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An evaluation of the climate change effects on ecosystems using fuzzy logic

Imran Hassan *

Basic Science Division, Faculty of Science and Engineering, World University of Bangladesh, Dhaka-1230, Bangladesh.

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Abstract

This study investigates the effects of climate change on ecosystems through the application of fuzzy logic, a mathematical approach that handles uncertainty and imprecision in environmental data. Climate change presents complex, dynamic challenges for ecosystems, where various factors such as temperature fluctuations, precipitation patterns, and extreme weather events interact in ways that are difficult to model using traditional methods. By utilizing fuzzy logic systems, this research aims to provide a more nuanced understanding of how these environmental variables affect biodiversity, ecosystem services, and overall ecosystem health. Through the development of fuzzy inference models, we assess the interactions between climate variables and ecological responses, incorporating both qualitative and quantitative data. The results of the study highlight the potential for fuzzy logic to improve predictions and inform adaptive management strategies in response to the unpredictable impacts of climate change on ecosystems. This approach offers valuable insights for policymakers, environmental managers, and researchers seeking to mitigate the effects of climate change on natural habitats and biodiversity.

Keywords: Fuzzy Logic; Fuzzy Model; Climate; Ecosystems; Tree Migration

1. Introduction

The accelerating pace of climate change poses a profound threat to ecosystems worldwide, with complex and often unpredictable consequences [1]. As temperatures rise, precipitation patterns shift, and extreme weather events become more frequent, ecosystems are forced to adapt or face degradation, leading to significant impacts on biodiversity, species distribution, and the provision of essential ecosystem services [2]. Traditional modeling approaches often struggle to account for the inherent uncertainties and nonlinearities in these interactions. In response, this article introduces a fuzzy logic framework designed to better capture the intricacies of climate change's effects on ecosystems [3].

Fuzzy logic is a well-known soft computing tool which develops the workable algorithms by embedding structed human knowledge. It is a logical system that presents a model designed for human interpretation modes that are inexact rather than precise. The fuzzy logic system can be applied to design intelligent systems on the basis of information expressed in human language (Bai et al. 2006). Fuzzy logic is one of the forms of artificial intelligence; however, its history and uses are newer than artificial intelligence based expert systems. Fuzzy logic deals with problems that have imprecision, vagueness, approximations, uncertainty or qualitative mess or partial truth.

Fuzzy logic was introduced by Professor L. A. Zadeh, University of California at Berkeley, in the year 1965 (Zadeh 1965; Bai et al. 2006) through his paper 'Fuzzy sets.' His work was not recognized until Dr. E. H. Mamdani, Professor at London University, practically applied the concept of fuzzy logic to control an automatic steam engine in the year 1974 (Mamdani and Assilion 1974; Bai et al. 2006). Since the beginning of applications of fuzzy logic in the domain of hydrology (Bogardi et al. 1983, 2004) a great sum of investigations has been undertaken, and presently, fuzzy logic has

* Corresponding author: Imran Hassan

turned into a useful approach in water resources assessment and hydrologic analysis. Hydrology is often vulnerable to uncertainties caused due to lack of data, nature causes (e.g., climate) and imprecision's in modeling. System limitations and initial conditions as well bring in uncertainty. In addition, potential pressure on the system cannot be clearly identified in many hydrologic studies. Fuzzy logic allows us to consider the handling of all such vagueness (or ambiguity) in hydrology (Bogardi et al. 2004).

