Eco. Env. & Cons. 27 (February Suppl. Issue) : 2021; pp. (S198-S204)

ISSN 0971–765X

Fuzzy - Augmented Geospatial Stormwater Suitability modeling for Chennai City of India

Stalin Subbiah, Parthiban P., Mahesh R. and Das A.*

Centre for Environmental Engineering, PRIST Deemed to be University, Thanjavur 613 403 Tamilnadu, India

(Received 6 January, 2020; Accepted 3 September, 2020)

ABSTRACT

Over the years, with spatio-temporal fluctuation in monsoonal precipitation, supported by rapid changes in landuse pattern, has created severe water-stress, especially in major urban cities of India, including Chennai. Under such changing scenario, proper delineation of stormwater regimes play a very vital role in designing an effective water management plan. With this view the present research work has been carried, with regard to Chennai city of India, by utilizing the thematic geospatial database, with integrated Fuzzy-based expert system, so as to demarcate the litho-climatic zones suitable for surface harvesting of stormwater. The geospatial analysis carried out in this work involves base map-preparation, with soil, precipitation, landcover, drainage, slope and road-layers. The specific set of attributes catering to different regions of the study area were evaluated with regard to stormwater suitability index, obtained by fuzzy inference system (FIS) using MATLAB, employing triangular membership functions, domain/expert based rule-set and weightages based on UC Davis Extension Fuzzy approach. The study reveals distinct delineation of storm water suitability zonation, ranging from very high (33.09 %) to high (25.70 %) to medium (24.46 %) to low (11.53 %) to exceptionally low (5.20%). The present geospatial approach, fuzzy-expert-system and specific weightages are easily replicable for other regions, as well, with suitable calibration.

Key words : *Stormwater suitability zonation, Fuzzy inference system (FIS), Geographic inference system (GIS)*

Introduction

Storm water essentially refers to the runoff generated from small upland/headwater watershed draining to ditch, stream or storm sewer, where base flow component does not form a significant proportion of total flow in the open channel during rainfall, which is actually the case in most of the urban areas, because of high degree of perviousness (Overton, Donald *et al.*, 1976); (Ragan, 1968) and (Betson, 1964). Hence, typical stormwater modeling involves prediction of watershed storm water discharge as a result of rainfall, with due consideration to landuse pattern (Dooge, 1973). Some of the standard stormwater modeling, especially parametric modeling, have been reported by Tennessee Valley Authority (TVA), because of the rich hydrological database available and these models are being utilized widely for regionalized landuse studies. (Tennessee Valley Authority, 1972) and (Tennessee Valley Authority, 1973). The various models conventionally used for stormwater modeling, apart from TVA model, are Stanford model, USGS model (esp. parametric models) and EPA models (esp. deterministic models) representing transport mechanism between runoff source to basin outlet. (Chen, *et al.*, 1971); (Dawdy, *et al.*, 1965); (Green, 1970); (Linsley, *et al.*, 1960) and (Linsley, 1971). Since the stormwater models are essentially meant for urban hydrology, its sensitivity to infiltration estimates plays a crucial role, and in relation to it, other related metero-hydrological variants as well, often utilizing GIS-platform (Papadakis *et al.,* 1973); (Rossman Lewis, 2006); (Seth *et al*., 2006); (Huber *et al.,* 1988); (Viavattene *et al*., 2008) and (Kumar *et al*., 2008). However, Fuzzy systems, introduced by Zadeh has been one of the most efficient systems especially dealing with uncertainties, associated with discrete systems () (Mosase *et al*., 2017) and (Ghosh Sasanka *et al*., 2019). Subsequently, usage of fuzzy-based geospatial modeling have been in vogue to capture parametric uncertainty, aimed at infrastructure development, flood management, agriculture, risk assessment and habitation (Yazdi *et al*., 2014); (Lyu *et al*., 2019); (Shariat *et al*., 2019) and (Seo Jin Ki *et al*., 2014). However, in the fuzzy-based GIS modeling of stormwater as carried out by most of the researchers are essentially parametric fuzzification integrated with conventional geospatial analysis, without much scope on optimization fuzzy-inference scheme. To counteract this limitation, the present research work involves development of a distinct fuzzy-based expert system with due choice of the specific membership function and domain-based rule base, with due weightage derived from established historical database. The specific stormwater-suitability scores for hydro-lithological signatures of the study area, as derived from the fuzzy-based expert system, is being utilized herewith for delineating the various storm-water regimes.

