EVOLVING FUZZY INFERENCE-BASED DECISION SUPPORT METHODOLOGY FOR RISK MAPPING OF WASTEWATER-FED AQUACULTURE SYSTEM

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ABSTRACT: Wetlands also serve as wastewater-fed aquaculture system for augmentation and recycling of municipal wastewater. These systems are not only the place for safe disposal of huge quantity of urban sewage, but also provider of food and employment. Anthropogenic interference with commercial interest and process of urbanization has made the system dynamic and vulnerable towards exploitation. Wetlands are often misunderstood as wastelands, and as a result easy victims of the development process. Fortunately water policies do exists in India that supports and accepts the wastewater reuse. For efficient utilization and conservation of these wetland ecosystems, proper assessment and mapping is essential. In this regard, there exists a huge gap. Selection of mapping and modeling techniques for wastewater-fed aquaculture system requires the understanding of the complex components related to social, economic, technical, and environmental processes; possible trade-off variables; and its related social and economic costs. All these related datasets are sometimes incomplete and vague, which are difficult to be captured by traditional threshold-based models. Such uncertainties can be addressed by fuzzy logic, whereby fuzzy set theory provides a unifying framework for vague and fuzzy information processing. This paper presents a conceptual framework of Fuzzy Inference System (FIS) for wetland risk mapping and assessment. The framework integrates multiple risk factors and quantification of uncertainties within a system to generate consistent outcome. Remote sensing and GIS plays an integral part in generating the base layers for the system. FIS-based wetland risk assessment includes: definition of membership functions, determination of linguistic variable, construction of fuzzy rules, determination of model properties, and defuzzyfication. The fuzzy inference-based decision support system for wetland risk mapping presented here can be a useful tool for decision makers involved in the planning and management of the ecosystem.

1. INTRODUCTION

Wetlands are a crucial part of our natural environment. Besides being a provider of a wide range of environmental, social, and economic services, this ecosystem is also known as “biological supermarkets” because of the rich biodiversity they support. They are the zone of transition between aquatic and terrestrial ecosystems. Although they share the character of both the environments, on ground they cannot be classified unambiguously as either of them. In the context of the onset of global water shortage and sustainable development, wetland as wastewater-fed aquaculture system has been emphasized in many parts of the globe for augmentation and recycling of municipal wastewater. These ecosystems are not only the place for safe disposal of huge quantity of urban sewage, but also provider of food and employment. For a sustainable city, wastewater-fed wetlands provide a sustainable solution, whereby it contributes to economy, community and environment altogether.

Wetlands are often misunderstood as wastelands, and as a result easy victims of the development process. Anthropogenic interference with commercial interest and process of urbanization has made this system dynamic and vulnerable to exploitation. Opportunely, water policies do exists in India that supports and accepts the wastewater reuse. For efficient utilization and conservation of these wetland ecosystems, proper assessment and mapping is essential. In this regard, there exists a huge gap. Selection of mapping and modeling techniques for wastewater-fed aquaculture system requires the understanding of the complex components related to social, economic, technical, and environmental processes; possible trade-off variables; and its related social and economic costs. Wastewater-fed wetland systems interlock social, economic and environmental aspects that are characterized by vague boundaries and uncertain relations (Figure 1). All these related datasets are sometimes incomplete and vague, which are difficult to be captured by traditional threshold-based models. Such uncertainties can be addressed by fuzzy logic, whereby fuzzy set theory provides a unifying framework for vague and fuzzy information processing. The present paper presents a conceptual framework of Fuzzy Inference System (FIS) for East Kolkata Wetland’s risk mapping and assessment. The framework integrates multiple risk factors and quantification of uncertainties within a system to generate consistent outcome. Remote sensing and GIS plays an integral part in generating the base layers for the system.