The Intergovernmental Panel on Climate Change (IPCC), created in 1988, is one of the agencies responsible for providing comprehensive assessments of the state of scientific, technical and socio-economic knowledge about climate change; its causes, possible repercussions, and response strategies; and warnings about climate change and possible scenarios which depend on human mitigation [3–4]. Climate change represents a prominent research topic over the last few decades, and climate impacts on heritage cities and constructions have a special significance which has recently been recognised [6]. Major disasters present impactful consequences and have a large influence on heritage building performance, but they have a low probability of occurrence. Deterioration effects related to climate change or rising sea levels occur over longer periods of time; nevertheless, when they occur, their effects are very serious in terms of the buildings' performance [8]. In this sense, effective risk management of cultural assets is uncommon because of inadequate knowledge of the assets, failure to calculate the true cost of loss and damage, and the effects of external hazards. The maintenance of cultural assets is also closely related to place resilience [11]. In this sense, resilience is understood as the capacity to cope with and recover from aggressive external events, for example, risks and effects of disasters such as earthquakes, conflicts and meteorological events driven by climate change, among so many others [2]. Thus, the preventive conservation programmes analyse the risk of constructions; their main objectives are to improve knowledge of the current conservation conditions (vulnerability) [9] and threats (hazards) in order to minimize further degradation and to increase service life over time [10]. Cultural heritage constructions are usually subject to [11] i) static-structural hazards such as floods, geotechnical problems and seismic action; ii) environmental hazards such as weather conditions, pollution and current climate change effects; and iii) anthropogenic factors such as fires, vandalism and population and tourism effects. Concerning the intrinsic vulnerabilities of heritage constructions and the external hazards affections, the maintenance of the buildings must be considered like the process of keeping the construction in operation over time, preserving a balance between the performance of the building (functional service life) and the resources required for this to occur [12]. This implies that the management and maintenance of heritage buildings consist of identifying a series of relative priorities for intervention in terms of preventive maintenance actions. Adger et al. [13] note that 'adaptation that requires large-scale investment is likely to be episodic and staggered'. Improvements to existing cultural heritage sites affected by climate-change-induced impacts might not be possible because of cost. The monitoring of such sites has revealed that those which are most at risk are in coastal areas which are experiencing greater impacts [14]. A long-term vision is required to develop appropriate strategies [14], including planning for disaster management and preservation strategies [15].

In this work we consider the possibility of analyzing the impacts, at the regional level, of temperature increase and precipitation changes from the perspective of the year in which some temperature is reached. Two sources of uncertainty are considered, the emissions of GHG and the climate sensitivity. We have learned that the larger concentration and sensitivity the sooner the successive thresholds of temperature will be reached. If the sensitivity is 6 °C/W/m2 there is no way of staying at two degrees unless the concentrations of CO2 had followed the 2CO2 trajectory: negative emissions that means very strong subtraction of CO2 from the atmosphere. We think that it is easier to consider a degree by degree strategy than one based on dates.

2. Methodology

In general, the workflow of our methodology can be divided into four analytical steps. The initial preparation phase was important to create an overview of current resilience measurements and the landscape of possible indicators. Based on these findings, dimensions, criteria and indicators in general, the workflow of our methodology can be divided into four analytical steps. The initial preparation phase was important to create an overview of current resilience measurements and the landscape of possible indicators. Based on these findings, dimensions, criteria and indicators representing climate resilience of a city were carried out as a hierarchical framework, integrating practical knowledge for adequate indicator selection and data acquisition that fit the priorities of Dortmund. The preparation and indicator grid calculation were based on ArcGIS for Desktop Advanced 10.4.1 (Environmental Systems Research Institute, ESRI) as well as its Spatial Analyst and Network Analyst extensions. In addition, the freely available landscape analysis program FRAGSTATS 4.27 [12,14] and remote sensing software ENVI 5.4 (Exelis Visual Information Solutions) were applied. representing climate resilience of a city were carried out as a hierarchical framework, integrating practical knowledge for adequate indicator selection and data acquisition that fit the priorities of Dortmund. The preparation and indicator grid calculation were based on ArcGIS for Desktop Advanced 10.4.1 (Environmental Systems Research Institute, ESRI) as well as its Spatial Analyst and Network Analyst extensions. In addition, the freely available landscape analysis program FRAGSTATS 4.27 [12,14] and remote sensing software ENVI 5.4 (Exelis Visual Information Solutions) were applied.

