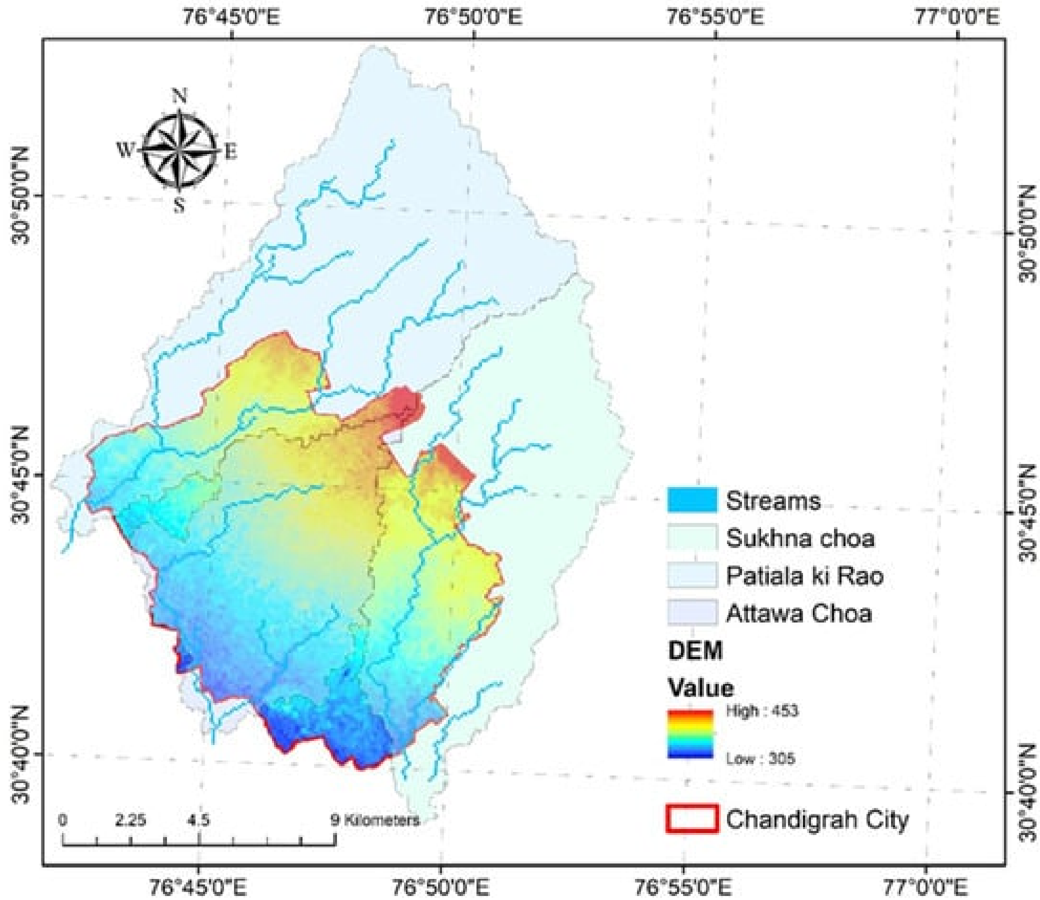

Fig. 2: Runoff diagram of Chandigarh.

2.5.2. Inclusion to Drainage Ratio

This quantifiable parameter was computed by juxtaposing the degree of affluence at a momentous juncture in chronology with the exigency for comprehensive efflux at the current juncture.

2.5.3. An Index of Penetration

The penetrable region was ascertained by amalgamating the agrarian and blossoming zones and deducting the metropolitan and desolate zones. Land utilization and land envelopment diagrams of the exploration domains are exhibited.

