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Groundwater potential evaluation using fuzzy inference system

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ABSTRACT

Fuzzy system uses human intelligence for quantifying the prediction in real world scenario through proper modelling of the fuzziness of real world data by defining rules. Fuzzy inference system (FIS) address the reasoning process of human thinking by means of fuzzy logic by giving set of fuzzy IF THEN rules. FIS are used to solve in making decisions to the problems. Here, below the ground is an imaginary sector that cannot be seen only measured and focused in research. The lithology below the ground is studied based on the data observed by observation wells. Nambiyar Watershed is an over-exploited zone in which the water level is under depletion day-to-day going down and is crucial at this state and its mandatory to be improved. This study helps to highlight the scenario of the study area and its potentiality of water resource. The analysis is carried out in ArcGIS software finding the site suitable for artificial recharge and the ground water potentiality is evaluated using FIS, which implies the human reasoning. The potential evaluation of ground water is found by the usage of FIS in the proposed work. This research identifies site suitable for groundwater recharge and these results are visualized for ground water remedial measures.

Keywords: Groundwater; Remote sensing; GIS; Potential evaluation; Fuzzy inference system

1. Introduction

In the recent decades, groundwater gets depleted and over-exploited in most of the hard rock terrain areas. The water level depletion is the very crucial challenging one in the field of civil engineering to protect and save the water resources. In this study, the water level potentiality is evaluated using fuzzy system. Fuzzy system is a challenge in the field of ground water engineering whereas Mamdani's method was among the first control systems built using fuzzy set theory by Mamdani in 1975. Fuzzy logic is widely used for process simulation control introduced by Mamdani and Assilian. Here, this is designed based on the results obtained in ArcGIS for the parameters, aquifer depth, ground water fluctuation (GWF), potential recharge in this study. The ranges are assigned based on the outcome of ArcGIS mapping results.

This paper introduces fuzzy inference systems (FISs) with the results derived from thematic maps prepared in ArcGIS and is given as input data. Here, 16 sets of rules were given to find out the potentiality of the ground water. The human intelligence can reason with uncertainties, vagueness, imprecision and judgments. Fuzzy logic simulates human uncertainty understanding of the world beyond which human can convey; FIS reflects the human reasoning processes into effect. There are numerous studies on remote sensing and GIS methods to map the ground water potential zones. Identification of potential artificial recharge zones using GIS was studied [1–3]. However, the usage of fuzzy inference in the proposed work allows providing human reasoning in the process of ground water potential evaluation.

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So, this study focuses on the watershed with the ArcGIS results given as input data sets in FIS which calculates and visualizes based on the status and ground water level, resulting in the potentiality of that particular area. It gives clear graphical visualization with knowledge for those particular ground water ranges to have research focus in a better way of understanding.

2. FIS model and its application

There are many papers using FIS model and few FIS application papers are listed below.

The most important water quality parameter, dissolved oxygen, one of the crucial parameter was analyzed [4]. The resulting configuration proved a good modeling approach for MWTP effluent quality prediction [5]. Study on potential zone of hydrocarbon in determining the subsistence using FIS [6]. Muka et al. [7] says in the paper, based on the problem the specific objectives are to explore the use of fuzzy logic and to develop a fuzzified model for rainfall amount. A file depicting the landslide susceptibility degrees for the study area was produced using the Mamdani FIS [8]. Uranium study based on modelling was studied [9]; irrigation water quality evaluation study has undergone [10]. MFIS is the acceptable, reliable and logical method in the classification of water quality for irrigation purposes than other methods [11]. Simple fuzzy controller architecture for a steam turbine was used to show how fuzzy control models work [12] and fuzzy applications are explained [13,14]; study on optimum orientation of solar panels was analyzed [15]. The study confirms the applicability of fuzzy logic for optimization of conditions in the decolourization process in textile wastewater treatment process [16]. Mamdani fuzzy logic in a geographic information system environment was used to evaluate forest fire vulnerability maps and their performances [17]. Comparison results of Mamdani type fuzzy logic were used for the valuation of properties of concrete [18]. In the paper, application of reinforced concrete structural problems such as prediction of concrete strength, optimizing the fibre RCC retrofit of columns, shear strength concrete beams, finding the optimal concrete mix design and concrete strength prediction [19]. A new method is proposed for the study on mining evocative using optimized Mamdani FISs to predict the strength of whole rocks and anisotropic rock [20]. A fuzzy model used to predict the uniaxial compressive strength of a problematic rock was studied [21]. New fuzzy model for risk assessment was studied [22]. Fuzzy rule model is a feasible model for classification of aqua sites [23]. Study on categorization of uniform plant and soil was evaluated [24]; colour image classifications were evaluated in poultry inspection [25]. Mamdani and Sugeno-type fuzzy inference models are used for management of water flow rate in a cement industry [26]. Predictions of crop growth strategy information in the soil were evaluated in the study [27]. Prediction of soil properties was studied using fuzzy [28]. It is one of the very important factors that identify the soil productivity [29]. The integration of these methods with main difference of the proposed approach is the way to provide a more accurate risk assessment [30]. The choice of fuzzy parameters and the comparison of different results were studied [31]. It has been shown to be a strong methodology of design and analysis in control theory [32]. In this research paper, FIS model helps to visualize the potentiality of groundwater for Nambiyar basin.