Study Area

Chennai city is one of the Capital of coastal city in the Tamil Nadu. It is located at (12°58'35.113''N to 13°9'17.858''N and 80°14'2.141.''E to 80°18'39.255''E), the total area of the municipality zone is 293.41 square kilometers (flanked by Royapuram town, Chennai town, Egmore town, Mylapore and Thiruvanmiyur town) with MSL 20 meters above the seawith northern and eastern zone rendered deltaic by dint of Adyar River, and its wide system of branches, inundated by the river of the Kuvam River. (Figure 1) shows the Chennai city along the East coast of Tamil Nadu. Study area along the coastal stretch extends about 1,076 kmto the south of Chennai town is the largest port in Tamilnadu. The study area falls under the Survey of India toposheets 66C/8 and 66D/1 & 5. This stretch consisting of a narrow region of world second largest sandy beach along the coast in the delta region of Adyar River.

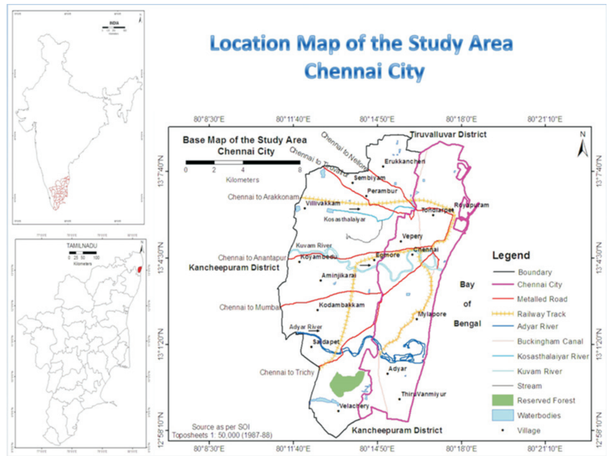

Fig. 1. Location map of the study area

Climate and Rainfall

Chennai city receives rain under the influence of both southwest and northeast monsoons. Most of the precipitation occurs in the form of cyclonic storms caused due to the depressions in Bay of Bengal chiefly during Northeast monsoon period. Chennai city received an average annual rainfall of 757.6 mm (2018) of which the northeast monsoon contributes a greater percentage than the southwest monsoon. The area receives maximum rainfall during the month of October (1470 mm). The region enjoys a humid and tropical climate. The average temperature of the district in 2018 was about 34.4 °C and the minimum temperature is 26.3 °C. Dust storms whirl winds and dusty winds blow from various quarters towards the end of May. The Southwest winds sets during April, it is strongest in June and continues till September. Northeast monsoon starts during the month of October and extends till January. Cyclonic storm with varying wind velocity affects once in 3 or 4 years during the month of November-December. During Southwest monsoon the air is calm and undisturbed.

Materials and Methods

The outline of the strategy used in the present research work is presented in Fig. 2, the basic three components of which are presented below.

Preparation of Base map of the Study Area

For base map preparation using ArcGIS 10.3, the following database were used (with geo-referencing