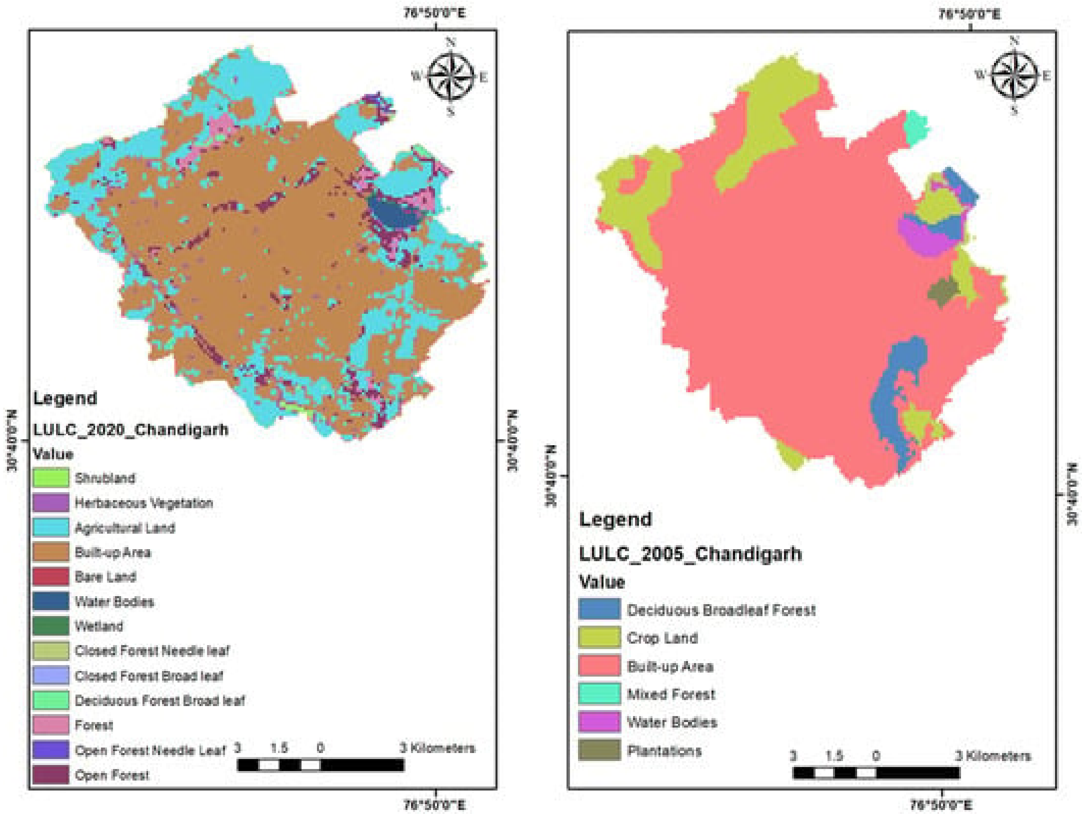

Fig. 3: LULC map of Chandigarh.

2.5.4. Rejuvenation of Water Bodies Index

The necessity for rejuvenation of an aqueous entity may be assessed utilizing the Aquatic Organism Revitalization Indicator. It was meticulously calculated by juxtaposing the entirety of aquatic formations at a historical baseline with the current state, precisely identifying encroached regions, and subsequently approximating the overall expanse necessitating restoration.

2.5.5. Wetness Measurement Index

Waterlogged areas were pinpointed using Indian Meteorological Department rainfall data, with the benchmark being areas inundated for over four hours and a water depth of over 6 inches. The study suggests reducing this time to one hour to improve effectiveness, based on past events in cities like Delhi, Mumbai, and Chennai, aiming to build cities with disaster resilience in mind from the start.

2.5.6. Area Vulnerability Index

The Region Susceptibility Indicator provides a detailed evaluation of a city's flood risk by analyzing elevation data, topography, and surface characteristics (Kourtis & Tsihrintzis 2021, Lashford et al 2020, Gimenez-Maranges et al 2020, Zahmatkesh et al 2015, Peterson &Wicks

2006). Through formulas, the study calculated potential flood basins within urban areas, estimating each basin's capacity based on average water depth. The total area at risk of flooding was determined by summing up these basins. Finally, the indicator was obtained by comparing the flood-prone area to the total urban area, offering a measure of the city's vulnerability to flooding.

2.5.7. Water Body Vulnerability Index

The Aquatic Entity Vulnerability Metric was computed utilizing an iterative methodology Acquiring a LULC (Land Utilization and Terrain Coverage), cartography of the exploration vicinity was the inaugural measure. This cartographic representation greatly assisted us in discerning the specific land cover that corresponded harmoniously, with the aqueous characteristics. ArcGIS 10.1 was employed to compute the aggregate expanse beneath the encroaching hydrophilic organisms, by amalgamating the dimensions of all pixels that are categorized as hydrophilic organisms at the current moment. Simultaneously the aggregate expanse engulfed by aqueous characteristics on the designated date was computed by amalgamating the dimensions of every pixel denoted as water features during said period.