We use the results reported by Gay and Sanchez (2013) consisting in linear emission paths, and the concentrations, forcings and temperatures calculated with the use of the Magicc/Scengen up to the year 2100, to discuss the timing of reaching a warming of 1, 2, 3 and 4 degrees centigrade. To illustrate how this can be done we observe from the temperature profile that corresponds to the emission path labeled 5CO2 (that is the linear profile whose value in 2100 is five times the emissions in 1990), when the curve crosses the 1, 2, 3 and 4 °C, thresholds and look at the time when this happens. These dates depend on the sensitivity used in the model and occur sooner as the sensitivity increases.

The art of applying fuzzy rule-based techniques for down scaling of climate variables can be seen since two decades. Bardossy et al. (1995) applied the fuzzy-based method to classify the daily atmospheric circulation patterns (CPs). They stated that the fuzzy rule-based approach has high potential applications in the classification of general circulation models (GCMs). Clustering and classification of large-scale atmospheric CPs using multi-objective fuzzy technique were done by Özelkan et al. (1998). An automated objective classification of CPs for precipitation and tempera ture downscaling on daily basis was carried out based on optimized fuzzy rules (Bárdossy et al. 2002). The method produced physically realistic CPs. Fuzzy-based classification for downscaling was compared with two methods, analog method and statistical downscaling model (Teutschbein et al. 2011). The study demonstrated that the suitability of downs caling technique was highly variable with river basin under consideration.

Input variables will be related to climate change factors (temperature, precipitation and extreme weather events) and output variables will be related to ecosystem responses (biodiversity, species distribution and ecosystem services).

2.1. Input Variables

Key environmental factors such as temperature increase, precipitation change, and habitat loss are identified. These variables are selected based on their influence on ecosystem health and biodiversity. Temperature variations affect species physiology and migration patterns, while precipitation changes influence water availability and vegetation growth. Habitat loss, driven by deforestation and land-use changes, impacts species survival and ecosystem stability. Additional factors, such as carbon dioxide levels and extreme weather events, may also be incorporated to refine the model.

2.2. Fuzzy logic Approach

Fuzzy logic is a superset of conventional Boolean logic that has been extended to handle the concept of partial truth, i.e. truth values between completely true and completely false. It was introduced by Zadeh in the 1960's as a means to model the uncertainty of natural language. We aim to use the fuzzy logic approach to the problem of global temperature change modelling because it allows to treat the uncertainty inherent in this system as part of the model, not trying to avoid it, as classical approaches do. In this paper it is intended to perform approximate reasoning by means of a powerful fuzzy logic methodology named Fuzzy Inductive Reasoning (FIR). Approximate reasoning is a process by which an imprecise conclusion is deduced from a collection of imprecise premises using fuzzy sets theory as the main tool.