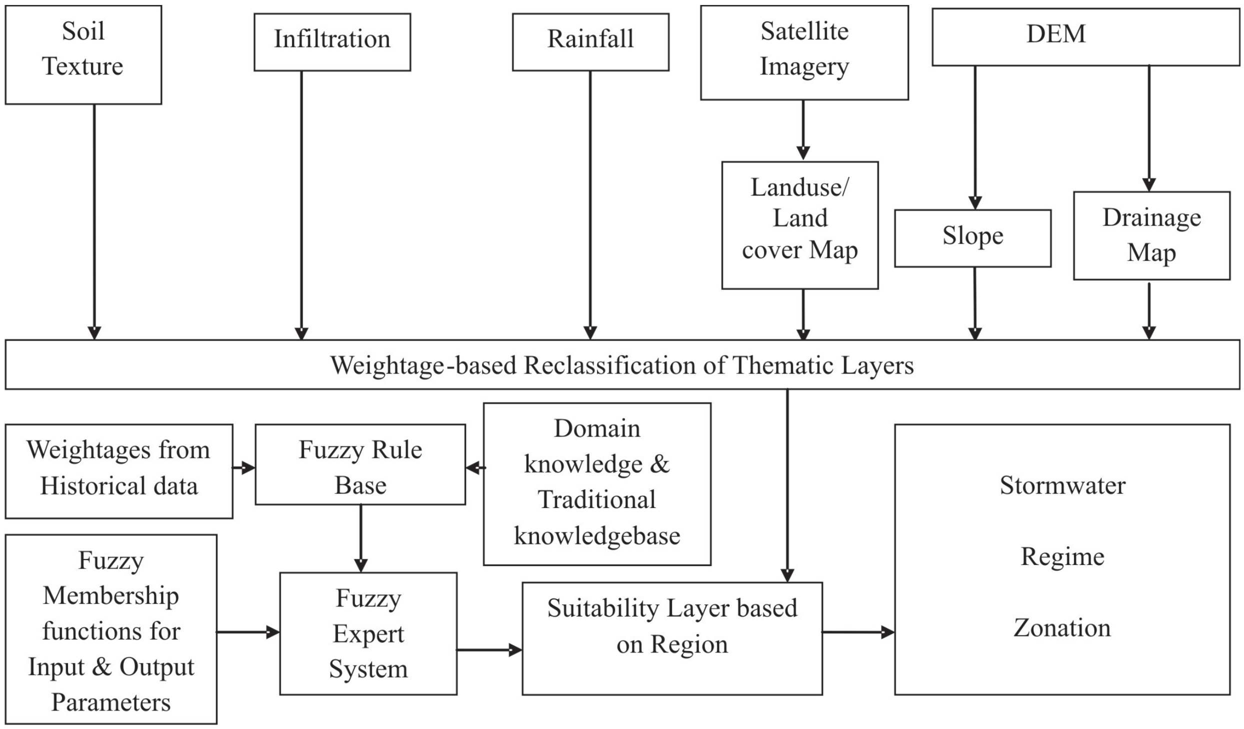

Fig. 2. Schematic representation of the procedures used in the Study

and digitization): (1) Survey of India toposheets (66C/8 and 66D/1&5; 1:50,000-scale) from Survey of India *for boundary and residence*, (2) Digital Elevation Model (DEM) from Bhuvan portal of NRSC (National Remote Sensing Centre) *for slope and drainage*, (3) *Soil-type* from Chennai Metro Water Supply and Sewage Board, (4) *Rainfall* from Meteorological Centre, Chennai and (5) satellite imageries (NRSC Resources at 2 LISS – III imagery on 11th September 2015) for land use-land cover map (by using ERDAS imagine 2015).

Development of Fuzzy Expert System

Using MATLAB (9.6), an FIS (Fuzzy Inference System)-Mamdani-type (23) (was created for four input parameters (land use, slope, infiltration & soil-type) and one output parameter (storm water-suitability), with triangular membership functions (with specifications designed by domain knowledge) and defuzzification using minimum, maximum and centroid, respectfully. The membership functions are presented in Fig. 3, with the rule-sets used, based on traditional knowledge-base with weightage obtained from UC Davis Extension Fuzzy Suitability (UCDAVIS Extension. 2017) with suitable calibration for stormwater (Table 1).

Integration of Fuzzy- suitability Scores unto Geospatial Database

Random locations were selected with complete coverage of the study area from the base-map and utilizing their spatial attributes, suitability scores were obtained from the fuzzy-expert system. The scores, thus obtained were used for creating storm-water suitability zones.

Results and Discussion

Geospatial Features of the Study Area

The various thematic layers prepared for the present study are presented in Figs. 4 to 8, referring to the soil-type, drainage Landuse-land cover, DEM and rainfall. As evident from these maps, the study area is mostly overlain by coastal sand, with patches of clay at the central west and hard rock in southern west side of the study area (Fig. 4). The drainage pattern is dendritic with two major rivers (Adyar and Kuvam) and their distributaries spread throughout the cross section of the study area, with more than 80% being the second order streams. (Fig. 5). Being highly urbanized, predominant regions of northern and central region of study area are

Table 1. Weightages and mutual relationships associated amongst the various parameters

Domain	Features	Rank	Weightage
Soil	Laterite Clay	Low	1.0
	Dark red fine loamy textured	Medium	2.0
	Pale brown non calcareous	Medium	2.0
	Alluvium Clay	High	3.0
Land use/ land cover	Built-up land	Medium	2.0
	Vegetation	High	3.0
	Water body	High	3.0
Hydrology	Rainfall	Low	1.0
	Drainage	Very Low	0.7
	Slope	Very High	5.0
	Infiltration	Medium	2.0

