New Dam Break Risk Assessment Method in Fuzzy Framework

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INTRODUCTION

Dams are useful for mitigation of floods, and at the same time there is risk of dam failure due to floods, seismic hazards and factors such as ageing of dam material.

There is need to perform risk assessment of dams as their failure can have catastrophic consequences on establishments located in their downstream locations.

Effective risk analysis requires accounting for both failure probability of dam and dam break consequences.

There are numerous factors which effect the consequences, and due to lack of data and knowledge there is considerable amount of uncertainty, vagueness and ambiguity among them.

Fuzzy hierarchical model for risk assessment based on combination of static and variable fuzzy set theory is proposed in the study.

Risk = Likelihood x Consequences

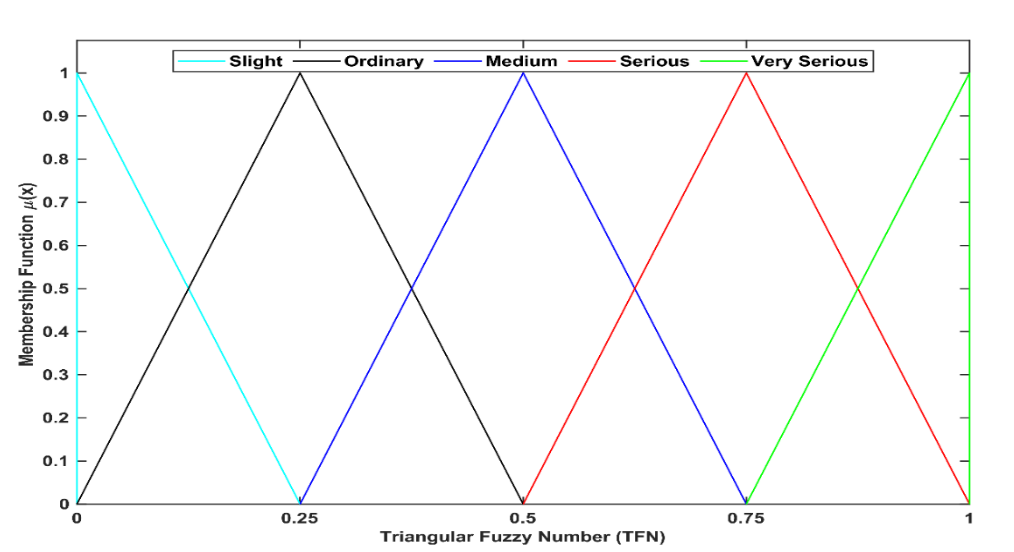
Risk Indexes classification in fuzzy framework

The model synthetically evaluates the dam break consequences based on exposure and Hazard Severity. Hence, the dam break risk can be assessed based on three evaluation indices i.e., ***likelihood of dam break flood, hazard severity (S_D) and degree of exposure.***

Evaluation Level	Likelihood	Hazard Severity (S_D)	TFN
Extremely Low	$> \frac{1}{10}$	< 0.3	< 0, 0, 0.25 >
Low	$\frac{1}{10} - \frac{1}{100}$	0.3 -0.6	< 0, 0.25, 0.50 >
Moderate	$\frac{1}{100} - \frac{1}{1000}$	0.6 – 1.0	< 0.25, 0.50, 0.75 >
Severe	$\frac{1}{1000} - \frac{1}{10000}$	1.0 – 4.0	< 0.50, 0.75, 1 >
Extremely Severe	$< \frac{1}{10000}$	> 4.0	< 0.75, 1, 1 >

$$R_i = f(\ell, S_D, e_i)$$

Linguistic classification of grades of likelihood of flood and hazard severity and their corresponding TFNs



Where.