3. Fuzzy model

Fuzzy logic is used to give significance of precision and the application of fuzzy set theory to many problems. The steps defining the fuzzy model are shown in Fig. 1.

Where, fuzzification is to translate input into values, rule evaluation is to compute output values and defuzzification is to transfer values into output.

3.1. Fuzzification

The purpose of fuzzification is to map the inputs from a set of values from 0 to 1 using a set of input membership functions. Once aggregation process is over, the next step there is a fuzzy set for each output variable that needs defuzzification. It increases the efficiency of the defuzzification process since it significantly simplifies the calculation required by the universal Mamdani method, which finds the centroid of a two-dimensional function. To determine the centroid value, the weighted average of a few data points is used. A membership function (MF) is a curve that defines each point in the input space mapped to a membership value. Zadeh [33] introduced MFs in the first paper on fuzzy sets. He proposed a MF with a range of interval (0, 1) working on the domain of all possible values. MFs allow us to graphically represent a fuzzy set [33].

There are different forms of MFs such as triangular MF (trimf), trapezoidal MF(trapmf), piecewise linear MF, Gaussian MF (gaussmf), Gaussian combination MF (gauss2mf), sigmoid MF (sigmf), difference sigmoidal MF (dsigmf), product sigmoidal MF (psigmf), bell-shaped function (gbellmf), singleton MF, quadratic polynomial curves, cubic polynomial curves named because of their shape (functions are smf, zmf, and pimf).

Among the existing MFs, the triangular MF is the simplest one, whereas the calculations are simple, easy, piecewise linear functions whose derivatives are not continuous facilitating easy computations. Both triangular and trapezoidal membership are simple as they are also piecewise linear providing a linear mapping of the universe of discourse. For triangular MFs, the membership value can be

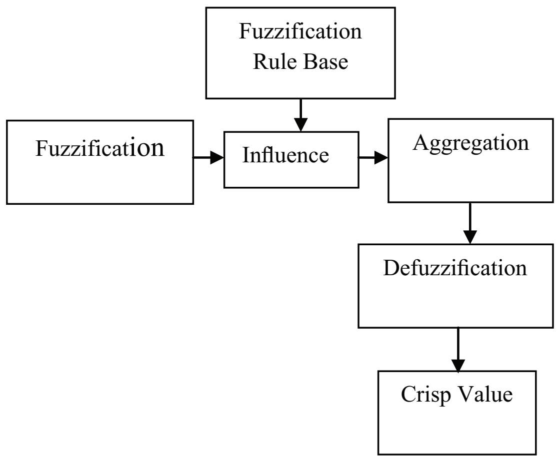

Fig. 1. Flowchart for fuzzy inference system.

easily computed, popular one and most commonly used. From the input range, the corresponding linear equation is identified for each input and solved to obtain the membership value, $i(x)$ is the degree to which a given input x belongs to that MF and $0 < f(x) < 1$.

Triangular function membership is defined by a lower limit a, an upper limit b, and a value m, where $a < m < b$ as in Eq. (1):

$$\begin{Bmatrix} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{Bmatrix} \tag{1}$$

$$f(x,a,b,c) = \max\left(\min\left(\frac{x-a}{b-a},\frac{c-x}{c-b}\right),0\right)$$

Each elements is mapped to [0, 1] by MF. μA: $X \to [0, 1]$ in fuzzy sets [34]. The x axis represents the universe of discourse, whereas the y axis represents the degrees of membership in the [0, 1] interval. The triangular MF used is shown in Fig. 2.

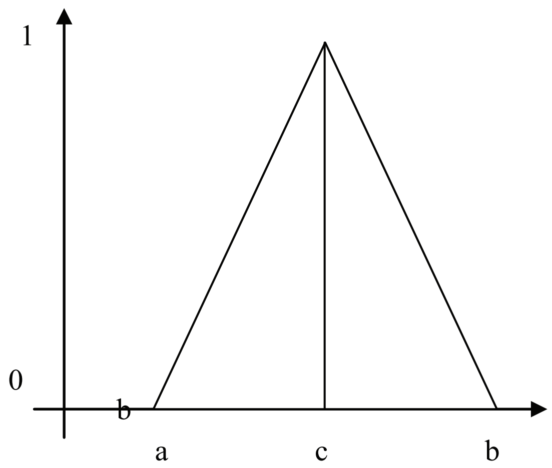

Fig. 2. Triangular membership function.