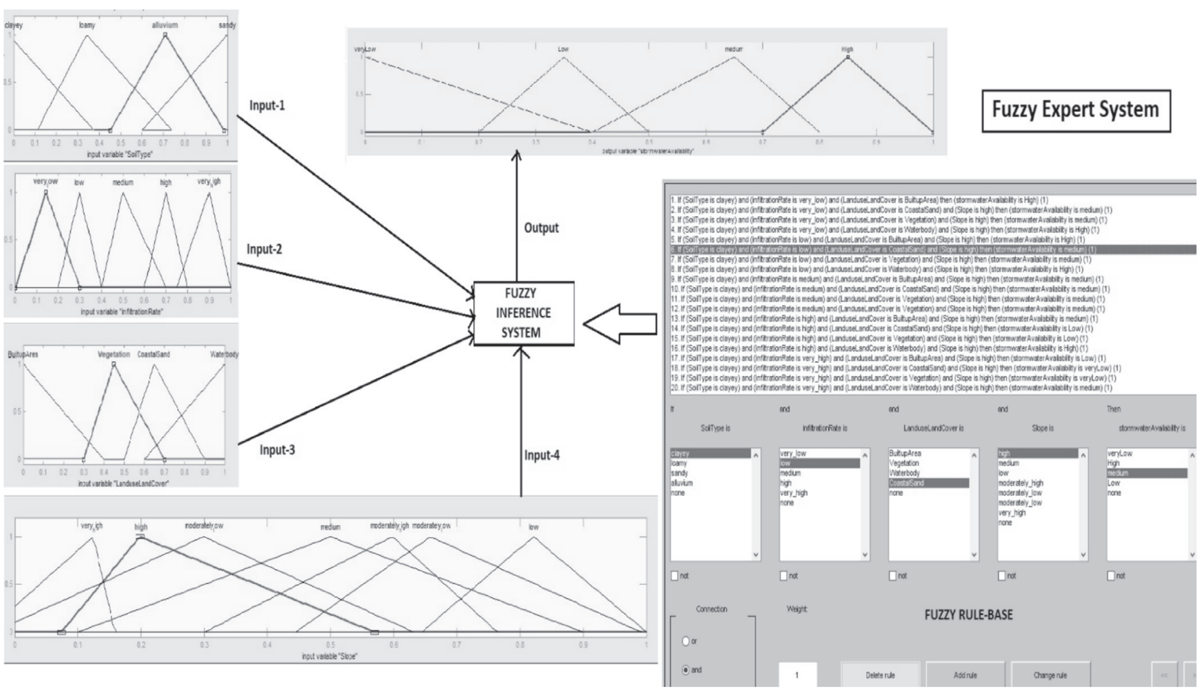

Fig. 3. Fuzzy Membership Functions of the variables and Fuzzy Rules (with weightages)

builtup land, sparsed by waterbodies (esp. towards the coastal part), with vegetation primarily dominating the southern and central western region (Fig. 6). As expected, the study area is primarily low-elevated (<8m) , especially towards the eastern coastal belt and the areas adjoining water bodies, with high

Fig. 4. Soil texture map of the study area

Fig. 5. Drainage map of the study area

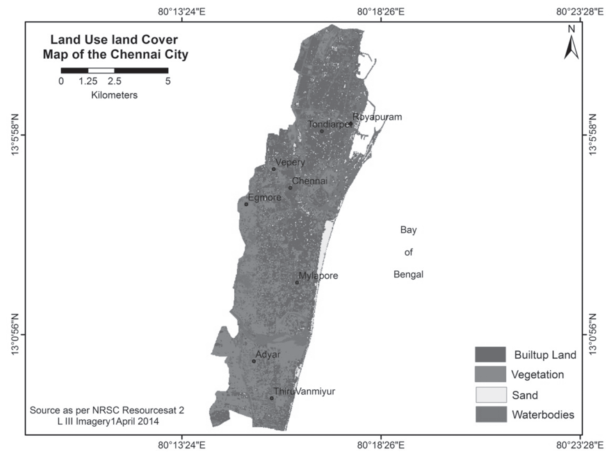

Fig. 6. Land use land cover map of the study area

elevation patches (12-20 m) mostly spread out in southern and central region of the study area (Fig. 7). The rainfall distribution is quite uneven, with high annual rainfall concentration (about 300 mm) towards the south and gradationally low (about