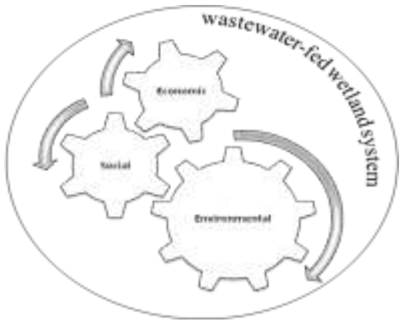


Figure 1 Wastewater-fed wetland system interlocks social, economic and environmental aspects

1.1 What is wastewater-fed aquaculture system?

Wastewater is mainly comprised of water (99.9%) and relatively small concentrations of suspended and dissolved organic and inorganic solids. Among the organic substances present in sewage are carbohydrates, fats, soaps, synthetic detergents, proteins and their decomposition products. Therefore, wastewater-fed aquaculture is a productive wastewater treatment system. It is different from conventional waste water treatment plants, where it normally consists of mechanical pretreatment, followed by activated sludge treatment and post-treatment units. In wastewater-fed aquaculture system, wastewater is respected as a resource and an economic opportunity, whereby waste water is reused instead of being disposed off. This system is an ancient but nevertheless innovative and successful way to treat and recycle wastewater. Wastewater is directly reused to produce fish and aquatic plants (duckweed) for human consumption and high-protein animal feed respectively. In a paper entitled "The future of ecological engineering", Guterstam and Etnier (1996) wrote that "it is feasible to use ecological engineering on a large scale because of examples in the world for wastewater-fed aquaculture systems: the Munich system as a 'historical monument'; and 'reality' in Asia in cities in China, Hanoi and Calcutta. Because of its nature-like, low-tech and income-generating structure, it has often proved to be a sustainable biological wastewater treatment method". Such type of wetland systems are mainly practiced in some countries of Asia (India, China, Vietnam, Bangladesh, Indonesia etc.); Europe (Germany); and Africa (Egypt).

1.2 Study Area

East Kolkata Wetlands (EKW), the world largest wastewater fed aquaculture system, is a unique and complex ecological process that has been adopted by the local community through their indigenous knowledge for mastering the resource recovery activities (Furedy and Ghosh, 1984; Ghose, 1999, Kundu et al.,2008). EKWs are located in the eastern side of Kolkata city, West Bengal, India; approximately between 22°25' to 22°40' lat. North and 88°20' to 88°35' long. East (Figure 2). EKWA encompasses 125 sq km. with 37 *mouza* (revenue villages). It is situated on the mature delta of River Ganga, with gradient towards south-east by about 0˚2' (Clarke, 1865), and elevation between 3-6m above mean sea level. The groundwater exists in perched aquifers, lying upto a depth of 100-150 m. However, owing to the high organic content of wetland's bottom soil, they are not efficient in groundwater recharging.

