Stormwater Suitability Zonation in Southern Indian Coastal City of Nagapattinam using Coupled FIS-GIS Modeling

Stalin Subbiah T., Mahesh R., Parthiban P. and Das A.*
Centre for Environmental Engineering, PRIST Deemed to be University, Thanjavur 613 403 Tamil Nadu, INDIA
*scientists.crd@gmail.com

Abstract

Availability of potable water is getting increasingly scarcer over time and certainly more so in coastal regions, especially hydro-dynamically active regions such as Nagapattinam. In fact, in the city of Nagapattinam, which is known for its high oceanographic variability as well as cluster of anthropogenic interventions (navigation, fishing, prawn-culture and so forth), spatio-temporal delineation and tracking of stormwater regime play a very crucial for sustainability of inhabitants with regard to availability of water.

The present research is carried out for demarcation of storm-water regions using an integrated Geographic Information System (GIS) through ArcGIS and Fuzzy Inference System (FIS) through MATLAB (Ver.R2019b). The geospatial study involves preparation of base map, involving soil, drainage, rainfall, landuse-landcover, road as well as digital elevation model (DEM). Development of suitable fuzzy-inference-system using suitable membership function and rules with weightages obtained from local inhabitants and expert-opinion, suitability mapping with relevant parameters was obtained which was applied for preparation of storm-water suitability zonation.

Based on the study, it was observed that the study area was found to have stormwater suitability ranging from extremely high (30.95 %) to high (23.72 %) to medium (19.39 %) to low (13.65 %) to exceptionally low (12.29%). The regions surrounding Pappakovil and Northwest of Terku poyyur (Gramathumedu) are especially found to be most suitable for stormwater retention and utilization. This approach presents a potential expert-based modelling system for location of stormwater suitability for suitable recommended engineered approaches for better stormwater preservation and utilization in any area of concern.

Keywords: Stormwater modeling, Fuzzy Inference System (FIS), Geographic Information System (GIS), Suitability Zonation.

Author for Correspondence

Introduction

Storm water delineation plays a crucial role in management of agriculture and water resources as well as assessment of climate change, ground-reconnaissance and even socioeconomic indices[1,17]. The standard storm water management models involve dynamic event-based simulation involving various hydro-meteorological variants, namely, precipitation, evaporation and runoff (surface and subsurface)[4,12,13,16,20]. Often several researchers augment the conventional geospatial overlay analysis with Analytical Hierarchical Process (AHP), Multi Criteria Decision Making (MCDM), Fuzzy Analytical Hierarchical Process (F-AHP) and so forth to involve domain-based hierarchy as well as incorporation of additional parameters, extending the realm of studies to area delineation for cropping, infrastructure and settlement, flood-risk management and so forth along with stormwater modeling and hydro-meteorological risk assessment[2,3,7-10,14,17,21-22]. The FIS-method used in augmentation to classical GIS-models can be used to design/calibrate storm-water zonation in other regions as well[18].

The specific approaches used by the approaches are based on incorporation of integration of algorithm-based incorporation of uncertainty and hierarchy with limited involvement of expert-base knowledge base into the modeling environment. In the present work, however, separate dedicated fuzzy inference system (FIS)-modeling is carried out with complete specification of fuzzification and defuzzification parameters, types and dimensions of the membership functions as well as incorporation of domain-specific rule-base with differential appropriate weights, so as to develop a fully integrated FIS-GIS system to estimate the suitability scores, which forms the basis for delineation of suitability zonation of stormwater regimes in the study area.

Study Area

Nagapattinam city is one of the coastal cities in the Tamil Nadu. It is located at (10°41’32.787’’N to 10°49’50.541’’N and 79°49’33.907’’E to 79°51’13.19’’E), the total area of the municipality zone is 17.92 square kilometers. (flanked by Nagore town, Nagapattinam town, Tottam town, Pappakovil and Terku Poyyur town) with MSL 10 meters above the sea with northern and eastern zone rendered deltaic by dint of Cauvery and its wide system of branches, inundated by the river of the Vennar river (Fig.1). Nagapattinam district is along the East coast of Tamil Nadu. Study area along the coastal stretch extends about 15 km. south of Nagapattinam town and is the largest swamp in Tamilnadu. The study area falls under the Survey of India toposheets 58N/14 and 15. This stretch is consisting of a narrow region of sandy beach along the coast in the delta region of Cauvery River.

Nagapattinam region 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. Nagapattinam received an average annual rainfall of 125.12 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 (780.2 mm). The region enjoys a humid and tropical climate. The average temperature of the district in 2018 was about 32ºC and the minimum temperature is 24.6ºC.

Dust storms whirl winds and dusty winds blow from various quarters towards the end of May. The southwest wind sets during April, it is strongest in June and continues until September. Northeast monsoon starts during the month of October and extends until 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.

Material and Methods

The accompanying schematic diagram demonstrates the procedure of the present work (Fig. 2), as outlined in the flowchart which involves three distinct phases.