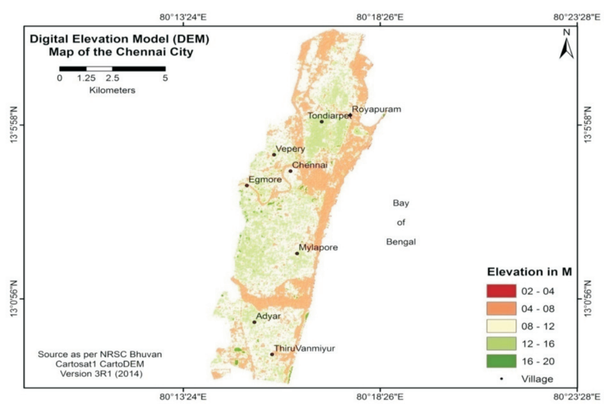

Fig. 7. Digital Elevation Model of the study area

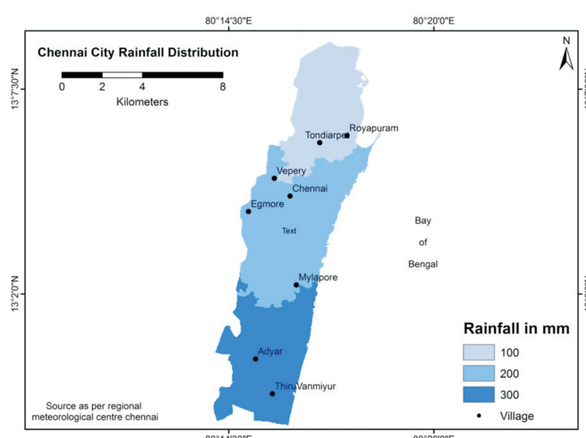

Fig. 8. Annual rainfall distribution of the study area

100mm) towards the north (Fig. 8).

Development of Fuzzy Expert System

Fuzzy-Suitability weighted rule-based investigation strategy was adopted to develop Fuzzy Inference System-based expert system (Fig.9), wherein with specific site attributes, the suitability can be forecasted. This expert system is location-independent, because of its strong basis on domain knowledge and historical data-base. The mutual parametric dependencies are highlighted in Fig.10, wherein it is clear that slope, landuse pattern and infiltration seemed to play more crucial role than the soil-type.

Delineation of Stormwater Suitability Zonation

Based on the suitability indices of various locations obtained from Fuzzy-based inference system, the stormwater suitability zones were inferred (Fig.11). As evident from this figure, the dark green shading in the investigation study area are extremely low for the stormwater zone, followed by light green shading region demonstrate the low potential site for the stormwater zone. The red shading demonstrates medium suitability for stormwater zone, as against the light pink shading zone which forms high potential stormwater sites. The blue shading zone are the high appropriate stormwater zone, and are predominant in the study area, as continuum in northern side and as patches in southern side, which is predominated by medium suitability zones, as patches..

When estimated in terms of are (Table 2), it is estimated that about 33.09 % of the areas have extremely high storm water potential, followed by 25.70 % (with high storm water potential), 24.46 %, (with medium storm water potential), 11.53% (with low stormwater potential), whereas only 5.20 % (very low stormwater potential).

Table 2. Area suitable for stormwater zone (Fuzzy Integrated) under different classes

Suitability class	Area km^2	Percentage Area
Very Low	15.27	5.20
Low	33.85	11.53
Medium	71.77	24.46
High	75.43	25.70
Very High	97.09	33.09
Total	293.41	100.00