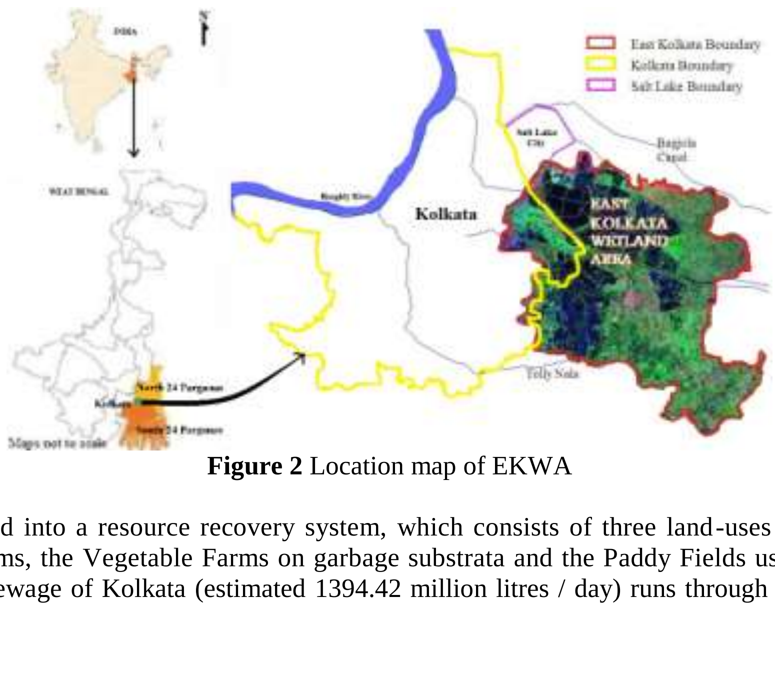


Figure 2 Location map of EKWA

EKWA was developed into a resource recovery system, which consists of three land-uses (besides settlements): Sewage-Fed Fish Farms, the Vegetable Farms on garbage substrata and the Paddy Fields using fishpond effluent. The entire domestic sewage of Kolkata (estimated 1394.42 million litres / day) runs through a network of principal and ancillary channels transversing through the East Kolkata Wetlands. Livelihoods of the local communities of EKWA are distinctly linked to wetland resources, with 74% of the working population drawing sustenance through primary activities (i.e., engagement in fish farming, agriculture and horticulture). Despite their potential to provide multiple natural and social services, these wetlands are under constant threat of conversion or exploitation (Mukherjee, 1990; Sikdar et al. 2002; Kundu et al. 2005; Paul et al. 2011). This has called for the urgency to map the wetland conversion risk of the study area.

2. METHODOLOGY

2.1 Concept of Fuzzy logic

Fuzzy logic has been introduced as a simple way to draw definite conclusions from vague, ambiguous or imprecise information. The difference between fuzzy sets and classical/ crisp sets can be characterized by means of a membership function. In a crisp set an element can be either of the two choices of whole or nothing i.e., [1, 0]. The concept of the fuzzy set softens this constraint and allows the concept of partial membership, where one element can be the member of both the choices simultaneously by holding nonzero membership grades (Figure 3).
Let *X* represent a universe of discourse composed of generic elements denoted by *x*. In classical set theory, crisp set *G* of *X* is defined as function $f_G(x)$ called the characteristic function of *G*:

$$f_G(x): X \rightarrow \{0,1\}, \text{ where } f_G(x) = \begin{cases} 1, & if \quad x \in G \\ 0, & if \quad x \notin G \end{cases}$$

This set maps, for any element x of universe X, characteristic function $f_G(x)$ is equal to 1 if x is an element of set *G*, and is equal to 0 if x is not an element of *G* .
However, a fuzzy subset *G* of *X* is determined by a membership function μG, which assigns a membership grade within the interval [0, 1] to each element *x*.

$$\mu_G(x): X \rightarrow \{0, 1\}, \text{ where } \mu_G(x) = 1, \text{ if x is totally in } G$$
$$\mu_G(x) = 0, \text{ if x is not in } G$$
$$0 < \mu_G(x) < 1, \text{ if x is partially in } G$$

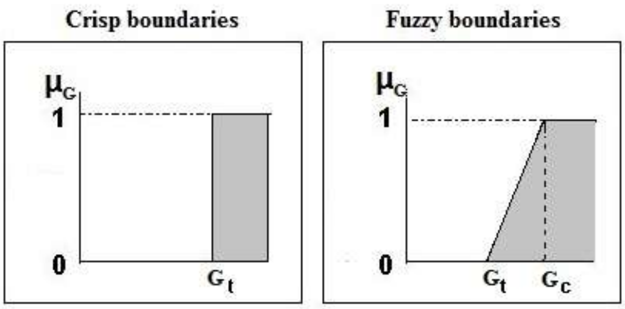


Figure 3 Boundary value (G_t) and Boundary core value (G_c) for set G of *X*

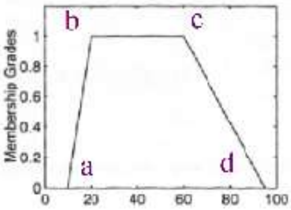
Therefore, Fuzzy approach uses an uncertainty gradient having values between zero (no membership) and one (full membership) that imitates the nature of imprecise data and makes it a prime candidate for inclusion in a model framework (Zadeh, 1965).

2.2 Fuzzy Inference System

Fuzzy Inference System is a simple but efficient scientific tool that simulates the system to draw inference from model inputs. The most commonly used fuzzy inference technique is the Mamdani method. The system basically includes four stages: 1) Fuzzification, 2) Rule evaluation, 3) Inference of fuzzy results, and 4) Defuzzification (Bojadziev and Bojadziev, 2007).
During fuzzification, the numerical values of the input and output factors are transformed into a fuzzy set through a membership grade. A membership function is a curve that represents the degree of belongingness of a point in the given input space to a membership value between 0 and 1. Fuzzy IF-THEN rules are constructed with the help of linguistic variables, where these variables are defined by membership functions. Since input data are described using linguistic variables and membership functions, fuzzy IF-THEN rule is viewed as a 'scheme for capturing imprecise knowledge'. The fuzzy sets interact among themselves through fuzzy rules that are expressed by mainly three operators, namely, AND, OR, and NOT operators. The last stage of the system is defuzzification. The resultant output data of the inference engine are fuzzy values. During defuzzification, these values are transformed to real numeric value.