In fuzzy logic, the basic operations union, intersection and complement fuzzy sets are given in Table 1.

3.2. Defuzzification

This crisp number is obtained in a process known as defuzzification. There are two common techniques for defuzzifying, one by center of mass and another by mean of maximum outputs. To clear determination of defuzzification, the best is to first draw in x-axis all the implied fuzzy sets to get a crisp value.

4. Study area and methodology

4.1. Study area

The Nambiyar Watershed study area is a hard rock terrain located in Tirunelveli district in Tamil Nadu state, India. The coordinates of the study area are between longitudes 77°30′ E and 78° E and latitudes 8°30′ N and 8°10′ N.

4.2. Methodology

The main concept of fuzzy logic is widely used in control system, precision system, and prediction system for design, development and decision making. Real system of groundwater studies is a very complex system and the prediction related potentiality is always impulsive, so this FIS helps to understand the variation of potentiality with respect to time. Fuzzy logic design is the best approach to get precise, accurate result and conclusions. Individual classes for Raster Maps are taken as fuzzy membership parameters, thus fuzzy membership curve is drawn. Prediction system using FIS model for groundwater potentiality helps and tests the potentiality and potential requirement to an extent. Fuzzy logic model can be used to combine aquifer depth to basement and ground water fluctuation along with potential recharge for estimating the potential capability of the study area of Nambiyar Watershed. Fig. 3 represents the flowchart for the ground water potential mapping.

Table 1
Relationship between logical operations and fuzzy operations

Logical operations	Logic	Fuzzy operations
AND	μA and μB be membership functions that define the fuzzy sets A and B, on the universe X.	Union (max) $\mu_{A\cup B}(x) = \mathrm{Max}(\mu_A(x),\mu_B(x))$
OR	μA and μB be membership functions that define the fuzzy sets A and B, on the universe X.	Intersection (min) $\mu_{A\cap B}(x) = \mathrm{Min}(\mu_A(x),\mu_B(x))$
NOT	μA be a membership function that defines the fuzzy set A, on the universe X.	$\mu_{A^c}(x) = 1 - \mu_A(x)$