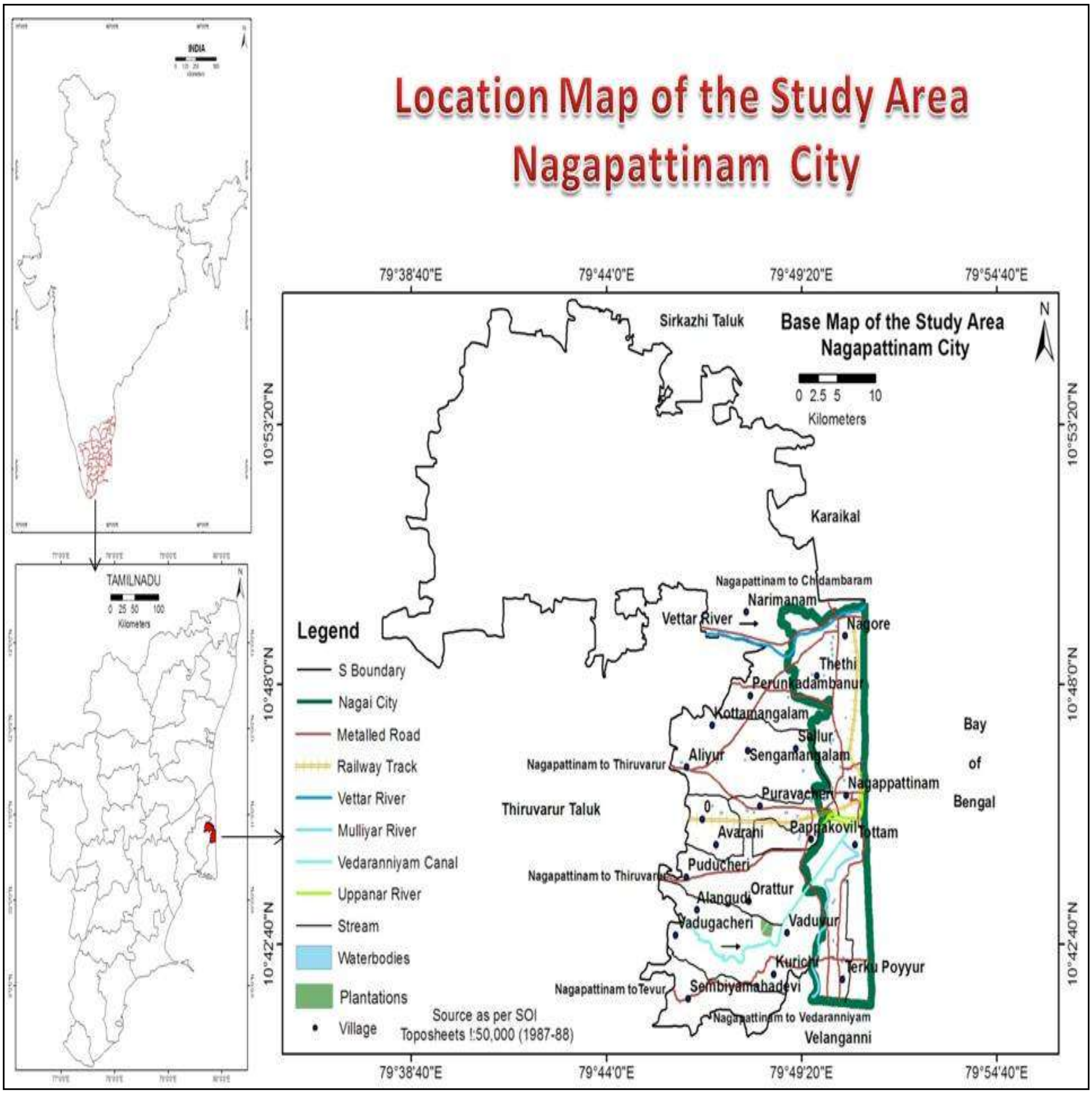

Figure 1: Location map of the study area

Preparation of Geospatial Overlay Map of the Study Area: The base-map was prepared utilizing Survey of India toposheets (58 N/14 and 58 N/15; 1:50,000-scale, after geo-referencing and digitization followed by generation of thematic layers (namely, roads, drainage, residence etc.). The satellite imageries (NRSC Resourcesat2 LISS – III sensor imagery on 11th September 2015) were employed for preparing landuse-landcover map using ERDAS imagine 2015. The DEM obtained from Bhuvan-portal of NRSC, Hyderabad was used to develop the slope and drainage maps using Cartosat 2 DEM, Resolution – 30 meter (2014). All these maps as well as rainfall-point data were apportioned with various weightages based on UC Davis Extension Fuzzy Suitability (Table 1) based on the potential for zonation of Stormwater appropriateness using ArcGIS (Ver.10.3) software. The various weightages and mutual relationships associated amongst the various parameters are presented in table 1.

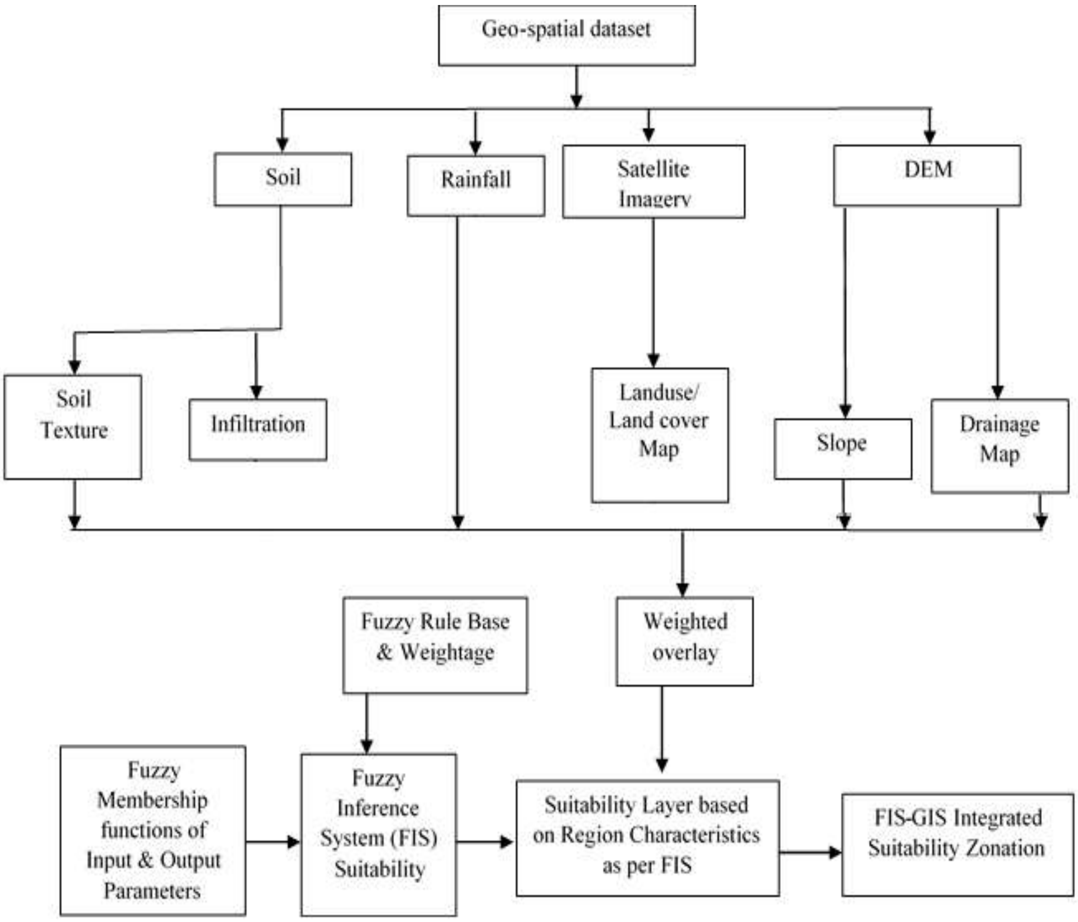

Figure 2: Schematic representation of the procedures used to generate criteria maps in GIS