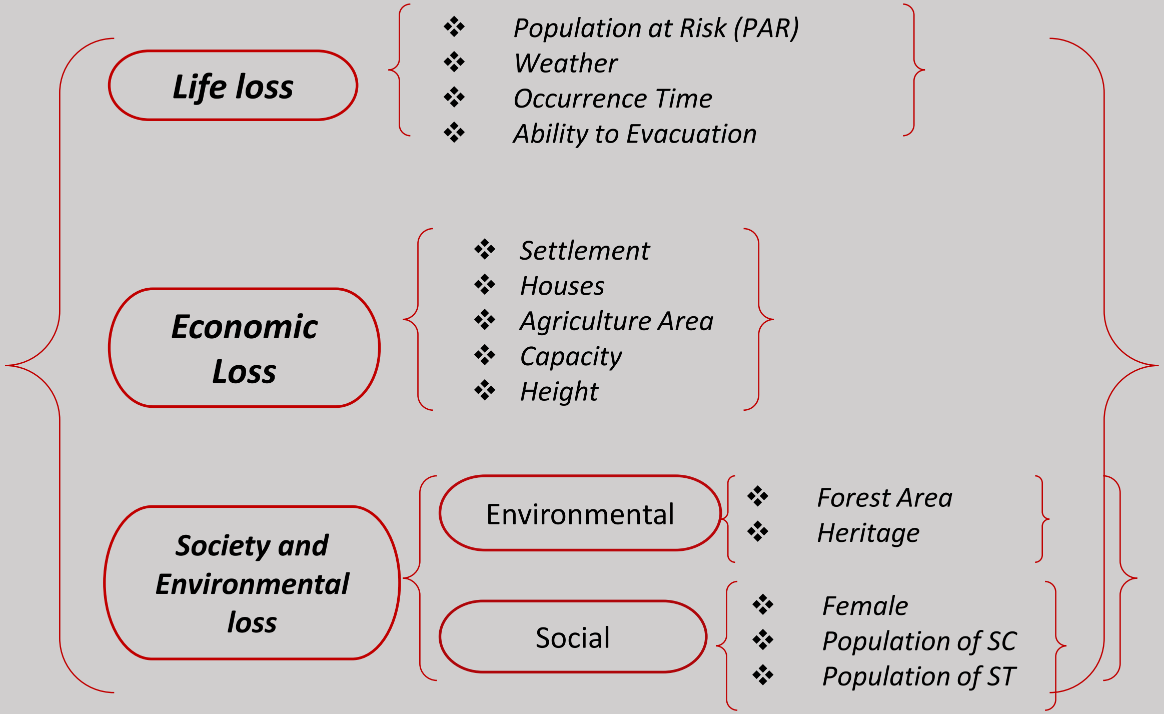
ℓ is the likelihood of occurrence of dam break flood,

S_D is the Hazard severity

e_i is the degree of exposure for i^{th} influencing factor of dam break consequences.

Dam break consequences

- ✓ To establish a hierarchical structure of influencing factors of dam break consequences, the exposure evaluation index is classified into 3 risk categories i.e., ***life loss, economic loss and social and environmental influence***, which are main contents of dam break consequence assessment.
- ✓ Furthermore, each risk category is sub-divided into influencing factors of consequences called exposure indices or risk items



Hierarchal Structure of influencing factors of Dam break consequences.

Quantitative Data					
Evaluation Level	**Slight**	**Ordinary**	**Medium**	**Serious**	**Extremely Serious**
Population at Risk (PAR)	< 500	501 - 1000	1001 – 2000	2001 - 3000	>3000
Households	< 100	101 - 200	201 - 300	301 - 450	> 450
Female Population	< 250	251 - 500	501 - 750	751 - 1000	> 1000
Schedule Caste Population	< 50	51 - 100	101 -200	201 - 300	>300
Schedule Tribe Population	< 50	51 - 100	101 -200	201 - 300	>300
Capacity (Mm^3)	< 1	1 - 10	10 - 100	100 - 1000	> 1000
Height (m)	< 10	10 - 20	20 - 30	30 - 60	> 60
Forests Area (Ha)	< 50	50 - 100	100 - 150	150 - 200	> 200
Agricultural Area (Ha)	< 100	100 -200	200 - 350	350 - 500	> 500
Qualitative Data					
Settlement	Few Households	Village	Town	City	Capital City
Heritage	General	Municipality	State	National	World
Weather	Sunny Day	Sprinkle	Moderate Rain	Rainstorm	Heavy Storm
Occurrence Time	Daytime	Working Day in Night	Holidays at Night	Working Days in Morning	Holidays in Morning
Ability to Evacuation	Extremely Sound	Sound	General	Unsound	Terrible Unsound