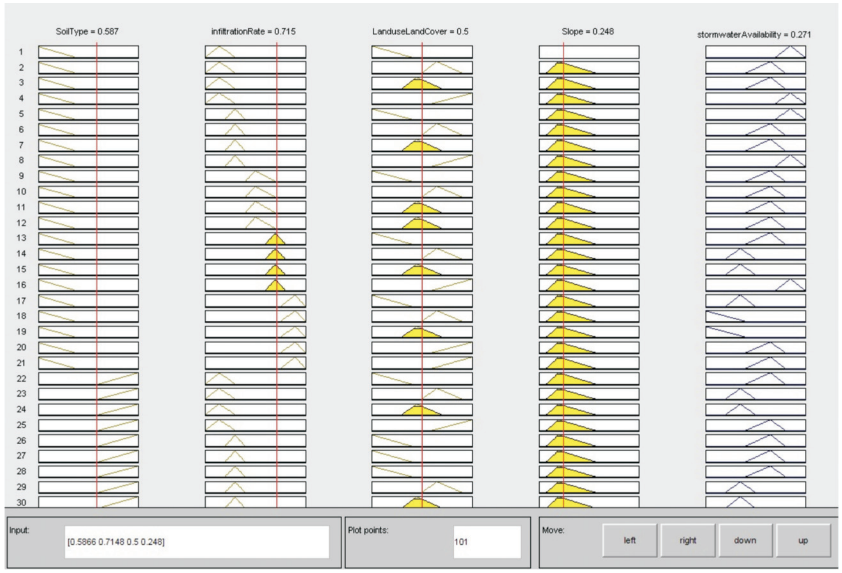

Fig. 9. Fuzzy expert system for Storm-water characterization Modelling

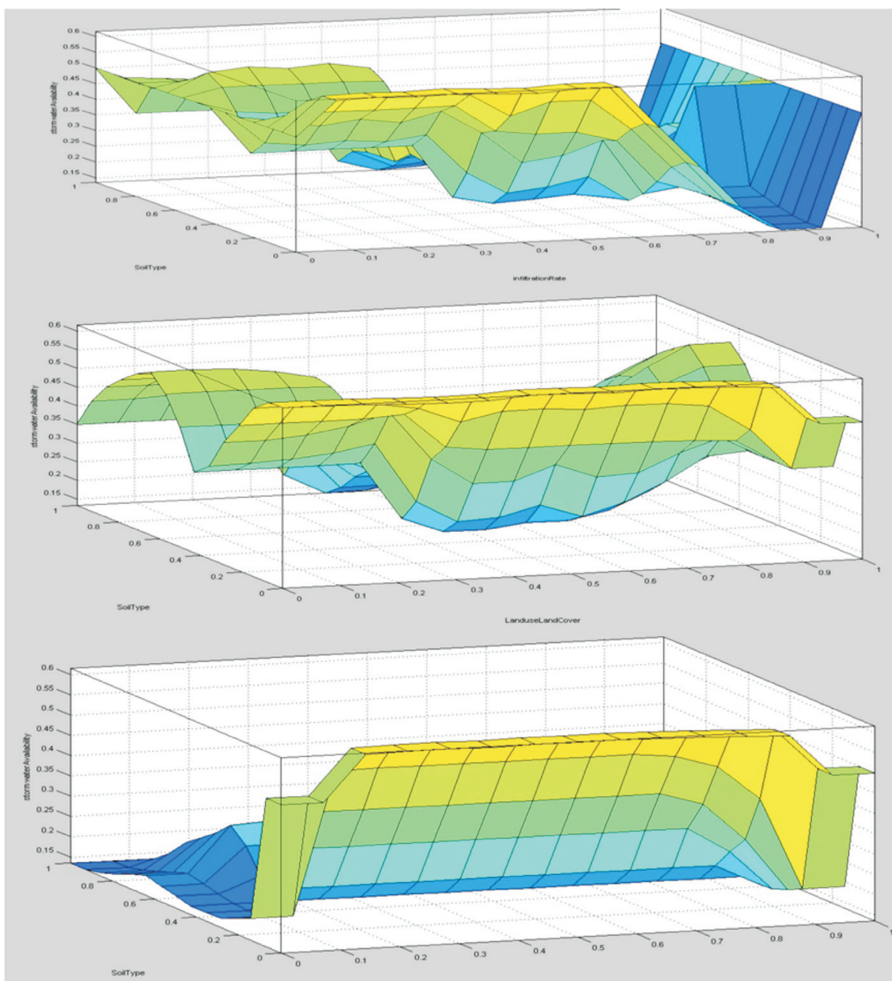

Fig. 10. Relationship between Input and Output variables in relation to Storm-water modelling

Conclusion

The present study established the need and robustness of a coupled geospatial and fuzzy-based expert system in storm water zonation in a highly urbanized city of southern India- Chennai. Based on the geospatial modeling of the terrain attributes, integrated with corresponding suitability scores using fuzzy-based expert system, it was estimated that more than half of the study area are of high to very high potential for stormwater collection and storage, which, when maintained properly, with suitable engineering intervention, can go a long way in meeting the water requirement of the rapid expanding and high water demanding city. The present study provides a strong base for similar study in any other place of concern, by dint of the augmentation of fuzzy based expert system, which is by and large standard (subject to minor calibration, if at all), unto the geospatial analysis.

Acknowledgement

The authors acknowledge Dept. of Science and Technology (DST): SUTRAM FOR EASY WATER (DST/TM/WTI/WIC/2K17/82(G)) for financial support for carrying out thisResearch.

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