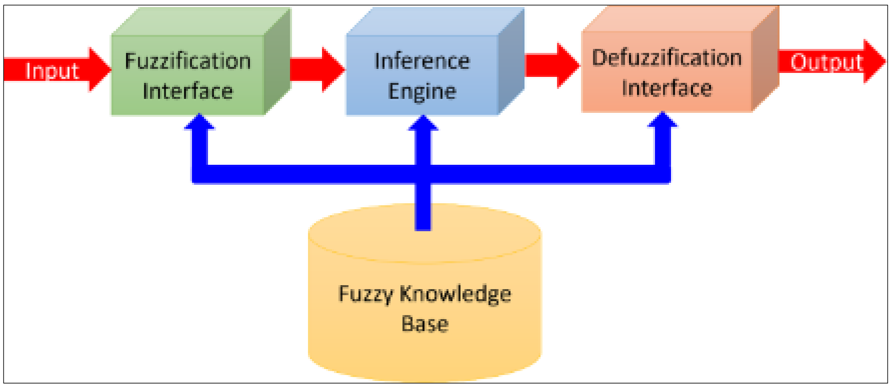

Figure 1 Fuzzy Logic

2.3. Fuzzy Inductive Reasoning (FIR)

The Fuzzy Inductive Reasoning methodology is a mathematical tool for modeling and simulation of complex systems. FIR is based on systems behavior rather than on structural knowledge. It is able to perform a selection of the system relevant variables and to obtain the causal and temporal relations between them in order to infer the future behavior of that system. It also has the ability to describe systems that cannot easily be described by classical mathematics (e.g. differential equations), i.e. systems for which the underlying physical laws are not well understood. It offers a model-based approach to predicting either univariate or multi-variate time series. A FIR model is a qualitative, non-parametric, shallow model based on fuzzy logic. FIR is executed under the Visual-FIR platform that runs under the Matlab environment (ESCOBET et al., 2007). In this section a brief explanation of the main aspects of FIR methodology are presented in order to facilitate the user the understanding of the FIR models presented in the next section. The FIR methodology performs two main tasks, i.e. the model identification and the prediction during which the model previously identified is used to estimate the future behavior of the system.

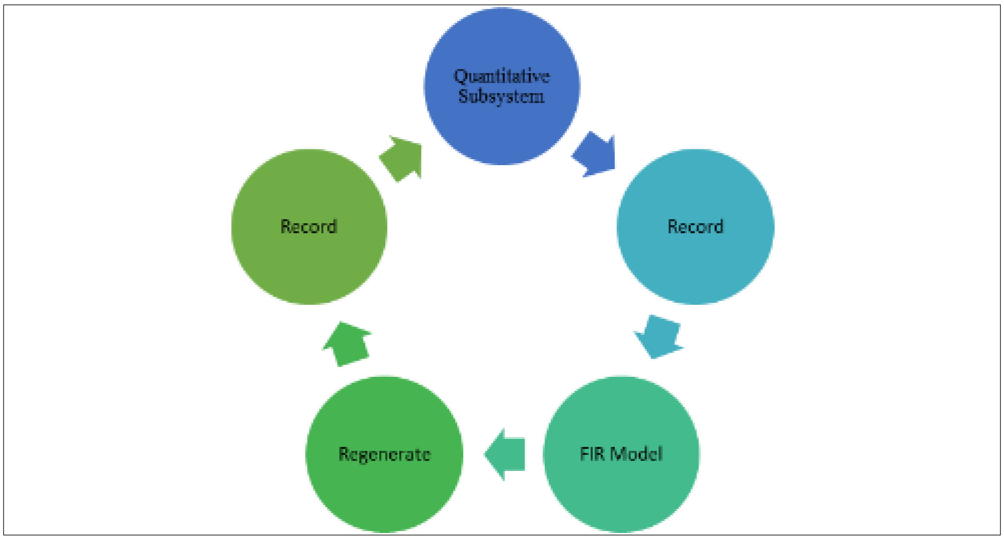

Figure 2 Fuzzy Inductive Reasoning

2.4. Fuzzy Model

A fuzzy logic model may also be known as a fuzzy inference system. In the current study, the two functional elements of the model are: firstly, the knowledge base, consisting of a number of fuzzy "if-then" rules; and secondly, a database that describes the membership functions of the fuzzy sets used in the fuzzy rules. The inference operations based on these rules are performed by the fuzzy reasoning or decision-making unit, which is founded upon the knowledge base. A typical process for building a fuzzy expert system will consist of the five steps set out below: 1. Define the linguistic variables and specify the problem; 2. Identify the fuzzy sets; 3. Create fuzzy rules by eliciting and constructing them; 4. Encode the fuzzy sets, fuzzy rules and fuzzy procedures in order to conduct fuzzy inference on the expert system; 5. Assess and adjust the system.