Table 1
Weightages based on UC Davis Extension Fuzzy Suitability

Features	Classes	Rank (Weightage)
Laterite Clay	SOIL	Low (1.0)
Dark red fine loamy textured		Medium (2.0)
Pale brown non calcareous		Medium (2.0)
Alluvium Clay		High (3.0)
Built-up land	LAND USE / LAND COVER	Medium (2.0)
Vegetation		High (3.0)
Water body		High (3.0)
Road		High (7.0)
Rainfall	HYDROLOGY	Low (1.0)
Drainage		Very Low (0.7)
Infiltration		Medium (2.0)
Slope		Very High (5.0)

In estimation of weightages, "weighted overlay analysis" was used along with reclassify method for preparing MCE and GIS Environment following UC Davis Extension Fuzzy methodologies Suitability maps[11,19]. Besides, in fact, each and every one of the maps with the exception of those of land use land spread and spatial circulation of rainfall, were changed over to raster layers and re-inspected to a resolution of 30 x 30 m to coordinate the spatial resolution of Cartosat DEM. They were then re-classified according to the details of each stormwater zone system.

The specific thematic maps of the study area (namely, roads, soil, drainage, landuse and landcover, slope, rainfall) are presented in figures 3, 4, 5, 6 and 7.

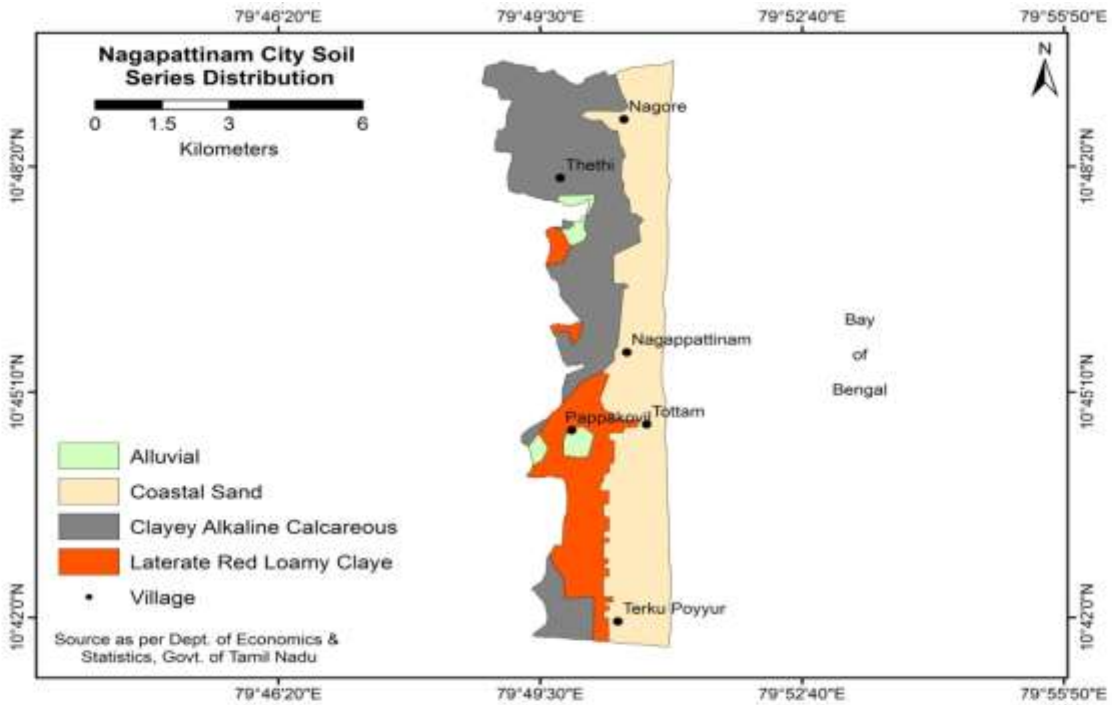

Figure 3: Soil texture map of the study area

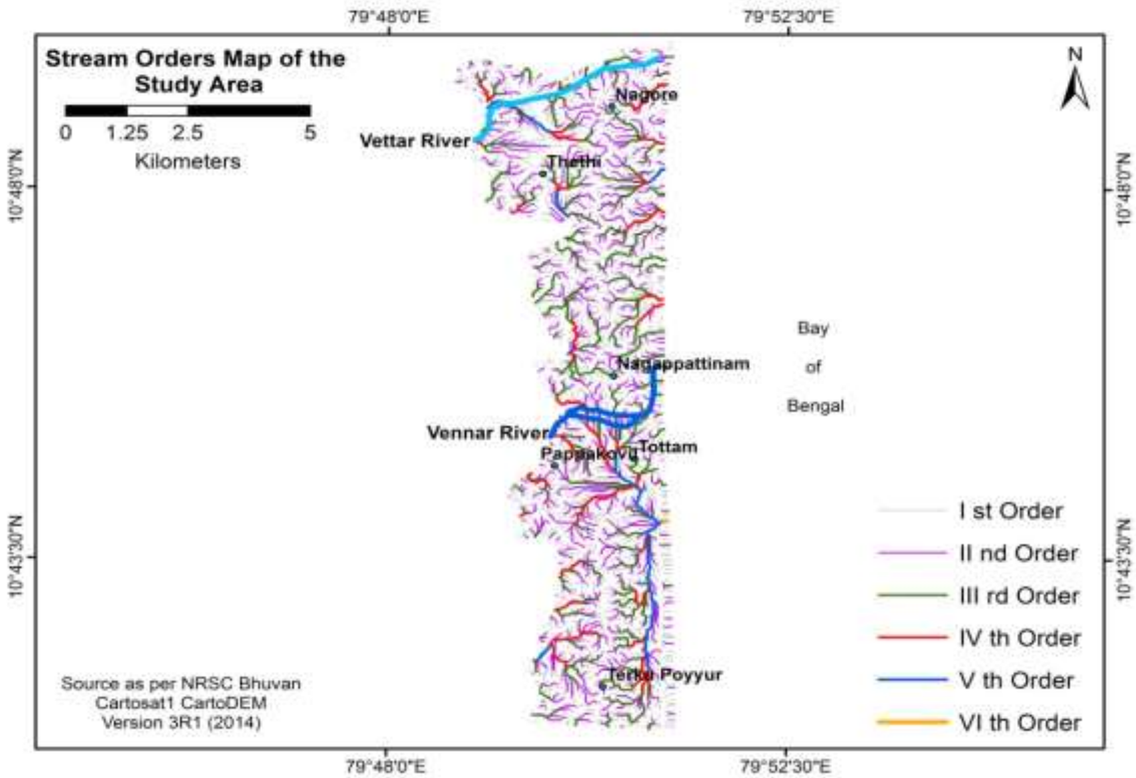

Figure 4: Drainage map of the study area