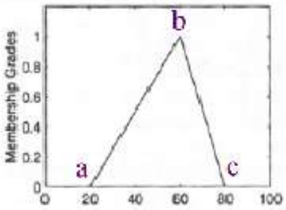
In the present assessment, Trapezoidal, Triangular and Gaussian membership functions are used to transform the risk factors/indicators into fuzzy sets. Trapezoidal membership function depends on four scalar parameters *a*, *b*, *c*, and *d*, where the parameters *a* and *d* locate the "feet" of the trapezoid and the parameters *b* and *c* locate the "shoulders" and is represented as in figure 4A. Triangular membership function depends on three scalar parameters a, b, and c, where the parameters *a* and *c* locate the "feet" of the triangle and the parameter *b* locates the peak and is represented as in figure 4B. Gaussian membership function is built on the Gaussian distribution curve (Normal curve) and depends on two parameters m, σ, where *m* and σ defines the center and width of the function, and represented as in figure 4C.

$$trapezoidal(x : a, b, c, d) = \begin{cases} 0 & x < a \\ (x-a)/(b-a) & a \le x < b \\ 1 & b \le x < c \\ (d-x)/(d-c) & c \le x < d \\ 0 & x \ge d \end{cases}$$



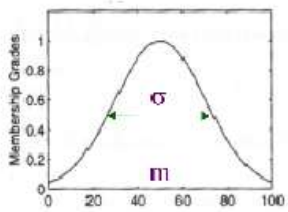
(A)

$$triangle(x : a, b, c) = \begin{cases} 0 & x < a \\ (x-a)/(b-a) & a \le x \le b \\ (c-x)/(c-b) & b \le x \le c \\ 0 & x > c \end{cases}$$



(B)

$$gaussian(x : m, \sigma) = e^{\frac{-(x-m)^2}{\sigma^2}}$$



(C)

Figure 4 Membership functions (A) Trapezoidal; (B) Triangular; and (C) Guassian.

2.3 Selection and formulation of wetland risk Indicators

In this study, eight indices were selected, which addresses the most vital issues concerning the wetland risk of the EKWA. Since every ecosystem is unique in its own way, the inference model was developed through available scientific knowledge and expert's opinion. Accordingly, at the first level 22 indicators were selected, which were further consolidated into eight indices, namely, 'Wetlands conversion rate', 'Canal proximity', 'Road proximity', 'Population density', 'Population growth rate', 'Infrastructure status', 'Livelihood status', and 'Social status'. Owing to the functional complexity of the region, the indicators were aggregated to generate an index ('Infrastructure Composite Rank Index', 'Livelihood Composite Rank Index', and 'Social Composite Rank Index'), and were considered to be of equal weightage. As per the expert opinion, giving different weight to the indicators may make the study biased, since all of them are significant for the index. All the selected indicators were categorised into 'ranks' for standardization in measurement.

The 'Wetlands conversion rate' was calculated through remote sensing based change detection technique. The Land-use/Land-cover (LULC) maps for year 2002 and 2012 were generated using Fuzzy c-Means (FCM) algorithm. Using the wetland change percentage for all the 37 *mouza* by IDW interpolation method, the wetland conversion rate map was generated. Buffers ranging from 200 m to 3000 m were created around the canals to generate the 'Canal proximity' map. 'Road proximity' map was generated by creating distance-wise buffers ranging from 200m to 3000m around the roads. Population density of EKWA was generated from *mouza*-wise population totals and area (in hectares) obtained from Census of India, 2011. While *mouza*-wise population growth rate was calculated from the population totals of 2001 and 2011.