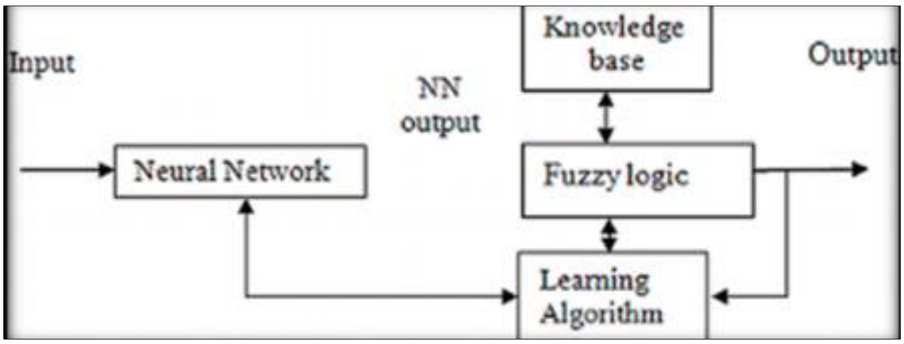

Figure 3 Fuzzy Model

2.5. Climate Change Effects on a Forest Ecosystem

To validate the proposed model, we apply it to a forest ecosystem experiencing climate change-induced stress. The model evaluates potential species migration, biodiversity loss, and habitat degradation based on fuzzy inputs. The case study focuses on a temperate forest where increasing temperatures and altered precipitation patterns threaten species diversity and ecosystem balance. The fuzzy logic model incorporates historical climate data, expert ecological assessments, and remote sensing inputs to determine ecosystem vulnerability. The results identify high-risk zones within the forest, where tree mortality rates are rising, and specific species are at risk of displacement. Conservation strategies such as assisted migration, habitat restoration, and sustainable land-use planning are recommended to mitigate the adverse effects.

Figure 4 Climate Change Effects on a Forest Ecosystem

2.6. Tree Migration

In response to climate change, some tree species will shift their ranges and migrate into landscapes in which they don't typically grow.

"Climate change can create new habitats for tree species and make existing habitats unsuitable. And like any other living thing, trees go where they can survive," Scheller said. "This process is already underway."

Some tree species are migrating uphill and northward as temperatures increase, while other species are migrating downhill and westward as changing precipitation patterns create drier conditions.

Palmetto trees, for example, could become more common throughout North Carolina in the next 50 or 60 years as they migrate from nearby states like Georgia and Florida, according to Scheller.

"Species redistribution isn't necessarily a bad thing. But it's possible that some trees could go extinct, especially those with small ranges," he said. "So if there are species we're concerned about, we need to collect their seeds and plant them in areas where we think they'll survive climate change."

Figure 5 Tree Migration

3. Result and Discussion

The logical inference rules are critical for the framework's flexibility and adaptability. They allow the model to simulate a wide range of climate scenarios, offering insights into potential ecosystem responses under varying conditions. This capacity to model complex and uncertain interactions makes the fuzzy logic framework a powerful tool for environmental management and policy-making, enabling more informed decisions to mitigate the effects of climate change on ecosystems. The "Surface Viewer Precipitation Changes and Temperature Fluctuations" section describes the visual representation of the relationship between two key input variables—precipitation changes and temperature fluctuations—and their combined impact on ecosystem responses within the fuzzy logic framework. Designed system was designed with inference mechanism Mamdani approach. In this system, the logical combination of inputs with AND operation is considered. For defuzzification process, `centroid' method is used in the designed system. The 3D surface viewer designed on the basis of the rule base. Case 1: The input variables of agriculture productivity are {(35˚C, Rise in Temperature), (35%, Weather Disasters), (4.5%, Fresh Water Availability), (125mm, Monsoon Level), (4%, Species Extinction), (17.5%, Spread of new Diseases), (0.75%, Deforestation)}.

- A1: Rise in Temperature = {(0, VL), (0, L), (0, M), (1, H), (0, VH)}.
- A2: Weather Disasters = {(0, VL), (0, L), (1, M), (0, H), (0, VH)}.
- A3: Fresh Water Availability = {(0, VL), (0, L), (1, M), (0, H), (0, VH)}.
- A4: Monsoon Level = {(0, VL), (1, L), (0, M), (0, H), (0, VH)}.
- A5: Species Extinction = {(0, VL), (0, L), (1, M), (0, H), (0, VH)}.
- A6: Spread of new Diseases = {(0, VL), (0, L), (1, M), (0, H), (0, VH)}.
- A7: Deforestation = {(0, VL), (0, L), (1, M), (0, H), (0, VH)}.