2.5.8. People Vulnerability Index

This quantitative measure was computed utilizing data from the Census of India, and other sources elucidating the demographics of metropolitan regions, by industry sector. The approach entailed discerning, and tallying the populace inhabiting perilous regions proximate to aqueous reservoirs (such as rivers or streams), that could potentially be engulfed amidst inclement climatic conditions. Upon gathering this valuable data, diligent researchers employed it to ascertain the precise proportion of the entire populace residing, within these flood-prone regions whether equipped with sufficient drainage systems or not that fell victim to the calamity.

2.5.9. Stormwater Discharge Quality Index

In the nonexistence of guidelines for the excellence of metropolitan surface runoff, information on overall suspended solids (TSS) and biochemical oxygen demand (BOD) were collected from recent scientific publications and suggested thresholds were established under standards for releasing treated effluent into surface water (30 mg/L for TSS and 20 mg/L for BOD). Although certain TSS thresholds may be quite stringent owing to the accumulation of loosened surface soil and dispersed substances by the runoff, the directory furnishes an assessment of adherence to TSS/BOD guidelines. Nevertheless, the compendium accentuates regions that might necessitate enhanced stormwater governance and filtration techniques in the forthcoming years.

2.5.10. Flood Moderation Index

The primary stage in computing this measurement (Webber et al. 2016) was identifying areas near aquatic characteristics that are exceedingly susceptible to inundation owing to an insufficiency of flood-mitigation measures such as dikes, reservoirs, or canal systems. Regional governmental archives may potentially offer valuable perspectives into flood-vulnerable regions and may serve as the foundation for this type of evaluation (Cuppens et al 2013, Singh et al 2012, Jones & Macdonald 2007, Swathi et al 2018, Sirishantha, Rathnayake 2017). Following that, regions that were spared from inundation or experienced diminished inundation as a consequence of the executed mitigation strategies were ascertained (De Almeida et al 2018). The Flood Moderation Index offers a comprehensive depiction of the effectiveness of flood prevention endeavors by quantifying the proportion of the area that remained unharmed as a result of moderation initiatives in the vicinity that would have otherwise been submerged without such interventions (Droogers et al 2010, Census of India 2011, Roy et al 2023).

2.5.11. Rainfall Intensity Index

Intensity-Duration-Frequency (IDF) diagrams were employed to augment the correlation amidst precipitation patterns utilized in catchment hydrology examination. These undulations were crafted across diverse temporal spans employing frequency analysis of information on yearly zenith rainfall. This investigation endeavored to fabricate IDF curves for the ensuing return periods: 5, 10, 25, 50, and 100 years. These curvatures were formulated utilizing diurnal precipitation data from both antiquated and projected climatic scenarios. Utilizing IMD's empirical reduction methodology, hourly precipitation data were derived from the daily records.

By employing the continuity equation and logical methodology, an approximation of the precipitation volume that instigated the inundation within the storm drain system was computed. Based on the historical archives for Chandigarh, Table 2 exhibits the precipitation magnitude (mm/h) for diverse storm recurrence periods. "

Table 2: Chandigarh's rainfall intensity, duration, and frequency analysis.

Return Period	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)
	20 min	40 min	60 min	80 min	100 min	120min
5 yr	115	95	75	65	45	35
10 yr	120	100	90	80	55	40
25 yr	160	120	110	90	65	50
50 yr	170	135	115	105	75	55
100 yr	195	155	135	115	80	60

2.6. Analytical Hierarchy Process (AHP): Concept and Function in the Research Aiming at Weight Coefficient Estimation

The Analytical Hierarchy Process (AHP) is a widely used technique for multi-criteria decision-making. It has been applied in various fields such as budget-conscious stormwater management, alternative energy selection, air pollution analysis, urban water systems evaluation, surface water quality, and wastewater treatment analysis. While AHP is known for its flexibility and intuitive approach, it is not without drawbacks, including its reliance on subjective judgments and the need for numerous pairwise comparisons.