Classification and grade suggestion for indexes of exposure

Fuzzy AHP for weight calculation

- **Construction of Fuzzy Pairwise Comparison matrix using Saaty scale of comparison**: Let W be the pairwise comparison matrix then,

$$W = [w_{ij}]_{n\times n} = \left[\frac{w_i}{w_j}\right]_{n\times n} = \begin{bmatrix} w_{11} & w_{12} & w_{13} & \cdots & w_{1n} \\ w_{21} & w_{22} & w_{23} & \cdots & w_{2n} \\ w_{31} & w_{32} & w_{33} & \cdots & w_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{n2} & w_{n3} & \cdots & w_{nn} \end{bmatrix}$$

- **Estimation of local weights of criterion using Eigen vector method**: if W is known and w is unknown then w can be recovered using eigen vector method

$$W \times w = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \frac{w_1}{w_3} & \cdots & \frac{w_1}{w_4} \\ \frac{w_2}{w_1} & 1 & \frac{w_2}{w_3} & \cdots & \frac{w_2}{w_n} \\ \frac{w_3}{w_1} & \frac{w_3}{w_2} & 1 & \cdots & \frac{w_3}{w_n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \frac{w_n}{w_3} & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} \lambda w_1 \\ \lambda w_2 \\ \vdots \\ \vdots \\ \lambda w_n \end{bmatrix} = \lambda \times w$$

Vector of weights

$$w = [w_1, w_2, w_3 \ldots \ldots . w_n]^T$$

- **Consistency Check**: After obtaining $\lambda_{max,}$ first Consistency Index (CI) and then consistency Ratio (CR) is determined as follows. If C.R. < 0.1 the inconsistencies are tolerable and reliable results are expected from F-AHP.

$$C.I. = \frac{\lambda_{max} - n}{n-1} \qquad C.R. = \frac{C.I.}{R.I._n}$$

n = number of criteria

- **Defuzzification:** Since the calculation so far involves fuzzy variables, the next step is to defuzzify the fuzzy weights to form meaningful local weights for analysis

$$M_i = \frac{[Lw_i + Mw_i + Uw_{i,}]}{3}$$

Risk Category	Intermediate Layer	Sub-Criterion / Index Layer	Weight
(Wi)		(W_{ij})	($W_n = W_i \times W_{ij}$)
Life 0.7338		PAR 0.5147	**0.42**
		Weather 0.1495)	**0.1097**
		Occurrence time 0.0532	**0.0390)**
		Ability to evacuation 0.2826	**0.2074**
Economy 0.0995		Settlement 0.3812	**0.0379**
		Houses 0.1229	**0.0122**
		Agriculture area 0.0508	**0.0050**
		Capacity 0.2225	**0.0221**
		Height 0.2225	**0.0221**
Environmental and Social 0.1667	Environmental (0.5)	Forest area 0.7424	**0.0618**
		Heritage 0.2576	**0.0214**
	Social (0.5)	Female 0.15	**0.0125**
		Population of SC 0.42	**0.0350**
		Population of ST 0.42)	**0.0350**

Step 1: Interval Matrix

$$I_{ab} = \begin{bmatrix} [a_{11}b_{11}] & [a_{12}b_{12}] & [a_{13}b_{13}] & \cdots & [a_{1c}b_{1c}] \\ [a_{21}b_{21}] & [a_{22}b_{22}] & [a_{23}b_{23}] & \cdots & [a_{2c}b_{2c}] \\ [a_{31}b_{31}] & [a_{32}b_{32}] & [a_{33}b_{33}] & \cdots & [a_{3c}b_{3c}] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ [a_{m1}b_{m1}] & [a_{m2}b_{m2}] & [a_{m3}b_{m3}] & \cdots & [a_{mc}b_{mc}] \end{bmatrix} = [[a_{ij}b_{ij}]]_{m\times c}$$

Step 2: Bound Matrix

Next step is to construct the indicator variable interval matrix I_{cd} also called extended interval matrix.