This is the fuzzy set which represents the state of medium agriculture productivity, whose linguistic string (Very Low (VL), Low (L), Medium (M), High (H), Very High (VH)). The rule states that if rise in temperature is high and weather disaster is medium and fresh water availability is medium and monsoon level is low and species extinction is medium and spread of new diseases is medium and deforestation is medium then agriculture productivity is medium. Hence, agriculture productivity is medium level with 0.5 membership grade.

The FIR model presented in the previous section has the ability of holding a high prediction power. The pattern rules interpretability is however quite low, and therefore, it is not a useful tool for decision makers. This paper is mainly focused on the global temperature change modeling for decision support and, therefore, the easy understanding and interpretation by decision makers of the model is of huge importance. In this section a model based on linguistic rules that is directly obtained from the FIR model of section 3 is presented. First, the main characteristics of the algorithm that performs the extraction of linguistic rules from the pattern rules that compose the FIR model are presented. Second, the linguistic rules model obtained for the application at hand is presented and analyzed.

In addition to these complex situations of maintenance and conservation policies, with the inclusion of possible current climate change conditions the casuistry becomes more complex. The average values of the meteorological parameters for the period 2015–2018 have been calculated based on weather reports from the last few years of the Meteorological Directorate of Chile (MDC) [56]. An annual average value growth of maximum, minimum and average temperature compared with the climatic values has been observed in recent years. According to the forecasting data obtained from CCRR [27] for the period 2045–2069, the average annual temperature in Valparaíso shows a trend of increasing by 1.30°C, the maximum temperature by 1.39°C and the minimum temperature by 1.24°C (these are average increases between the projections of RCP2.6 and RCP8.5). Generally, for the geographical area, future temperature growth will be a little below expected values for the planet [5].

After this analysis, it can be observed that the model does not show significant changes in the system output variable (functional service life of heritage buildings). Table 11 presents the functionality levels of the heritage buildings considered before (2015 2018) and after climate change variations (2045–2069). This analysis focused on the atmospheric input variables (r12, rainfall, and r13, temperature) in the current scenario and in the scenario of climate change considered, leading to the following conclusions:

Considering these scenarios related to future climate change affections, future preventive militance plans for the built heritage of Valparaíso should incorporate direct effects of atmospheric risks and natural risks, such as floods and even heavy rainfall, which can definitively affect built heritage preservation. These kinds of approaches to analyzing maintenance activities and climate change affections will ensure that heritage constructions are treated with care in order to preserve their cultural and historic values for as long as possible at adequate levels of performance (functionality). Using this approach, two elements can be discussed: (i) that the model was not previously designed for direct application to situations of climate change. However, it is able to model such situations after some careful analysis of the constructions and contexts; and (ii) that a slight decrease in the amount of rainfall and an increase in temperature over 1.5 ºC do not mean a large increase in the service life of the building. For more accurate approaches in this area, building management models should be developed with a special focus in this regard. On the other hand, if the weather forecast is checked, the years 2050 and 2080 show the largest increase in catastrophic phenomena that will clearly affect the state of conservation of the built heritage in our cities [60], with phenomena such as floods caused by heavy rainfall, concentrated within a short period of time [61]. This set of eventualities which have occurred in recent years makes it increasingly necessary to promote public policies focused on the education, preservation and conservation of tangible and intangible cultural values of today's communities. Hence, the application of methodologies such as those carried out in this study helps to establish protocols which consider intervention priorities for heritage constructions with constructive analogies. This translates to a new contribution towards economic, environmental and social policy management that is regionally, publicly and locally oriented to safeguard the cultural values of a community over time.