Equation (3) illustrates the comprehensive assessment lattice diagram as well as the lattice portrayed with magnitude coefficients.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_2n & \cdots & 1 \end{bmatrix} \begin{bmatrix} w1/w1 & w1/w2 & \cdots & w1/wn \\ w2/w1 & w2/w2 & \cdots & w2/wn \\ \vdots & \vdots & \ddots & \vdots \\ wn/w1 & wn/w2 & \cdots & wn/wn \end{bmatrix} \quad (3)$$

The subsequent measure is to compute the magnitudes for every constituent, indicator, and facet once the verdict grid A has been formulated, where aij represents the assessments between elements i and j for all i, j 1, 2,… n. Subsequently, it is imperative to authenticate the coherence of the acquired outcomes.

$$CR = \frac{CI}{RI} \quad (4)$$

The coherence coefficient (CC), ascertained utilizing Formula (5), can be utilized to compute the arbitrary coefficient (AC), which is derived from the average of the coherence coefficient (CC) that is generated and depends on the configuration of the matrix provided by Saaty.

$$CI = \frac{\lambda max - n}{n - 1} \quad (5)$$

The utmost eigenvalue is indicated by the foremost eigenvalue, maximum, and the tally of rows or columns in the square assessment matrix is denoted by n. The matrix consistency is evaluated to be satisfactory if the coherence ratio (CR) is less than or equal to 0.1. Nevertheless, if the CR surpasses 0.1, it implies that the evaluations might necessitate fine-tuning to mitigate disparities.

2.7 Aggregation of Indices Process

The comprehensive gauge of system sustainability was computed utilizing a weighted linear summation of eleven distinct metrics, as articulated in the subsequent equation.

$$SSIa = \sum_{i=1}^{n} w_i I_i \quad (6)$$

3. RESULTS AND DISCUSSIONS

The results and discussion are displayed in the two subsequent sections, highlighting comprehension of enumerated indicators in the autonomous mode and in the amalgamated mode, respectively.

3.1. Sustainability Indices in a Standalone Mode

Table 3 exhibits the outcomes of the solitary stormwater drainage indicators computed for Chandigarh. For every indicator, the specified values must be examined against their corresponding optimal condition and minimal desired intervals. These furnish significant perspectives on the condition of stormwater governance and urban adaptability in these regions. Disparities in indicator values manifest the diverse ramifications of urbanization, hydrological variables, and the extent to which cities are equipped to handle precipitation.

Table 3: Calculated sustainability indices for study sites.

S.N	Cities	NDSI	DCI	PI	WBRI	WLI	AVI	WBVI	PVI	SWDQI	FMI	RII
Ideal/Mini. Desirable Condition		1.0/.7	1/.7	.3/.7	1.0/.8	0	0	1.0/.6	0	1	1/.7	Variable
1.	Chandigarh	0.86	0.76	0.43	0.82	0.12	0.1	0.82	0.1	0.56	0.84	0.64”

Table 3 presents a detailed comparison of sustainability indicators across study sites, highlighting Chandigarh's stormwater management performance. It lists various indices, such as Ecological Drainage, Drainage State, Pooling, and Aquifer Susceptibility, among others, and compares them to ideal and minimum desired states. Chandigarh's scores, such as 0.86 on the EDSI and 0.76 on the DSI, are relatively high, indicating a strong sustainability status. However, a higher Pooling Index score of 0.43 compared to the ideal 0.3 suggests potential issues with water stagnation. This comprehensive analysis provides insight into the effectiveness and areas for improvement in the city’s stormwater management practices. Certain indicators performed better or worse because of the strong ecological drainage state, reflecting effective natural water flow and minimal ecological disruption. Some suggest that the city's drainage systems are functioning well but could still benefit from improvements to reach optimal performance. Some suggest that certain areas may be prone to pooling, which can lead to problems such as mosquito breeding and waterborne diseases.