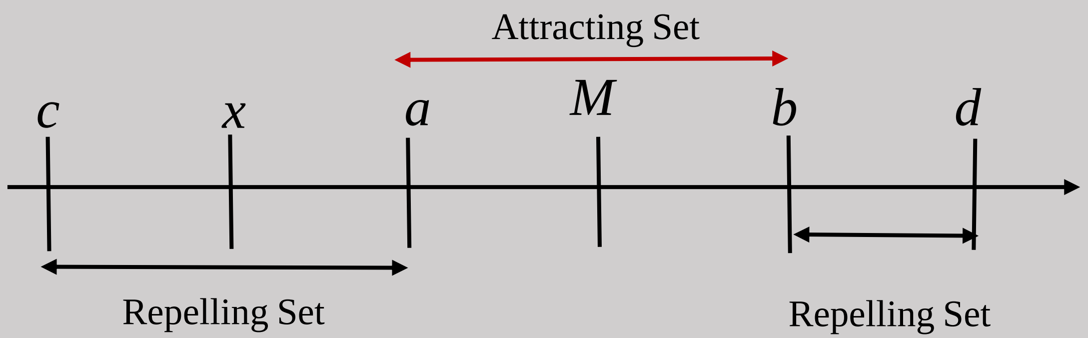
$$[c_{ij}d_{ij}] \begin{cases} a_{ij-1}b_{ij+1}, & j-1>0, j<c \\ a_{i1}b_{ij+1}, & j-1=0 \\ a_{ij-1}b_{ic}, & j=c \end{cases}$$

$$I_{cd} = \begin{bmatrix} [c_{11}d_{11}] & [c_{12}d_{12}] & [c_{13}d_{13}] & \cdots & [c_{1c}d_{1c}] \\ [c_{21}d_{21}] & [c_{22}d_{22}] & [c_{23}d_{23}] & \cdots & [c_{2c}d_{2c}] \\ [c_{31}d_{31}] & [c_{32}d_{32}] & [c_{33}d_{33}] & \cdots & [c_{3c}d_{3c}] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ [c_{m1}d_{m1}] & [c_{m2}d_{m2}] & [c_{m3}d_{m3}] & \cdots & [c_{mc}d_{mc}] \end{bmatrix} = [[c_{ij}d_{ij}]]_{m\times c}$$

Step 3: Point value matrix

$$M_{ij} = \begin{cases} \dfrac{a_{ij}+b_{ij}}{2} & j \neq 1, c \\ a_{ij} & j = 1 \\ b_{ij} & j = c \end{cases}$$

Step 4: Relative Membership Degree (RMD)



When x is located to the right of M, then relative membership function can be expressed as:

$$\mu_A(u) = 0.5 \times \left\{1 + \frac{(x-b)}{(M-b)}\right\}^{\beta}, \quad x \in [M, b]$$

$$\mu_A(u) = 0.5 \times \left\{1 - \frac{(x-b)}{(d-b)}\right\}^{\beta}, \quad x \in [b, d]$$

When x is located to the left of M, then relative membership function can be expressed as:

$$\mu_A(u) = 0.5 \times \left\{1 + \frac{(x-a)}{(M-a)}\right\}^{\beta}, \quad x \in [a, M]$$

$$\mu_A(u) = 0.5 \times \left\{1 - \frac{(x-a)}{(c-a)}\right\}^{\beta}, \quad x \in [c, a]$$

Where, β is index bigger than 0, usually we take it as 1, above become linear functions.

Step 5: Risk Assessment Matrix

The RMD matrix of the m indexes to the c levels can be calculated illustrated as follows:

$$\mu_A(u)_{m\times c} = \begin{bmatrix} \mu_A(u)_{11} & \mu_A(u)_{12} & \mu_A(u)_{13} & \cdots & \mu_A(u)_{1c} \\ \mu_A(u)_{21} & \mu_A(u)_{22} & \mu_A(u)_{23} & \cdots & \mu_A(u)_{2c} \\ \mu_A(u)_{31} & \mu_A(u)_{32} & \mu_A(u)_{33} & \cdots & \mu_A(u)_{3c} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mu_A(u)_{m1} & \mu_A(u)_{m2} & \mu_A(u)_{m3} & \cdots & \mu_A(u)_{mc} \end{bmatrix}$$

Step 6: Synthetic Relative Membership Degree (SRMD)

$$\mu'_h = \left\{ 1 + \left[\frac{\sum_{i=1}^{m} \left[\omega_i \left(1 - \mu_A(x_i)_j\right)\right]^p}{\sum_{i=1}^{m} \left[\omega_i \left(\mu_A(x_i)_j\right)\right]^p} \right]^{\frac{\alpha}{p}} \right\}^{-1}$$

SRMD can be calculated using variable fuzzy synthetic evaluation model.