4. Conclusion

This study demonstrates the potential of fuzzy logic as a powerful tool for evaluating the complex and uncertain effects of climate change on ecosystems. The application of fuzzy inference models allowed for a more flexible and holistic analysis of the interactions between climate variables and ecological responses. Our findings emphasize that climate change impacts on ecosystems are not only multifaceted but also variable across different regions and environmental conditions. By incorporating both quantitative and qualitative data, fuzzy logic models provide a more accurate and comprehensive understanding of ecosystem dynamics under changing climatic conditions. The results suggest that adaptive management strategies, informed by fuzzy logic-based predictions, can enhance the resilience of ecosystems to climate change. Furthermore, this approach facilitates the development of more targeted and effective policies aimed at mitigating biodiversity loss and preserving ecosystem services in the face of ongoing environmental stressors. Future research should continue to refine fuzzy logic models, expanding their application to various ecosystems and integrating additional climate variables for more robust and precise assessments

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] "Mathias Schaefer 1, *, Nguyen Xuan Thinh 1 and Stefan'', How Can Climate Resilience Be Measured and Visualized? Assessing a Vague Concept Using GIS-Based Fuzzy Logic, Sustainability 2020, 12, 635; doi:10.3390/su12020635.

[2] "D. McNeil and P. Frecilberger, Fuzzy Logic: The Freiberger, Fuzzy Logic: The Discovery of a Revolutionary Computer Technology and How it is Changing Our World. New York: Simon and Schuster, 1992.

[3] "Carlos Gay García and Oscar Sánchez Meneses, The Fuzzy Nature of Climate Change Scenarios Maps, pages 863-873 ISBN: 978-989-758-038-3, DOI: 10.5220/0005141208630873.

[4] "Shruti Kambalimath, Paresh Chandra Deka, A basic review of fuzzy logic applications in hydrology and water resources, Applied Water Science (2020) 10:191 https://doi.org/10.1007/s13201-020-01276-2.

[5] Imran Hassan and Suman Kar, ''The application of fuzzy logic techniques to improve decision making in apparel size'', (2023), Volume 19, issue 2, pp. 607-615.

[6] "S. Karthika, N. Punithavelanb, Saroj Kumar Dasha, A. Felixa, Fuzzy Expert system for the Impact of Climate Change in Indian Agriculture, International Journal of Pure and Applied Mathematics Volume 118 No. 5 2018, 455-473.

[7] Imran Hassan, Suman Kar, Md. Toriqul Islam, "Block diagram analysis of speed time characteristics of a simple DC motor and modeling of a PID controller in fuzzy systems engineering", (2024), Volume 22, issue 2, pp. 657-664.

[8] "Rahib Imamguluyev, Sevinj Maharramova, A Fuzzy Logic Framework for Modeling Climate Change Impacts on Ecosystems, International Journal of Innovative Science and Research Technology, Volume 9, Issue 9, September–2024 ISSN No: -2456-2165.

[9] Imran Hassan and Suman Kar, "Graphical representation of addition and subtraction of Fuzzy numbers with composition table". (2023), Volume 12, issue 1, pp. 249-254.

[10] POPE, V.D.; GALLANI, M.L., ROWNTREE, P.R., and STRATTON, R.A. (2000). "The impact of new physical parameterizations in the Hadley Centre climate model-HadAM3". Climate Dynamics, Vol. 16, pp. 123-146.

[11] Md. Alamin, Imran Hassan, Suman Kar, "Examining multiplication and division on fuzzy numbers using composite tables", (2024), Volume 23, Issue 01, pp. 1075-1082.

[12] Agboola, A. H., Gabriel, A. J., Aliyu, E. O., and Alese, B. K. (2013). Development of a fuzzy logic-based rainfall prediction model. International journal of Engineering and Technology, 3(4), 427-435.

[13] Zadeh, L.A., Aliev, R.: Fuzzy Logic Theory and Applications: Part I and Part II (2018). https://doi.org/10.1142/10936.

[14] P. Muthukumar. Fuzzy Logic in Artificial Intelligence. International Journal of Research Publication and Reviews, Vol 5, no 3, pp 6061-6063 March 2024.

[15] Rahib Imamguluyev. (2023). Optimizing Room Maintenance Factor Evaluation Using Fuzzy Logic Model. Journal of Multiple-Valued Logic and Soft Computing, 41.3-5, pp. 319-337.