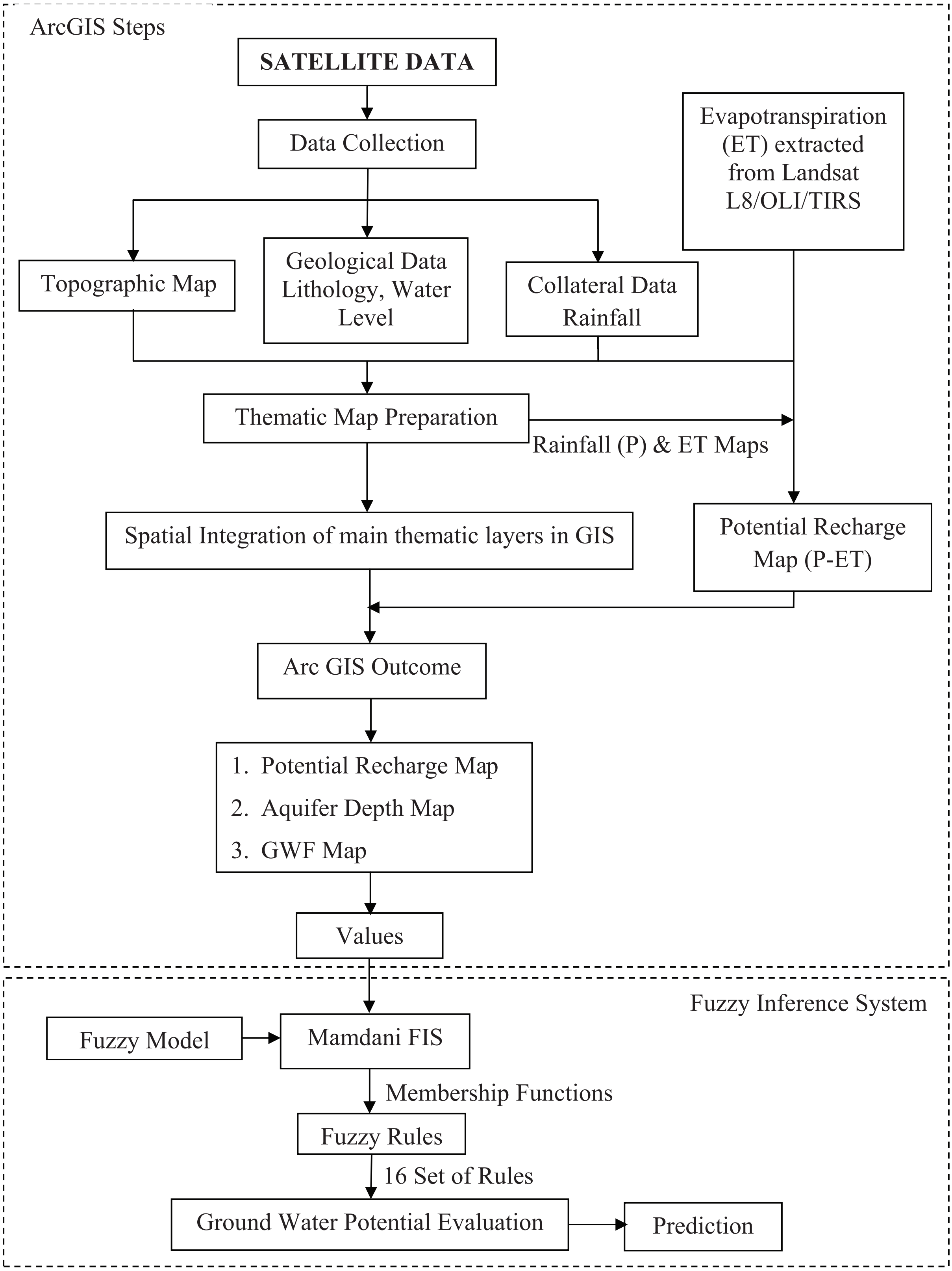

Fig. 3. Flowchart for ground water potential mapping and prediction.

5. Results

5.1. ArcGIS results

The aquifer depth, potential recharge map, ground water fluctuation map are ArcGIS raster maps are prepared for Nambiyar Watershed shown in Figs. 4–6. These thematic maps show the ranges of high to low for GWF as its the water table variation in pre-monsoon and post monsoon, aquifer depth, potential recharge (RF-ET) influencing the scenario of the study area. These maps give the ranges of parameters MF for the FIS model.

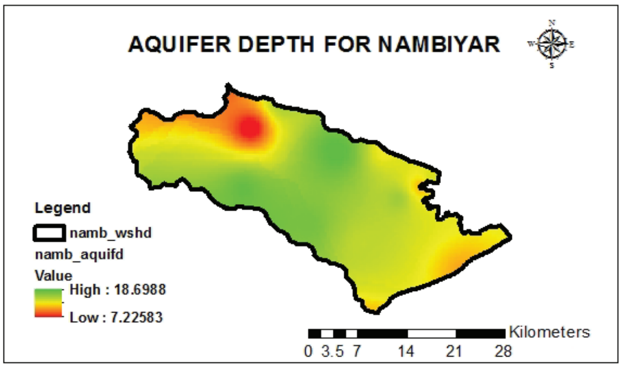

Fig. 4. Aquifer depth of Nambiyar study.

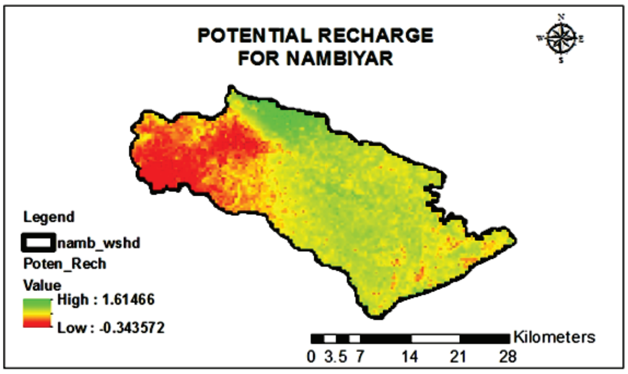

Fig. 5. Potential recharge map obtained for Nambiyar study.

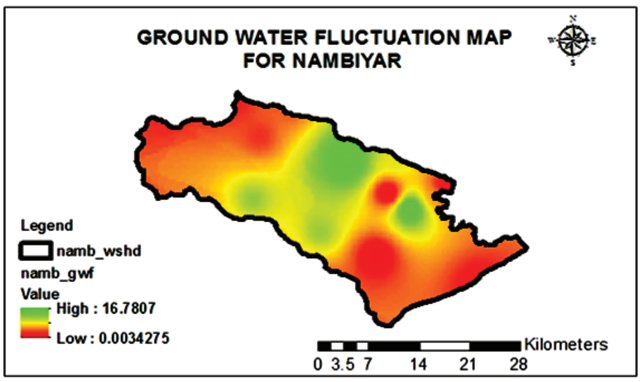

Fig. 6. Ground water fluctuation map obtained for Nambiyar study.