The 'Infrastructure status' was generated from 'Infrastructure Composite Rank Index', which was computed on the basis of Medical facilities availability, Educational institution status, Electricity availability, Availability of Irrigation facilities, Supply of Newspaper and Magazines, and Presence of Banks and Post-offices. The 'Livelihood status' was generated from 'Livelihood Composite Rank Index'. The Index was calculated on the basis of following indicators: Work participation, Work duration by type of workers, Saving account status, Participation of women workers, and Availability of Livestock. The 'Social status' was generated from 'Social Composite Rank Index'. The Index was calculated on the basis of following indicators: Literacy rate, Female literacy rate, House type, Fuel sources, and Toilet facilities.

2.4 Construction of Risk Assessment Model

A four stage process was followed to achieve the risk map of the study area. They are:

1) Problem identification and Selection of model input indicators
2) Determine fuzzy sets and define linguistic variables
3) Construction of fuzzy rules
4) Determination and selection of operators and inference, and defuzzification methods

Figure 5 shows the framework for wetland risk mapping in EKWA with the application of fuzzy inference-based risk assessment model.

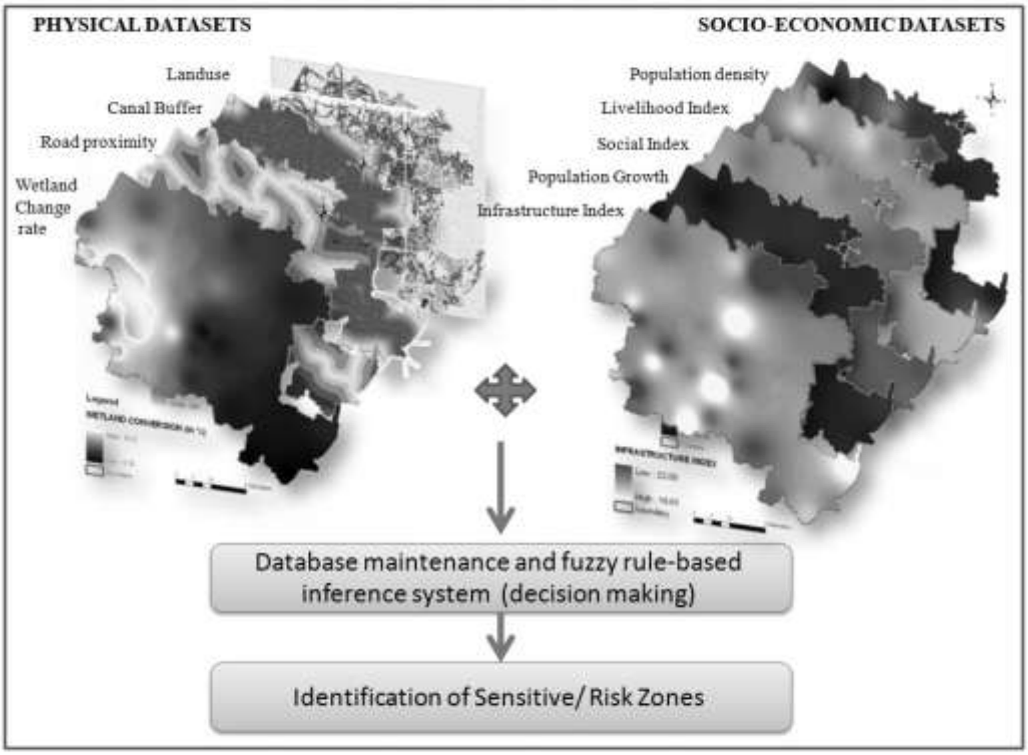


Figure 5. Framework for wetland risk mapping by Fuzzy Inference System

3. RESULT AND DISCUSSION

3.1. Analysis of Input variables

The 'Wetlands conversion rate' map was generated from the Landuse/landcover (LULC) maps for 2002 and 2012. To identify the areas where the conversion of wetlands to other land cover classes has taken place, change detection matrix was calculated and subsequently, a wetland change detection map was generated.

The final outputs of rest of the indices, like, 'Road proximity' and 'Canal proximity' maps; 'Population growth' and 'Population density' maps; 'Infrastructure status'; 'Livelihood status'; and 'Social status', have been presented in figure 6.