Step 7: Normalized SRMD

$$\beta_j = \frac{\beta'_j}{\sum_{j=1}^{c} \beta'_j} \quad ,(j = 1,2,3 \cdots\cdots\cdots c)$$

Step 8: Level feature value (H) using rank feature values (RFV) equation (Chen, 1998)

$$H = (1,2,3 \cdots\cdots\cdots c) \blacksquare \beta \qquad H = \sum_{j=1}^{c} \beta_j \times j \quad ,(j = 1,2,3 \cdots\cdots\cdots c)$$

Step 9: Calculation of exposure degree by discrimination rule

$$\begin{array}{ll} 1 < H < 1.5 & ,\in grade\ 1 \\ j - 0.5 < H < j + 0.5 & .\in\ grade\ j, j = 1,2,3 \cdots\cdots\cdots c \\ c - 0.5 < H < c, & ,grade\ c \end{array}$$

Step 10: Calculation of Risk Rate (Type 1)

Likelihood→ $A_i \rightarrow < a_{i1}, a_{i2}, a_{i3} >$

Hazard severity → $B_i \rightarrow < b_{i1}, b_{i2}, b_{i3} >$

Exposure → $C_i \rightarrow < c_{i1}, c_{i2}, c_{i3} >$

Risk rate→ $g = A \otimes B \otimes C$

g→ $< a_1 b_1 c_1, a_2 b_2 c_2, a_3 b_3 c_3 > \rightarrow < l_i, m_i, u_i >$

$$g_i = \frac{[Lw_i + Mw_i + Uw_i]}{3}$$

Calculation of Risk Index using Static Fuzzy Set Theory

Step 10: Calculation of Risk Rate (Type 2)

Risk rate→ $g_{improved} = \sqrt[3]{A \otimes B \otimes C}$

Step 11: Fuzzy Risk assessment matrix

Let V = $\{V_1, V_2, V_3, V_4, V_5\}$ be the set of rating for each risk item (exposure index). By fuzzy relation on C × V; the fuzzy assessment matrix (M) for C × V is established

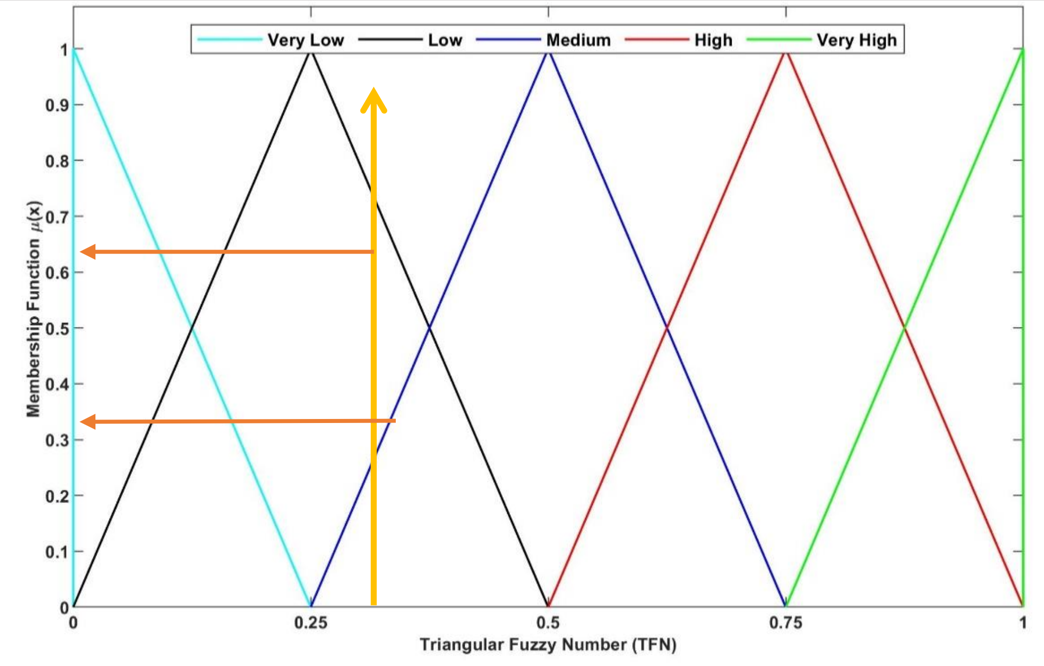
$$M = \begin{array}{c|ccccc} & V_1 & V_2 & V_3 & V_4 & V_5 \\ C_1 & V(A, B_1, C_1, 1) & V(A, B_1, C_1, 2) & V(A, B_1, C_1, 3) & V(A, B_1, C_1, 4) & V(A, B_1, C_1, 5) \\ C_2 & V(A, B_2, C_2, 1) & V(A, B_2, C_2, 2) & V(A, B_2, C_2, 3) & V(A, B_2, C_2, 4) & V(A, B_2, C_2, 5) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ C_N & V(A, B_N, C_N, 1) & V(A, B_N, C_N, 2) & V(A, B_N, C_N, 3) & V(A, B_N, C_N, 4) & V(A, B_N, C_N, 5) \end{array}$$