5.2. GIS outcome

The aquifer depth, potential recharge derived based on rainfall minus evapotranspiration for the year 2014 are analyzed in ArcGIS, ground water level ranges obtained are shown below:

Aquifer depth – High – [15 – 18.7]
Mod – [12 – 15]
Low – [10 – 12]
Poor – [7 – 10]
Potential recharge – High – [1 – 1.7]
Mod – [0.5 – 1]
Low – [0.1 – 0.5]
Poor – [–0.93 – 0.10]
GWF – High – [15.1 – 16.8]
Mod – [10 – 15.1]
Low – [5 – 10]
Poor – [0.0034 – 5]

As mentioned in Eq. (1) above, a triangular MF is specified by three parameters [*a*, *b*, *c*]. A set containing elements that have varying degrees of membership in the set is defined to be fuzzy set [13].

There are four fuzzy variables and four fuzzy sets used in this study. Aquifer depth, potential recharge and GWF are three input variables and ground water potential evaluation is the output variable. In each fuzzy variables, four fuzzy sets say; high, moderate, low, poor with MF parameters given as [*a*, *b*, *c*] in triangular MF.

Here, in aquifer depth variable, high water level potential of high fuzzy set for parameter *a* is 15, *b* is 16, *c* is 18.7; for moderate fuzzy set, the parameters *a* is 12, *b* is 13.5, *c* is 15; for low fuzzy set, parameters *a* is 10, *b* is 11, *c* is 10; for poor fuzzy set, parameters *a* is 7, *b* is 8.5, *c* is 10.

Here, in potential recharge variable, high water level potential of high fuzzy set for parameter *a* is 1, *b* is 1.35, *c* is 1.7; for moderate fuzzy set, the parameters *a* is 0.5, *b* is 0.7, *c* is 1; for low fuzzy set, parameters *a* is 0.1, *b* is 0.3, *c* is 0.5; for poor fuzzy set, parameters *a* is –0.93, *b* is –0.49, *c* is 0.10.

Here, in GWF variable, high water level potential of high fuzzy set for parameter *a* is 15.1, *b* is 15.9, *c* is 16.8; for moderate fuzzy set, the parameters *a* is 10, *b* is 12.5, *c* is 15; for low fuzzy set, parameters *a* is 5, *b* is 7.5, *c* is 10; and for poor fuzzy set, parameters *a* is 0.0034, *b* is 2, *c* is 5.

In potential evaluation variable, high water level potential of high fuzzy set for parameter *a* is 14, *b* is 17, *c* is 20; for moderate fuzzy set, the parameters *a* is 10, *b* is 12, *c* is 14; for low fuzzy set, parameters *a* is 6, *b* is 8, *c* is 10; and for poor fuzzy set, parameters *a* is 0, *b* is 3, *c* is 6. All parameters are in meters (m).

The results of Nambiyar basin were taken from ArcGIS and given as input in fuzzy to perform the analysis to find out the potentiality of water on the ground for the study area based on the conditions. This fuzzy model helps to find out the status of today in real time.

Triangular fuzzy numbers have been extensively applied in fuzzy control and fuzzy decision-making [35].

5.3. Fuzzy results

The fuzzy step-by-step procedure is done and the results are shown as follows. The FIS MFs are given in Fig. 7.

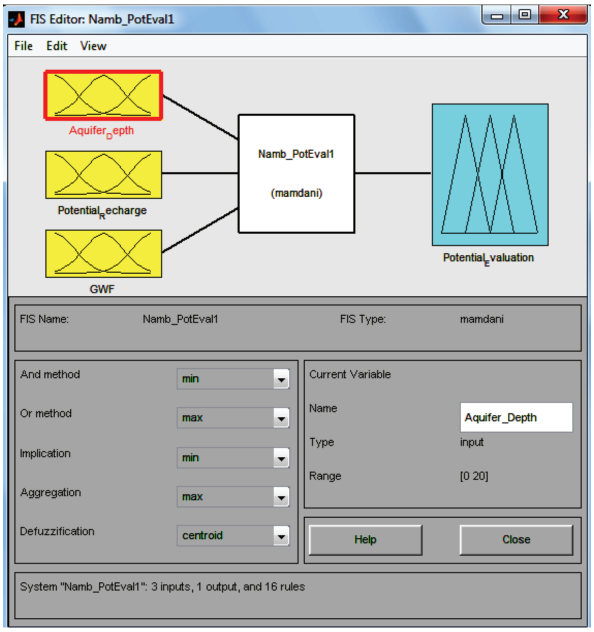

Fig. 7. Developed fuzzy inference system.