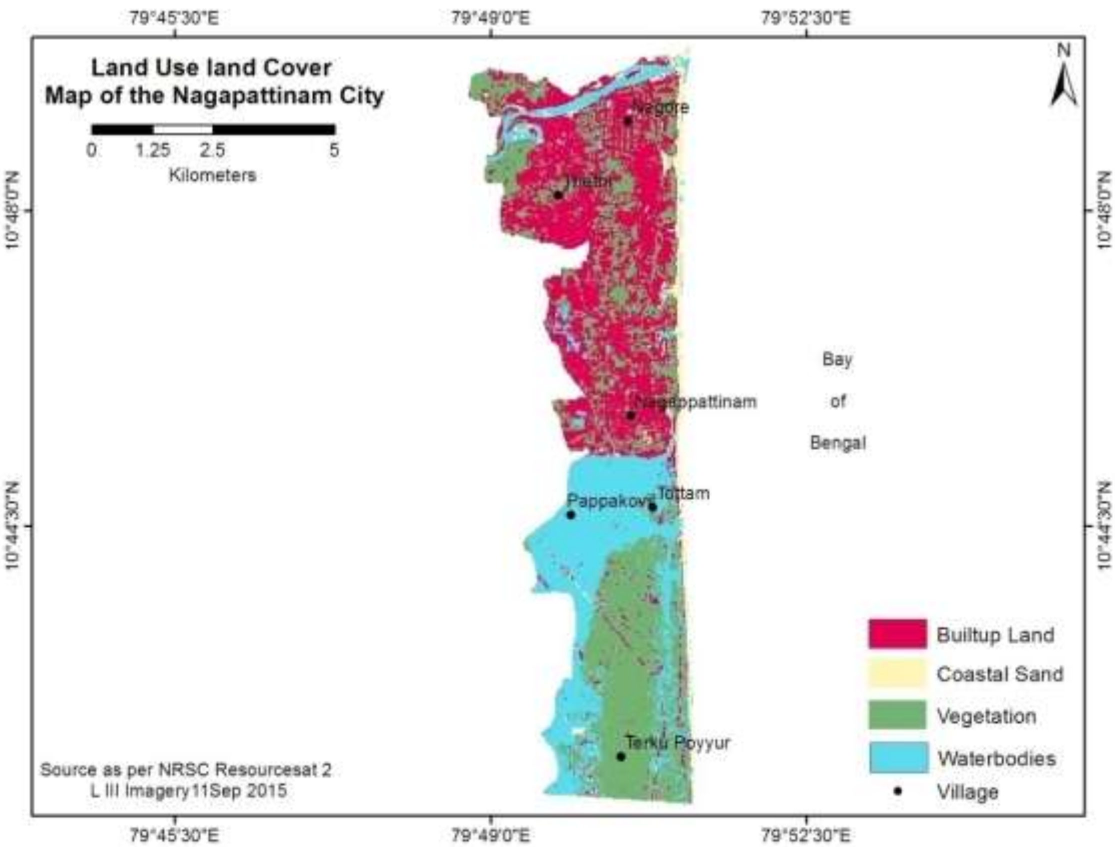

Figure 5: Land use land cover map of the study area

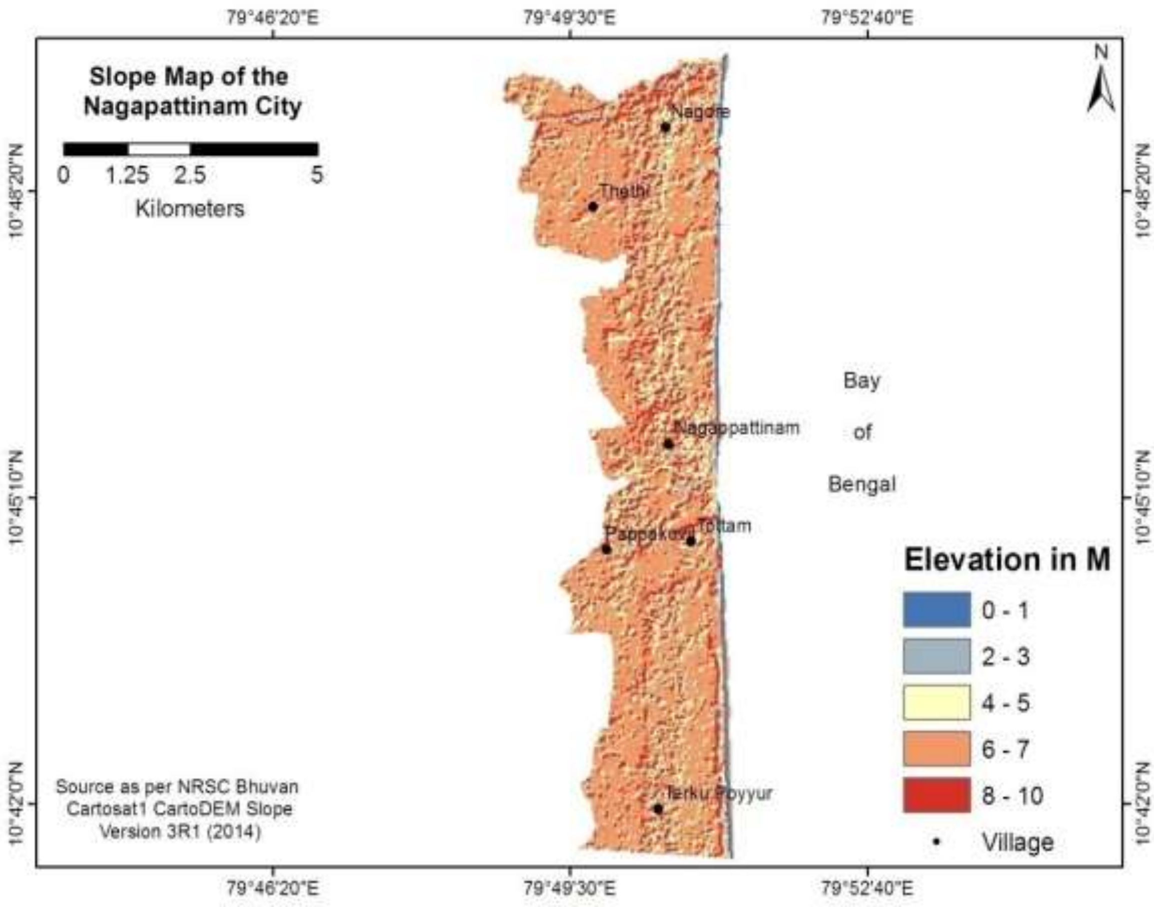

Figure 6: Digital Elevation Model map of the study area

Development of Fuzzy Inference System (FIS) For Parameters affecting Storm-Water Regime: To calibrate the weightages provided by UC Davis Extension with regional variability, a fuzzy inference system was developed using MATLAB (Ver. R2019b), taking advantage of the local expertise available with the researchers and experiences with local inhabitants. Based on the suggestions provided, fuzzy membership functions (Mamdani type) were developed for four input variables (soil type, infiltration rate, landuse/ landcover and slope) and one output variable (stormwater availability). In all these cases, triangular membership functions were used with parameters agreed upon by five researchers working in the same domain and on the same study area. The fuzzy rules (totaling 30) were generated, with weightages obtained using historical data available on the study area. The FIS model is provided in fig. 8. The relationship between various inputs with the outputs in the FIS model developed is presented in fig. 9.

Integration of Fuzzy Based Suitability Scores unto the Suitable Geospatial Coordinates to obtain Stormwater Suitability Zonation: An integration of the suitability indices obtained from FIS-model for various locations of the study area was incorporated as point data (comprising, more than 100 locations) unto the geospatial model developed and finally suitability model was explored.

Results and Discussion

The thematic maps obtained from the base map (Fig. 3-7) with assignment of suitable indices were derived from the fuzzy-inference system (with the criteria as specified in UC Davis Extension Fuzzy Suitability weighted overlay) corresponding to the locational data of the layers followed by using integration through Arc GIS 10.3 software.

FIS Integrated Geospatial Stormwater Zonation of the Study Area: The resultant suitability map for stormwater zone was generated as displayed in fig. 10. As presented, on application of Fuzzy Suitability weighted overlay investigation strategy, the delineated stormwater suitability zonation was quite distinct wherein the red-shade refers to extremely low stormwater zone and the pink-shade region to low stormwater zone. The light yellow-shade to medium stormwater zone, the light green-shade zone located at the center, south-west part of the study area, refer to moderately favorable stormwater zone. The dark green-shaded zone is located principally in the south and north-west pieces of the study area are the highly appropriate stormwater sites.