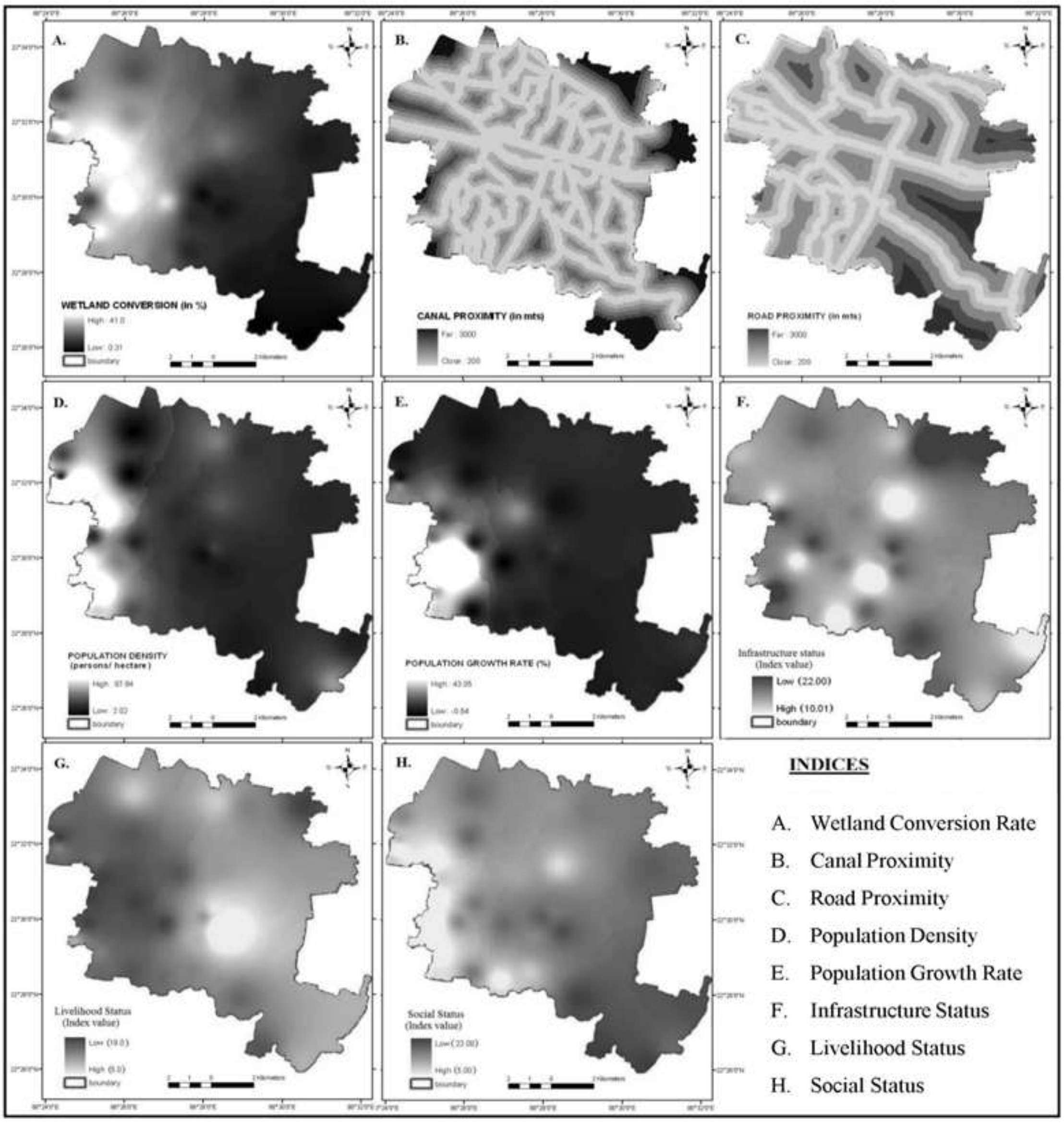


Figure 6 Final input indices' maps.

3.2. Membership Functions and Linguistic Variables

All the input layers of selected indices were created under GIS environment, and were integrated through Fuzzy Inference System for wetland risk assessment modelling. The selected indices for 'Risk Assessment Model' were developed with ArcGIS software, and the 'Fuzzy Inference System' of 'Fuzzycell' software developed by Yanar, 2003 was used for wetland risk assessment modelling.