The FIS MF is generated for each variables. Fig. 8 shows the MFs for each input and output parameters.

Fuzzy model is the fuzzy decision making system used here to predict the potential evaluation capability of the study area. The dependent parameters are taken with the range values and with the help of fuzzy, the inference rules are framed using 16 rules in the form of IF…THEN structures in MATLAB for developing a prediction model as in Fig. 9. It is interesting to denote how to control a process. The rules in general are represented as If premise Then consequent [32]. Fuzzy model is used for the prediction of potential evaluation of the study area based on the effective data derived.

If-then rule for a single fuzzy; The if-part of the rule "*x and y* is *A*" and "B" called the *antecedent* or premise, while the then-part of the rule "*z* is *C*" is called the *consequent* or conclusion.

Following fuzzy rules showed in fuzzy editor, the FIS rules are shown below as:

1. If (aquifer depth is high) and (potential recharge is high) and (GWF is high) then (potential evaluation is high)
2. If (aquifer depth is moderate) and (potential recharge is moderate) and (GWF is moderate) then (potential evaluation is moderate)
3. If (aquifer depth is low) and (potential recharge is low) and (GWF is low) then (potential evaluation is low)
4. If (aquifer depth is poor) and (potential recharge is poor) and (GWF is poor) then (potential evaluation is poor)
5. If (aquifer depth is high) and (GWF is high) then (potential evaluation is high)

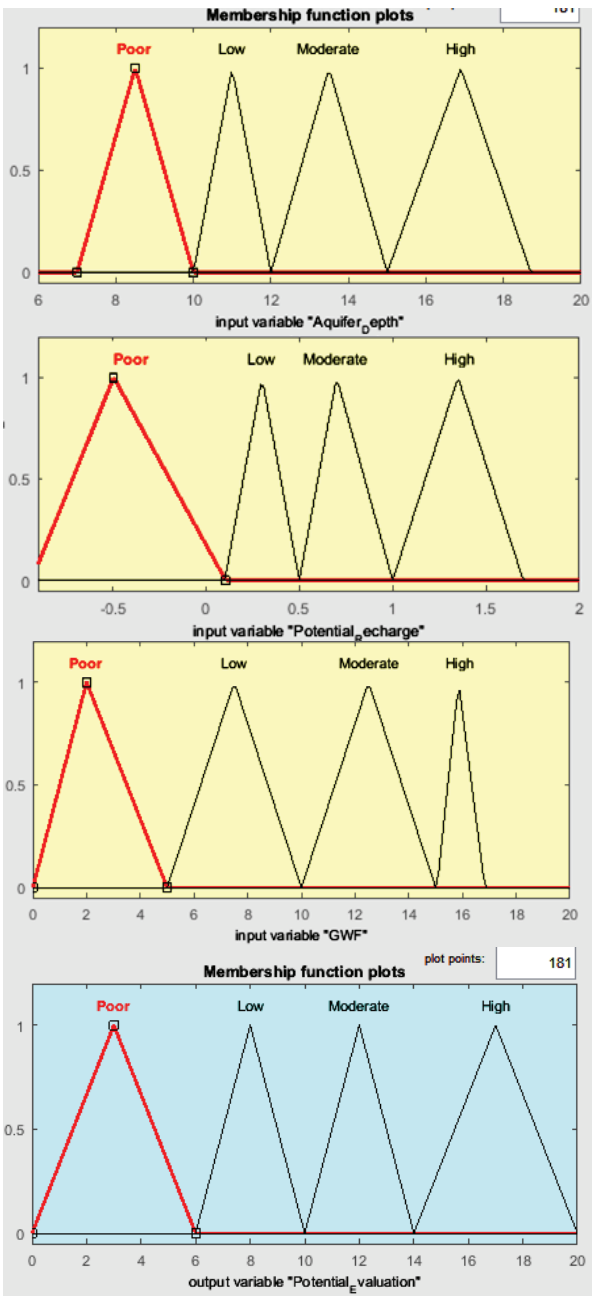

Fig. 8. Membership function for input and output parameters.