The Internet of Things (IoT) can play a significant role in addressing the issues highlighted by these indicators by providing real-time data on water levels, flow rates, and precipitation, enabling more responsive and adaptive management of stormwater systems. By using predictive analytics, IoT systems can forecast potential pooling events and allow for pre-emptive measures to be taken, reducing the likelihood of water stagnation and associated issues. IoT enables remote control of stormwater infrastructure, such as automated gates and pumps, which can be adjusted based on real-time data to optimize drainage and prevent pooling. The integration of IoT in stormwater management can lead to more efficient use of resources and cost savings by reducing the need for manual monitoring and intervention. By leveraging IoT technologies, cities like Chandigarh can improve their stormwater management systems, addressing the specific issues indicated by performance metrics and enhancing overall urban water resilience.

Recent stormwater management studies can help urban planners develop more efficient and sustainable systems. IoT can improve stormwater management systems efficiency and efficacy. IoT allows real-time data collecting, predictive analytics, and remote infrastructure control, which can help predict and mitigate excessive rains and flooding. Sustainable Urban Drainage Systems (SUDS) replicate natural processes to manage stormwater holistically. These systems reduce runoff, improve water quality, and beautify and entertain cities. AI modelling can anticipate stormwater behavior and optimize stormwater system design and operation. These tools improve water quality and decrease flooding by delivering precise and timely decision-making information. Understanding conduit shape and physical factors in karst environments can improve stormwater management models. Complex subterranean drainage systems require this understanding. Urban planners may design stormwater systems that are more resilient to harsh weather and improve urban sustainability and livability by using these tactics.

3.2. Aggregated Overall System Sustainability Index

The input parameters utilized to ascertain the relative significance of diverse stormwater drainage indicators differed among municipalities. Carefully chosen for their pertinence to stormwater management, these parameters encompassed elevation, slope, precipitation, land use/land cover, stream and streamflow density, NDVI, TSS, and BOD measurements. The Analytical Hierarchy Process (AHP) methodology, as elaborated in Section 2.5, offered a systematic approach to allocating importance to the indicators through paired evaluations and mathematical calculations. For every municipality, Table 4 exhibits the magnitude values allocated to diverse stormwater drainage indicators. The Homogeneity Quotient (HQ) was computed to assess the consistency of the findings. If the CR is less than or equal to 0.1, the matrix is sufficiently homogeneous, whereas a value exceeding 0.1 implies that modifications are necessary to diminish disparities. A congruity proportion of lesser than or equivalent to 0.1 was necessitated as the sole criterion for ascertaining the weightage magnitudes in every urban matrix.

“

Table 4: Priority ranking for technology selection based on criteria for Chandigarh.

Indicators	Class	Sustainability Class Ranges and Ratings	Sustainability Class Ratings	Weight %
Natural Drainage System Index	0.7–1	Very High	4	16
	0.7–0.78	High	3	
	0.5–0.49	Moderate	2	
	0.3–0.48	Low	1	
	0–0.18	Very low	1	
Drainage Coverage Index	0.7–2	Very High	4	16
	0.5–0.88	High	3	
	0.3–0.48	Moderate	2	
	0.1–0.8	Low	1	
	0–0.18	Very low	1	
Permeability Index	0–0.17	Very High	4	12
	0.3–0.28	High	3	
	0.3–0.58	Moderate	2	
	0.7–0.89	Low	1	
	0.9–1	Very low	1	
Water Body Rejuvenation Index	0.9–1	Very High	4	12
	0.5–0.89	High	3	
	0.5–0.68	Moderate	2	
	0.3–0.48	Low	3	
	0–0.18	Very low	1	
Water Logging Index	0–0.18	Very High	4	6
	0.2–0.48	High	3	
	0.3–0.68	Moderate	2	
	0.7–0.78	Low	3	
	0.9–1	Very low	1	
Area Vulnerability Index	0–0.18	Very High	4	2
	0.1–0.29	High	3	
	0.3–0.68	Moderate	2	
	0.5-0.89	Low	1	
	0.5–1	Very low	1	
People Vulnerability Index	0–0.19	Very High	4	2
	0.2–0.29	High	3	
	0.3–0.89	Moderate	2	
	0.5–0.78	Low	1	
	0.8–1	Very low	1	
Stormwater Discharge Quality Index	0.8–1	Very High	4	9
	0.6–0.79	High	3	
	0.4–0.49	Moderate	2	
	0.2–0.49	Low	1	
	0–0.18	Very low	1	
Rainfall Intensity Index	0.7–1	Very High	4	11
	0.5–0.68	High	3	
	0.5–0.48	Moderate	2	
	0.2–0.29	Low	1	