Step 12: Evaluation of Aggregative Risk:

$$[\boldsymbol{R}]_{1\times5} = [\boldsymbol{W}]_{1\times N} \times [\boldsymbol{M}]_{N\times5}$$

$[W]$ = Weight vector of Sub criteria estimated using AHP and FAHP.

$[M]$ = Fuzzy Risk assessment matrix



Step 13: Calculation of Risk Index using RFV equation (Chen, 1998)

$$RI = [1\ 2\ 3\ 4\ 5] \times [R]_{1\times5}$$

Evaluation Level	Risk Index
Very Low	1.0 <RI< 1.5
Low	1.5 <RI < 2.5
Moderate	2.5 <RI< 3.5
High	3.5 <RI<4.5
Very High	4.5 <RI < 5.0

Methodology

1 PMP Estimation:

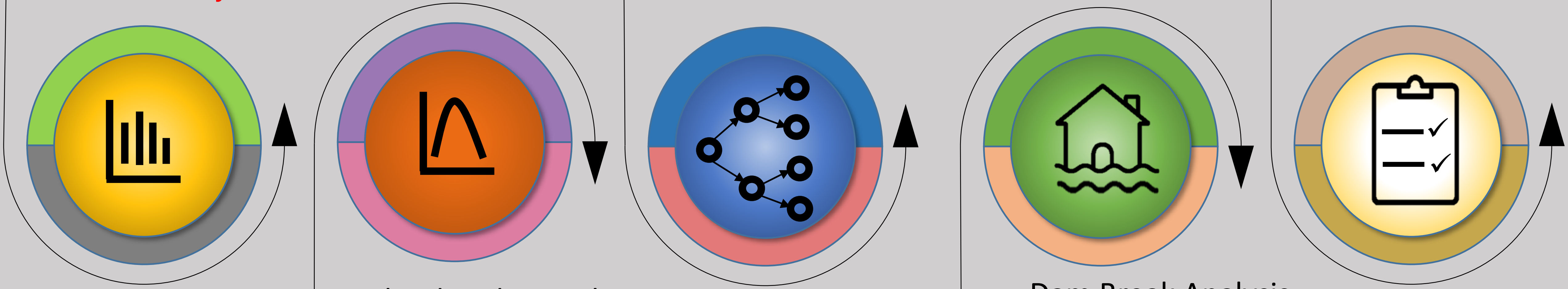
Design Hyetograph are constructed by time disaggregating 1-Day and 2-Day PMP.

3 Event Tree Analysis

ETA was performed to estimate likelihood of dam break flood.

5 Risk Index:

Risk index based on and Fuzzy framework is estimated utilizing likelihood of flood, severity of flood and consequences.