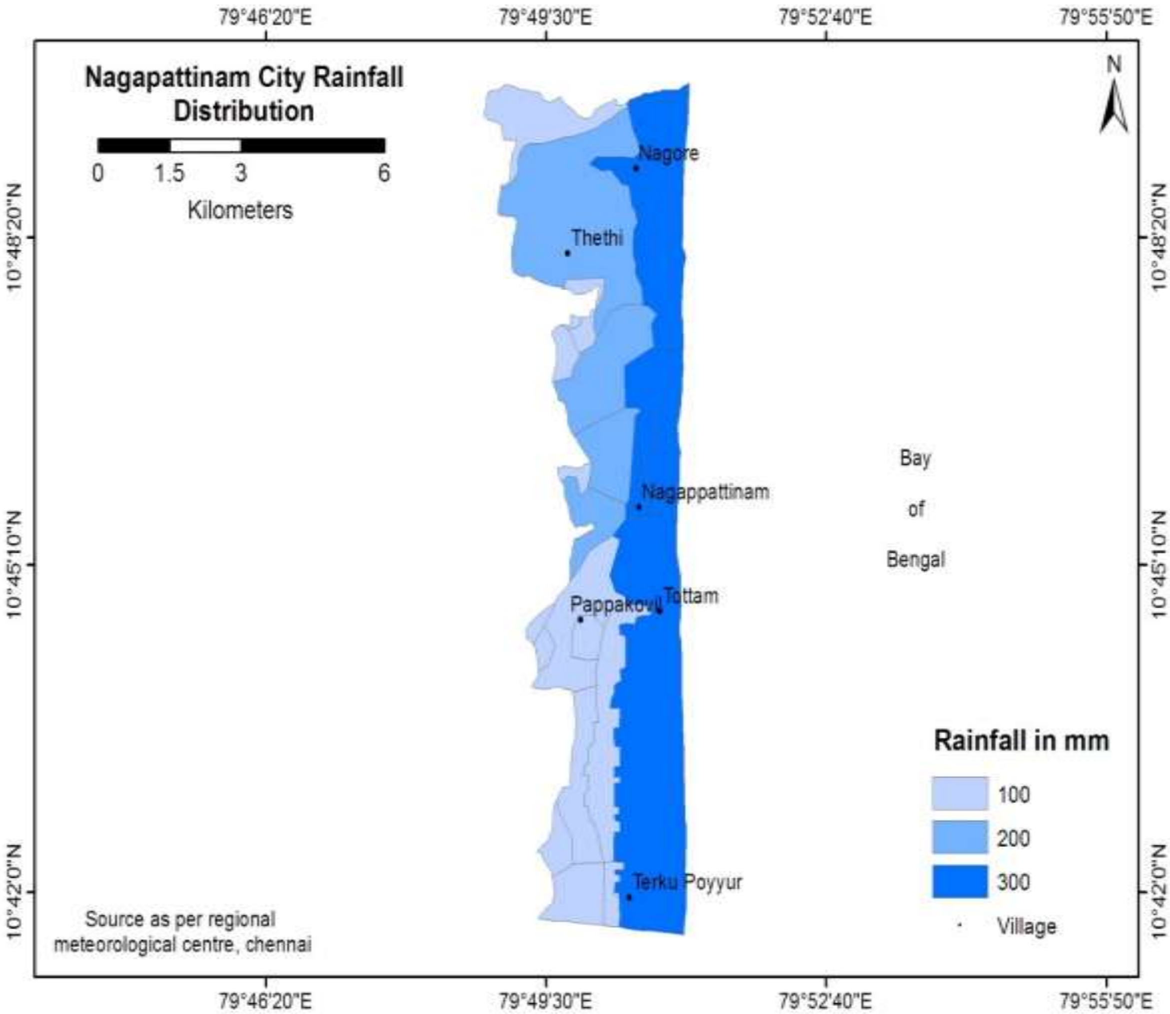

Figure 7: Seasonal and mean annual rainfall distribution of the study area

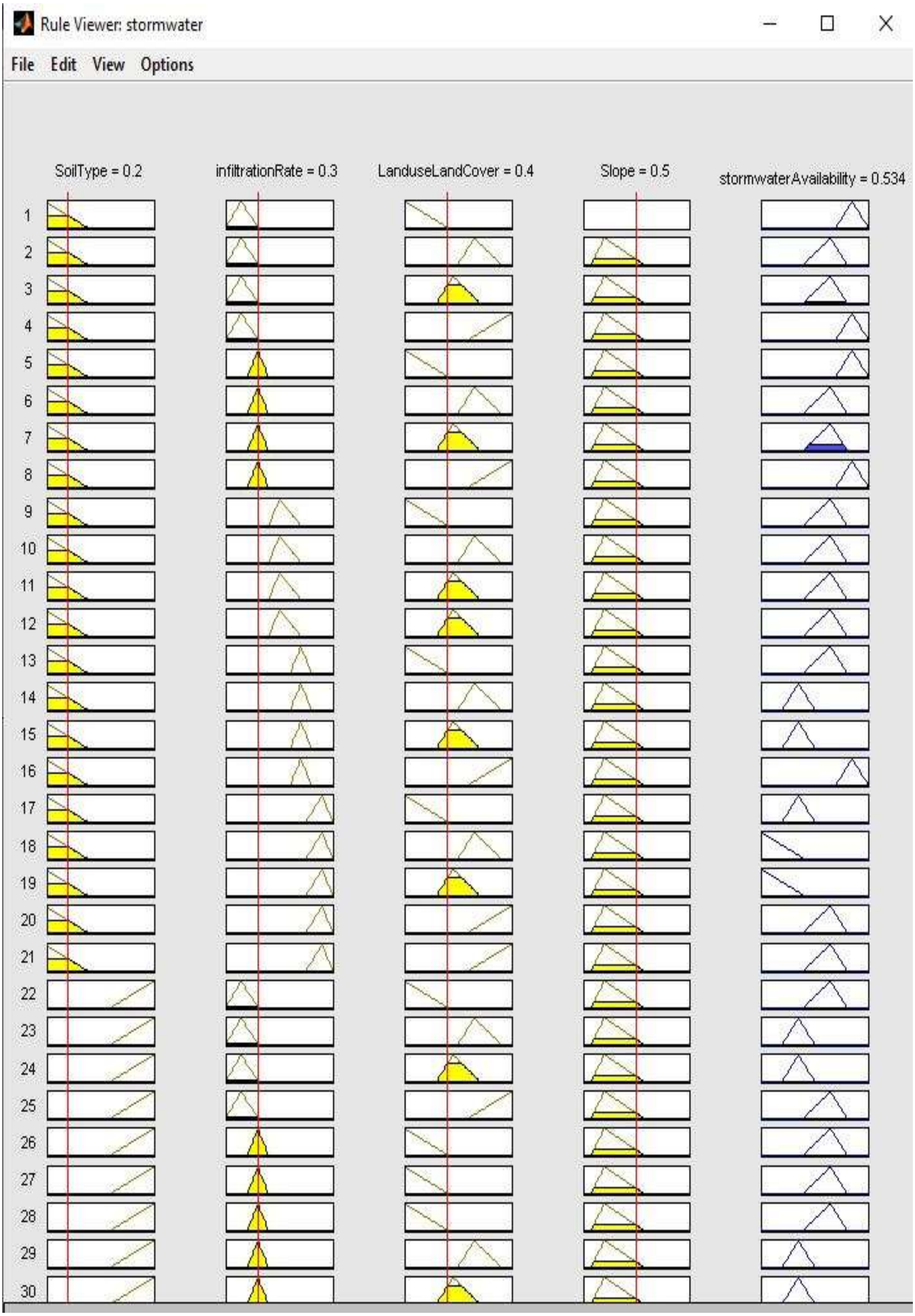

Figure 8: Fuzzy Expert System for Storm-water characterization Modelling

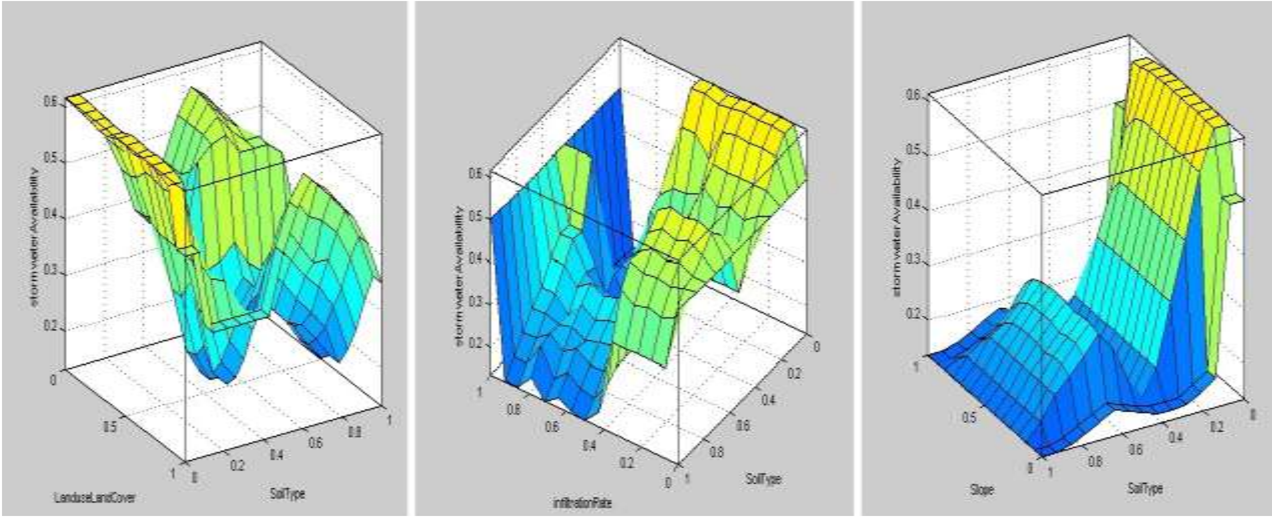

Figure 9: Relationship between Input and Output variables in relation to Storm-water modelling

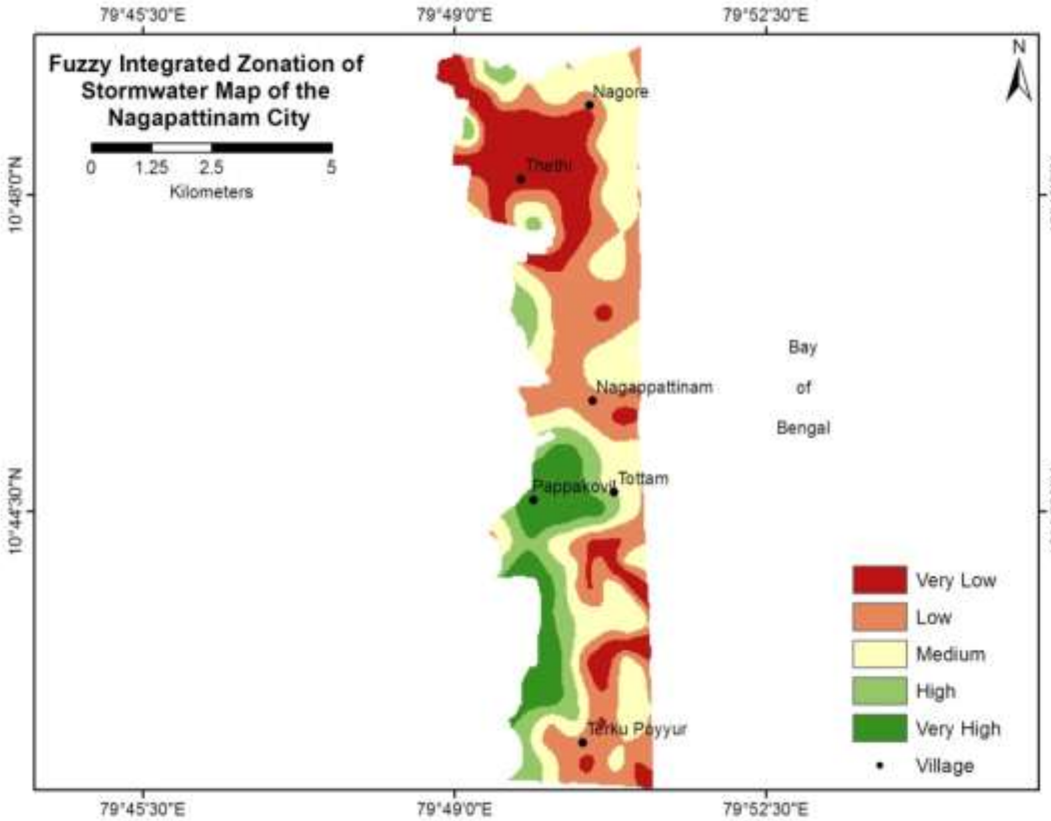

Figure 10: Suitability map of stormwater zonation technique using Fuzzy Integrated approach

Areal Extent of Stormwater Suitability Regime: As given in the table 2, about 30.95 % of the total study area are highly suitable for stormwater storage and management whereas the areas with progressively lower suitability indices are 23.72 % (high), 19.39 % (medium), 13.65 % (low) and 12.29 % (very low). The two most prominent locations which are most suitable for stormwater storage by dint of their suitability index (as obtained from the present study) and larger areal extent are the regions surrounding Pappakovil and Northwest of Terku poyyur (Gramathumedu) which are mostly made up of alluvial soil with slope 6-7 degree interleaved by tributaries of Vettar River receiving moderately high rainfall. Since these areas are mostly free from habitations and other built up structures, vegetation, forest cover as well as agricultural fields and development of suitable stormwater retention structures would be techno economically feasible.

North eastern zone of the study area (in and around Thethi), on the contrary, presents the least stormwater retention option by virtue of its clayey top soil and dense built up area, in spite of moderately high rainfall pattern and moderately dense tributaries of Vennar River.

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

Suitability Class	Area km^2	Areal Coverage (%)
Very Low	1.99	12.29
Low	2.21	13.65
Medium	3.14	19.39
High	3.84	23.72
Very High	5.01	30.95
Total	**16.19**	**100.00**

Conclusion

The suitability assessment for stormwater procurement and storage has been increasingly becoming prime necessity, thanks to the vagaries of weather pattern and galloping adverse-anthropogenic influences. Geographic information system offers a practical way of assessment of the characteristics of various thematic levels associated with a specific area, so as to demarcate the stormwater suitability zonation using the standard layer-weightages derived from historical data. The present study involving the development of a suitability expert system based on FIS based analysis (utilizing the local expertise and traditional knowledge base) provides a more consistent and integrated approach for evaluating stormwater suitability score.