In fuzzy interface system various membership functions are available. For 'Wetland Conversion rate', 'Population density', 'Population growth rate', 'Infrastructure index', 'Livelihood index', and 'Social index', Trapezoidal membership function was selected with three fuzzy sub-regions as 'High', 'Moderate' and 'Low'. For 'Road proximity' and 'Canal proximity', Triangular membership function was selected with three fuzzy sub-regions 'Near', 'Moderate' and 'Far', and for risk factor, Gaussian membership function with a scale of '0 to 100' risk gradient was selected with three fuzzy sub-regions namely 'high', 'moderate' and 'low' (Figure 7).

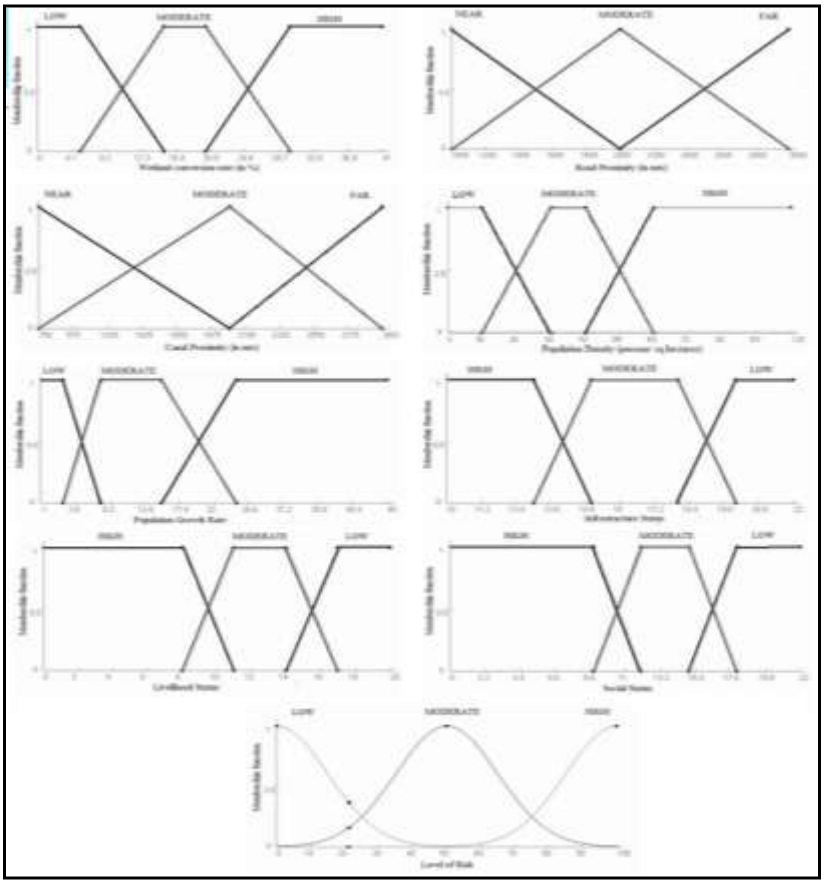


Figure 7. Linguistic variables and Membership functions of input and output indices.

3.3. Fuzzy rules

The fuzzy If-then rules for the model were constructed with the help of expert opinion. Finally following rules were constructed to map wetland conversion risk existing in EKWA (Table 1):

Table 1. Model Rules.

	Operators	RULE 1	*Operators*	RULE 2	*Operators*	RULE 3
If						
Wetland conversion		High	*Not*	Low		Low
	And		*And*		*And*	
Population density	*Not*	Low		Low		Moderate
	And		*Or*		*Or*	
Population growth rate	*Not*	Low		Moderate		Low
	And		*And*		*And*	
Infrastructure status	*Not*	Low		Low		Low
	Or		*Or*		*Or*	
Livelihood status		Low	*Not*	High		High
	And		*Or*		*Or*	
Social status	*Not*	Low		Moderate		Low
	And		*And*		*And*	
Canal proximity				Close		Close
					Or	
Road proximity		Close				Moderate
Then						
Risk factor		High		Moderate		Low

3.4. Model Properties

After the construction of the multi-rules, model properties were determined (Table 2). Mamdani model has been used, since it provides more functionality to approximate human experience and knowledge in classification and decision making process (Mamdani, 1977); and in practice it is one of the widely used fuzzy model (Yanar, 2003). In this model, the output of a rule-based fuzzy model is computed by the max-min relational composition.