6. If (aquifer depth is moderate) and (GWF is moderate) then (potential evaluation is moderate)
7. If (aquifer depth is low) and (GWF is low) then (potential evaluation is low)
8. If (aquifer depth is poor) and (GWF is poor) then (potential evaluation is poor)
9. If (potential recharge is high) and (GWF is high) then (potential evaluation is high)
10. If (potential recharge is moderate) and (GWF is moderate) then (potential evaluation is moderate)
11. If (potential recharge is low) and (GWF is low) then (potential evaluation is low)

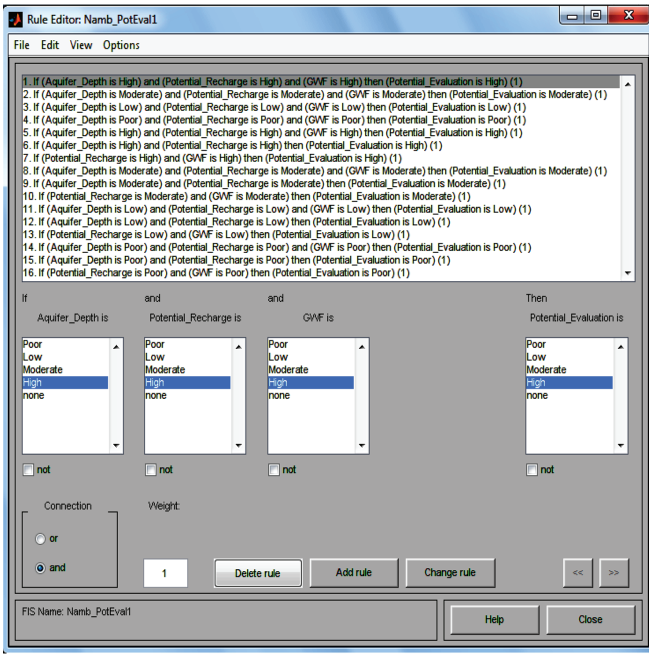

Fig. 9. Creating fuzzy rules.

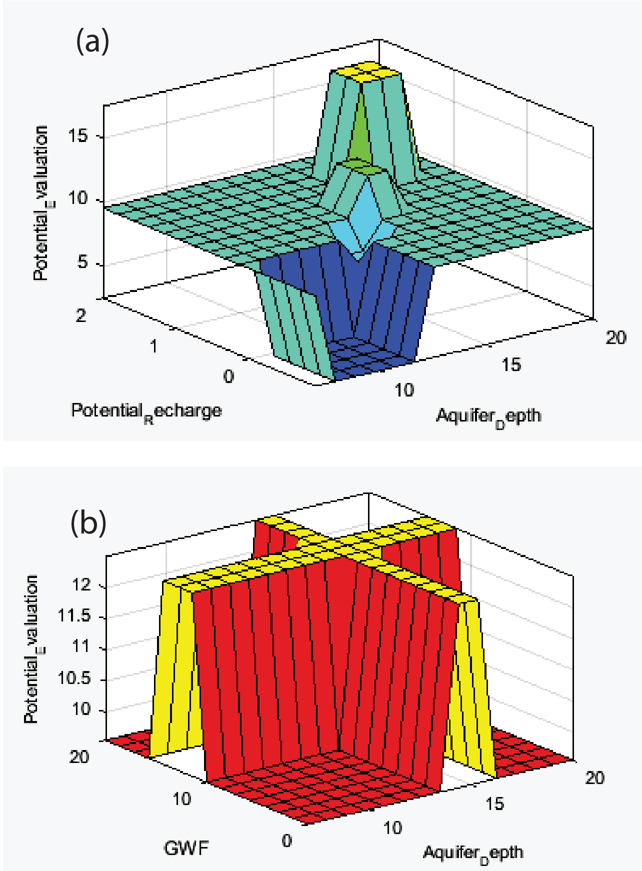

Fig. 10. (a) and (b) 3D surface viewer for FIS.

12. If (potential recharge is poor) and (GWF is poor) then (potential evaluation is poor)
13. If (GWF is high) then (potential evaluation is high)
14. If (GWF is high) or (potential recharge is high) then (potential evaluation is high)
15. If (potential recharge is high) then (potential evaluation is high)
16. If (aquifer depth is high) and (potential recharge is high) then (potential evaluation is high)

These 16 rules for the FIS were defined for fuzzy set as per domain expert. Fuzzy rules are given as a collection of set of rules to make a decision [36].

The surface viewer is used for representing the mapping of potential evaluation as shown in Figs. 10(a) and (b).

In the 3D surface viewer, the *X* and *Y* axis represent aquifer depth and potential recharge with respect to potential evaluation in *Z* axis as shown in Figs. 10(a) and (b) represents the potential recharge and GWF in *X* and *Y* axis, respectively, and potential evaluation in *Z* axis.

The centroid of area from the total curve is the centre of the curve, bisector of area which is the maximum value obtained as the potential evaluation. The ground water level varies on the place based on time. It may vary for each month and year can be viewed and studied by this rule viewer. So it acts as a four-dimensional study.

Syntax:

```
ruleview(fis)
```

It is used to view the entire variation of those particular ranges of variable parameters by moving along the line indices that correspond to the inputs and can view the new output computed. The variables can be adjusted to see the changes based on the Ste conditions with respect to time, the variations of ground water potential are visualized in the rule viewer.