In the present research work, the specific zones were distinctly identified with estimation of the available area which can form an important base for better resource management. As discussed earlier, the regions surrounding Pappakovil and Northwest of Terku poyyur (Gramathumedu) are found to be most suitable for stormwater retention and storage. In fact, the method discussed herewith can be utilized for any area with the same expert system (or with suitable region-based calibration) for stormwater suitability zonations.

Acknowledgement

The authors acknowledge Dept. of Science and Technology (DST): SUTRAM FOR EASY WATER (DST/TM/WTI/WIC/2K17/82(G)) and Indian Space Research Organization (ISRO): (ISRO/RES/4/684/19-20) for financial support for carrying out this research

References

1. Al-Adamat R., Diabat A. and Shatnawi G., Combining GIS with multicriteria decision making for siting water-harvesting ponds in Northern Jordan, *Journal of Arid Environments*., **74(11)**, 1471 **(2010)**

2. Bahram C., Karim S., Fereidoun R., Mahmoud H.R., Arash M. and Shahaboddin S., Stream flow regionalization using a similarity approach in ungauged basins: Application of the geo-environmental signatures in the Karkheh River Basin, Iran, *CATENA*, **182**, 104 **(2019)**

3. Ceballos-Silva A. and Lopez-Blanco J., Delineation of suitable areas for crops using a multi-criteria evaluation approach and land use-cover mapping: A case study in Central Mexico, Agricultural Systems, *Scientific Research*, **77(2)**, 117 **(2003)**

4. Huber W.C. and Dickinson R.E., Storm Water Management Model. User's Manual Ver. IV, U.S. Environmental Protection Agency **(1988)**

5. Jeetendra S., Prashant K., Sisay D., Christos S. and Silvana D., Hydro-meteorological risk assessment methods and management by nature-based solutions, *Science of the Total Environment*, https://doi.org/10.1016/j.scitotenv.2019.133936, **15**, 133936 **(2019)**

6. Jeganathan C., Development of fuzzy logic architecture to assess the sustainability of forest management, International Institute for Geo-information Science and Earth Observation Book **(2003)**

7. Kumar M., Agarwal A. and Bali R., Delineation of potential sites for water harvesting structures using remote sensing and GIS, *Journal of the Indian Society of Remote Sensing*, **36(4)**, 323 **(2008)**

8. Lyu Hai-Min Shen, Shui-Long Zhou, An-Nan Zhou and Wan-Huan, Flood risk assessment of metro systems in a subsiding environment using the interval FAHP–FCA approach, *Sustainable Cities and Society*, **50**, 101682 **(2019)**

9. Meng Y., Malczewski J. and Boroushaki S., A GIS-Based multicriteria decision analysis approach for mapping accessibility patterns of housing development sites: A case study in Canmore, Alberta, *Journal of Geographic Information System*, **3**, 50 **(2011)**

10. Mosase N., Kayombo B., Tsheko R. and Tapela M., Assessment of the Suitability of Rain Water Harvesting Areas Using Multi-Criteria Analysis and Fuzzy Logic, *Advances in Research*, **10(4)**, 1 (**2017)**

11. Pandian M. and Kumanan C.J., Geomatics approach to demarcate groundwater potential zones using remote sensing and GIS techniques in part of Trichy and Karur district, Tamilnadu, India, *Scholars Research Library Archives of Applied Science Research*, **5(2)**, 234 **(2013)**

12. Rossman Lewis A., Storm Water Management Model Quality Assurance Report. Dynamic Wave Flow Routing, EPA/600/R-06/097 **(2006)**

13. Rossman Lewis A., Storm Water Management Model User's Manual, EPA/600/R-05/040, U.S. Environmental Protection Agency, Cincinnati, OH **(2007)**

14. Ghosh Sasanka and Das Arijit, Urban expansion induced vulnerability assessment of East Kolkata Wetland using Fuzzy MCDM method, *Remote Sensing Applications, Society and Environment*, **13**, 191 **(2019)**

15. Seo Jin Ki and Chittaranjan Ray, Using fuzzy logic analysis for siting decisions of infiltration trenches for highway runoff control, *Science of the Total Environment*, **493(15)**, 44 **(2014)**

16. Seth I., Soonthornnonda P. and Christensen E., Use of GIS in urban stormwater modeling, *J. Environ. Eng.*, **132(12)**, 1550 **(2006)**

17. Shariat R., Roozbahani A. and Ebrahimian A., Risk analysis of urban stormwater infrastructure systems using fuzzy spatial multi-criteria decision-making, *Science of the Total Environment*, **10(647)**, 1468 **(2019)**

18. Stalin Subbiah T., Parthiban P., Mahesh R. and Das A., Fuzzy based hydro-lithological zonation of Stormwater regime in Thanjavur City of Southern India, *Disaster Advances*, **13(11),** 42-52 **(2020)**

19. UCDAVIS Extension, Fuzzy Suitability Analysis Methods Geographic information system, ARC GIS – ESRI Copyright © The Regents of the University of California https://www.youtube.com/watch?v=lzEh95rjvh A Published on Nov 28 **(2017)**

20. Viavattene C., Scholes L., Revitt D. and Ellis J.A., GIS based decision support system for the implementation of stormwater best management practices; Paper presented at the 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK **(2008)**

21. Yangfan Xiao, Shanzhen Yi and Zhongqian Tang, Integrated flood hazard assessment based on spatial ordered weighted averaging method considering spatial heterogeneity of risk preference, *Science of the Total Environment*, **599–600(1)**, 1034 **(2017)**

22. Yazdi S.J. and Salehi Neyshabouri A.A., Identifying low impact development strategies for flood mitigation using a fuzzy-probabilistic approach, *Environmental Modelling and Software*, **60**, 31 **(2014)**.

(Received 03rd November 2020, accepted 16th December 2020)