Table 2. Model properties for classification of risk factor layer using multi rules.

Fuzzy Interface System model	Mamdani Model
AND operation	Minimum operator
OR operator	Maximum operator
Implication	Minimum operator
Aggregation	Maximum operator
Defuzzification process	Centre of area (COA) defuzzifier

3.5. Model result analysis

The resultant output of the classification based on rule and model properties, generated a soft output map with various shades of gray. The gray colour array represents the varing intensity of risk, ranging from 11 to 88 risk gradient. The gradual change of shades from dark to light demarcate the wetland conversion risk status over EKWA from low to high. Further, the whole region of EKWA was divided into five ‘Risk Zones’ on the basis of obtained risk gradient scale (Figure 8), i.e., very high (>60), high (50-60), moderate (40-50), Low (30-40) and Very low (<30). Later the risk zone classified map was superimposed by *mouza* boundary to identify the *mouza* that are falling under different risk zones. The map shows that *mouza* located close to the Kolkata city are under very high risk of wetland conversion, indicating the city influence on wetland area.

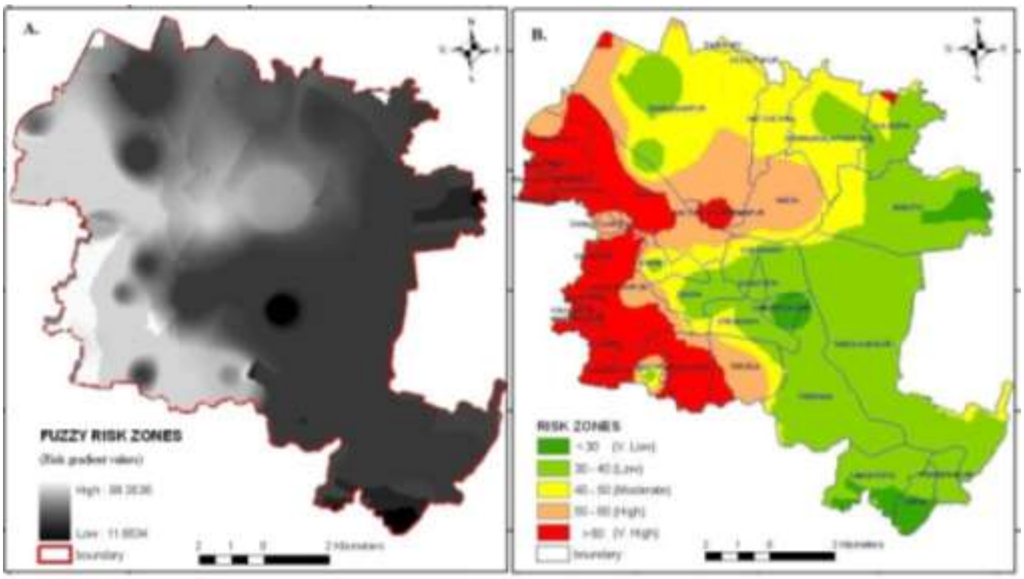


Figure 8 (A.) Fuzzy output of level of risk; (B.) Categorization of Risk Zones superimposed by *mouza* boundaries

4. CONCLUSION

The study applied Fuzzy Inference System to map the wetland conversion risk of EKWA. Like many other geospatial entities, wetlands have fuzzy boundaries in both attribute space and geographic space. Fitting such entities and their risk factors into discrete categories with crisp boundaries induces uncertainties in the class assignments. Therefore, fuzzy logic has provided a simple way to capture and map the uncertainty or vagueness in natural resources boundaries. The fuzzy inference-based decision support system for wetland risk mapping presented here can be a useful tool for decision makers involved in the planning and management of the ecosystem. Understanding the wetland conversion risk of EKWA, we are exploring the feasibility of the present model on other such wastewater aquaculture systems of Bally-Kona, Titagarh-Bandipur and Kalyani in West Bengal.

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