	0–0.18	Very low	1	
Water Body Vulnerability Index	0.7–1	Very High	4	11
	0.5–0.68	High	5	
	0.5–0.48	Moderate	2	
	0.1–0.38	Low	3	
	0–0.18	Very low	1	
Flood Moderation Index	0.7–1	Very High	4	6
	0.5–0.68	High	5	
	0.3–0.48	Moderate	2	
	0.2–0.28	Low	3	
	0–0.18	Very low	1	
			Total	100”

Table 4 outlines a method to prioritize technology choices for Chandigarh's stormwater management using sustainability indicators across various categories, each weighted by importance. Key indicators include the Organic Drainage System Index (15% weight) assessing natural drainage effectiveness, the Drainage Coverage Index (17%) for infrastructure extent, and the Percolation Quotient (11%) for ground absorption capabilities. The Aquatic Rejuvenation Metric (13%) and Aquatic Inundation Metric (5%) gauge water body recovery and flooding issues, respectively. Additionally, the susceptibility of the area and population to water-related issues is covered by the Region and Individuals Susceptibility Indexes (1% each), while the Stormwater Emission Excellence Indicator (8%) evaluates stormwater quality. Precipitation Intensity (12%) and Aquatic System Susceptibility Index (12%) measure weather severity and water system fragility, and the Deluge Moderation Index (5%) considers flood mitigation effectiveness. This comprehensive weighting system, totaling 100%, helps stakeholders make informed decisions for enhancing the city’s stormwater management sustainability.

“Table 5: Aggregated overall sustainability indicators.

Sr. No.		Chandigarh		
	Indices	Ii	Wi	Ii Wi
1	NDSI	0.86	0.15	0.129
2	DCI	0.26	0.17	0.044
3	PI	0.53	0.11	0.057
4	WBRI	0.82	0.13	0.107
5	WLI	0.32	0.05	0.076
6	AVI	0.58	0.01	0.058
7	WBVI	0.82	0.01	0.028
8	PVI	0.6	0.08	0.048
9	SWDQI	0.56	0.12	0.067
10	FMI	0.84	0.12	0.101
11	RII	0.74	0.05	0.042
12	OSSI			0.761”

Table 5 combines various sustainability indicators to measure Chandigarh's stormwater management performance. Each indicator is given a weight reflecting its importance, and the overall score is the sum of each indicator's value multiplied by its weight. For instance, the Ecological Drainage System Indicator (EDSI) with a weight of 0.15 has a weighted score of 0.129, while the Drainage Inclusion Indicator (DII) with a higher weight of 0.17 scores 0.044. After evaluating all indicators, including the Percolation Quotient, Aquatic Habitat Restoration, and Hydrological Saturation, the resulting Comprehensive Sustainability Indicator (CSI) totals 0.761. This metric synthesizes Chandigarh's approach to sustainable stormwater management and helps identify strengths and areas for improvement.

4. CONCLUSIONS

Ecological Drainage, Drainage State, Pooling, and Aquifer Susceptibility were used to evaluate Chandigarh's stormwater management. EDSI scores of 0.86 and DSI values of 0.76 indicated high sustainability. Water stagnation may occur with a higher Pooling Index score. The study also prioritised stormwater drainage indicators using the Analytical Hierarchy Process (AHP). The Organic Drainage System Index, Drainage Coverage Index, Percolation Quotient, Aquatic Rejuvenation Metric, Region and individual susceptibility Indexes, Stormwater Emission Excellence Indicator, Precipitation Intensity, Aquatic System Susceptibility Index, and Deluge Moderation Index scored high for technology selection in Chandigarh. The Comprehensive Sustainability Indicator (CSI) determines Chandigarh's stormwater management strengths and weaknesses using multiple sustainability metrics. The Comprehensive Sustainability Indicator (CSI) evaluates Chandigarh's sustainable stormwater management and identifies strengths and weaknesses. This comprehensive research illuminates the city's stormwater management efficacy and areas for improvement. The findings offer valuable insights for urban planners and policymakers aiming to advance sustainable stormwater infrastructures in Chandigarh and cities with similar challenges.

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