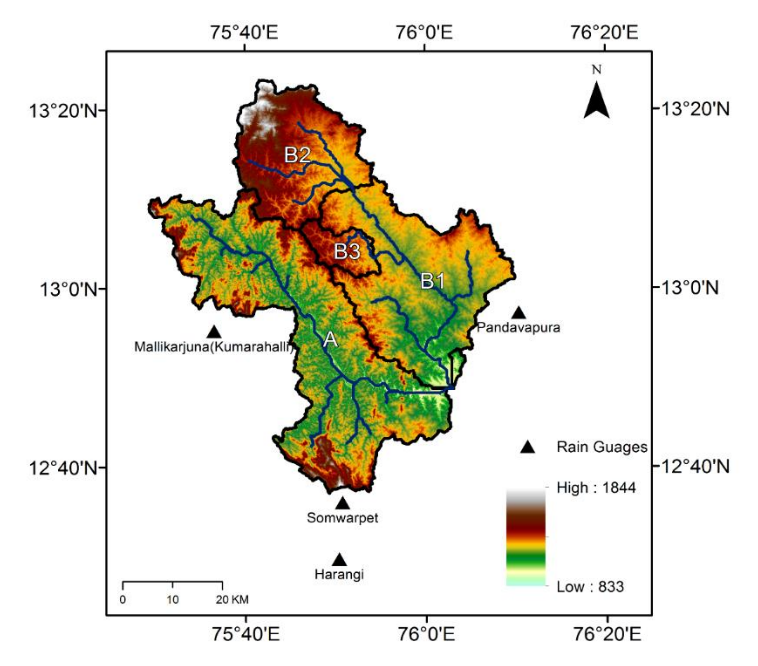
2 Flood Hydrograph:

Design Hyetograph is convoluted with 1h Unit Hydrograph to estimate Flood Hydrograph entering the reservoir.