Fuzzy logic is used to translate heuristic control rules affirmed by a human operator into an automatic control strategy [37].

Rule viewer gives clear graphical representation showing the status of ground and its potentiality up to 20 m below ground. For example in Fig. 11(a), the diagram shows that if the aquifer depth is 17.1 m, potential recharge is 1.5 m and GWF is 15.5 m, then at the same location the water potentiality will be as 17.5 m for 20 m depth. Likewise, Fig. 11(b), in case if the aquifer depth is 17.1 m, potential recharge is –0.35 m and GWF is 2.29 m, then at the same location the water potentiality will be as 2.5 m for 20 m depth. The ground water potentiality can be viewed for all certain cases inside this constraint of 20 m depth for this particular study. If the condition is entered, the output is computed and shown graphically.

Syntax:

```
ps = evalfis ([1 1 1], filename);
```

The summary of FIS method used is shown below using command:

```
readfis
ans =
 name: 'Namb_PotEval1_Updated'
```

type: 'mamdani'
andMethod: 'min'
orMethod: 'max'
defuzzMethod: 'centroid'
impMethod: 'min'
aggMethod: 'max'
input: [1x3 struct]
output: [1x1 struct]
rule: [1x16 struct]

This model predicts the potentiality and shows results for any situations of the ground with respect to time.

6. Conclusions

Below the Earth is an imaginary sector that cannot be seen only measured and focused in research. This particular method based on GIS and remote sensing was applied to assess groundwater potentiality in the Nambiyar watershed. Over this the parameters with different weights (potential recharge, aquifer depth, and GWF) were used. Using the monthly rainfall data for the year 2014 and monthly evapotranspiration is extracted from satellite data, from which potential recharge is evaluated. These maps are categorized into four classes namely high, moderate, low, and poor in ArcGIS and the same results were taken for further study into fuzzy. Remote sensing and GIS techniques can identify the location of potential zones of ground water and capability of each well location by fuzzy model. This study succeeds in proposing sites for groundwater zones, based on which suitable locations for groundwater withdrawals can be done. Therefore, the identification of suitable site for recharge is done effectively to undergo further studies and suggest remedial measures for sustainable management.

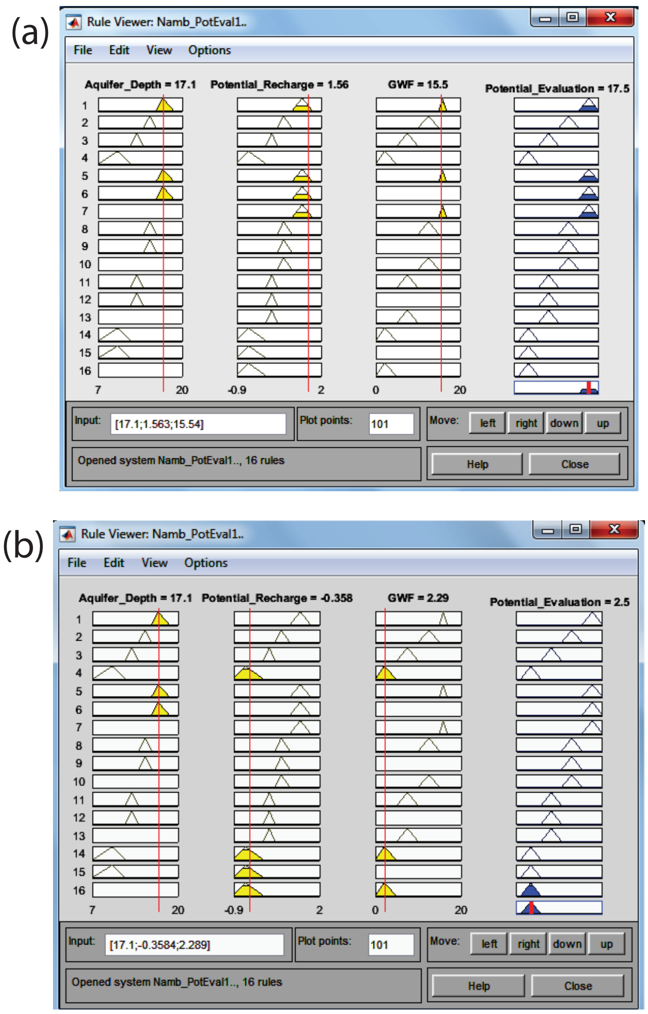

Fig. 11. Rule Viewer showing the potentiality as (a) 17.5 m for 20 m depth and (b) 2.5 m for 20 m depth.

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