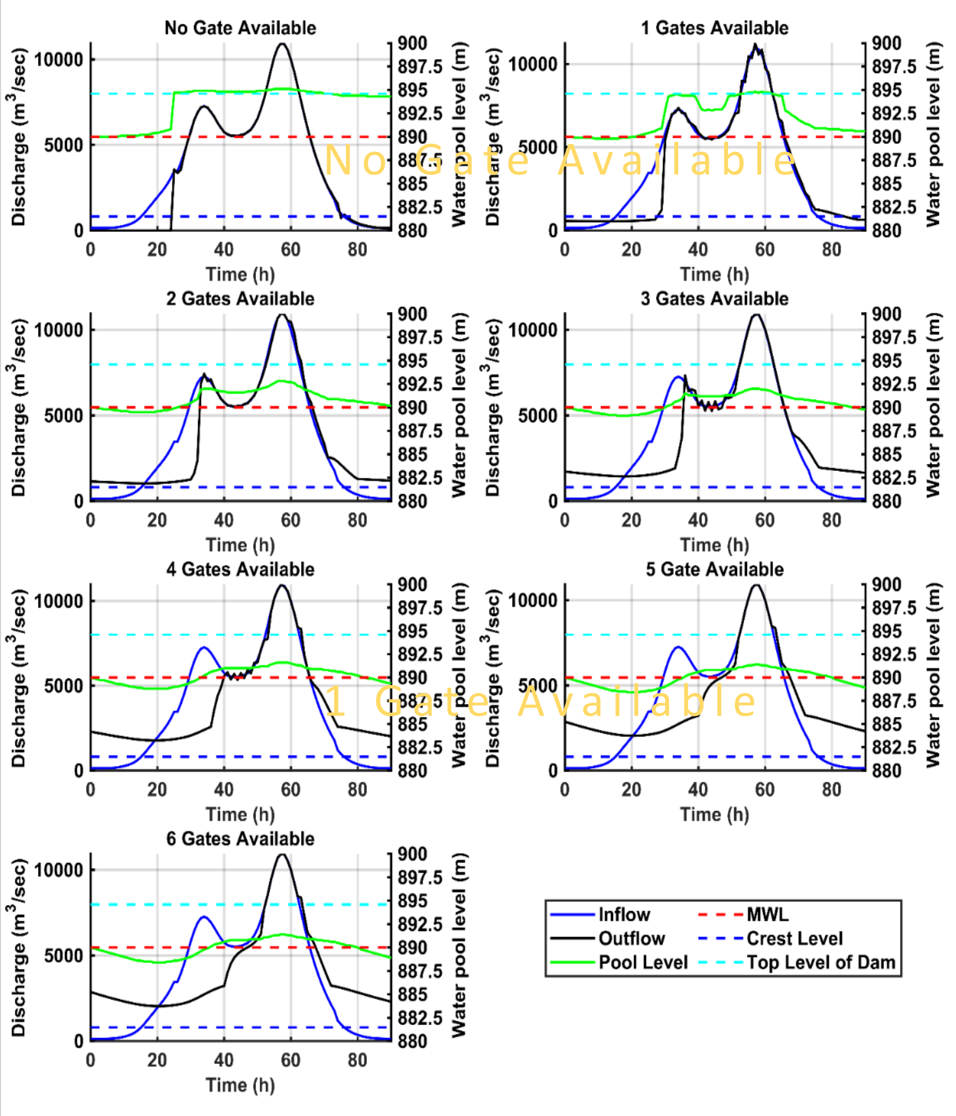
4 Dam Break Analysis

DBA is performed in 1D-2D coupled HEC-RAS dam break model to estimate extent of Flood inundation, maximum depth and flood velocity at locations downstream of dam.

Catchment Plan of Hemavathy Dam.

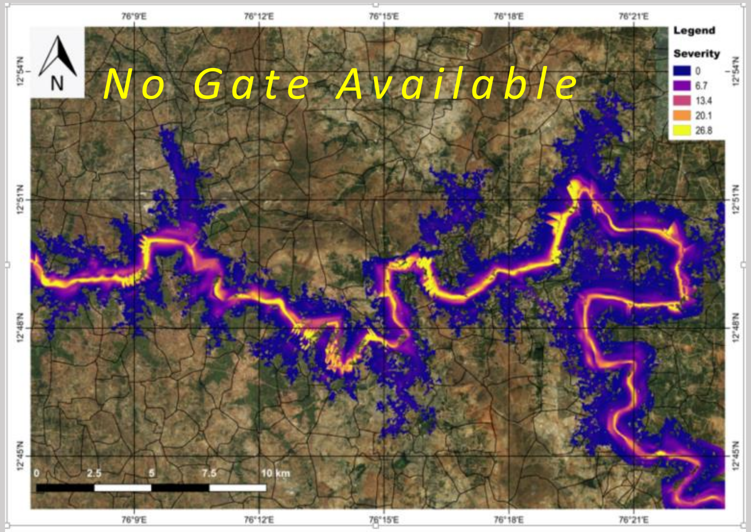


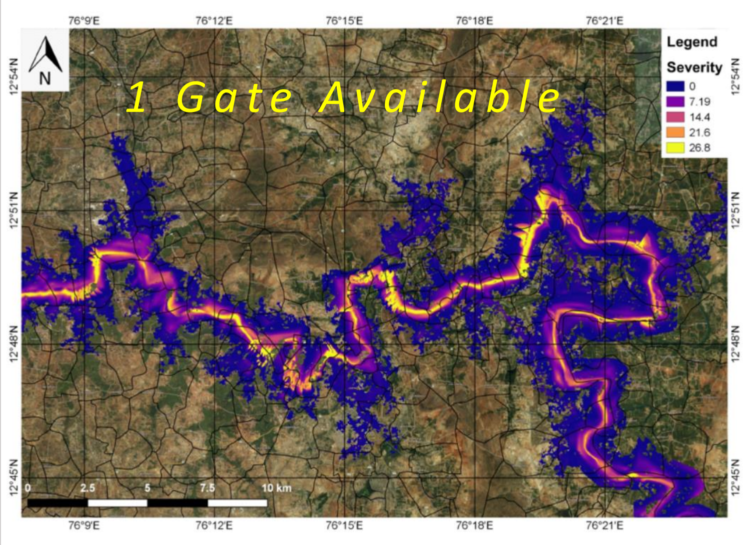
River	*Hemavathy*	Full Reservoir Level	*890.62 m*
Longitude/ Latitude	*76°03' E/ 12°45' N*	Min. Drawdown Level	*872.33 m*
Capacity of Spillway	*3624.55 cumecs*	No. of Spillway Gates	*6*
Type of Dam	*Earthen + Gravity Dam*	Type of Spillway Gates	*Radial*
Length of Dam	*4692 m*	Size of Spillway Gates	*10.67m x 15.24m*
Height of Dam	*58.5 m*	Shape of Spillway	*Ogee*
Catchment Area	*2810 Sq. Km*	Length of Spillway	*94.5 m*



Flood Routing Calculation corresponding to design flood based on each case of gate availability, ranging from 0 to 6. for Hemavathy reservoir project

Results

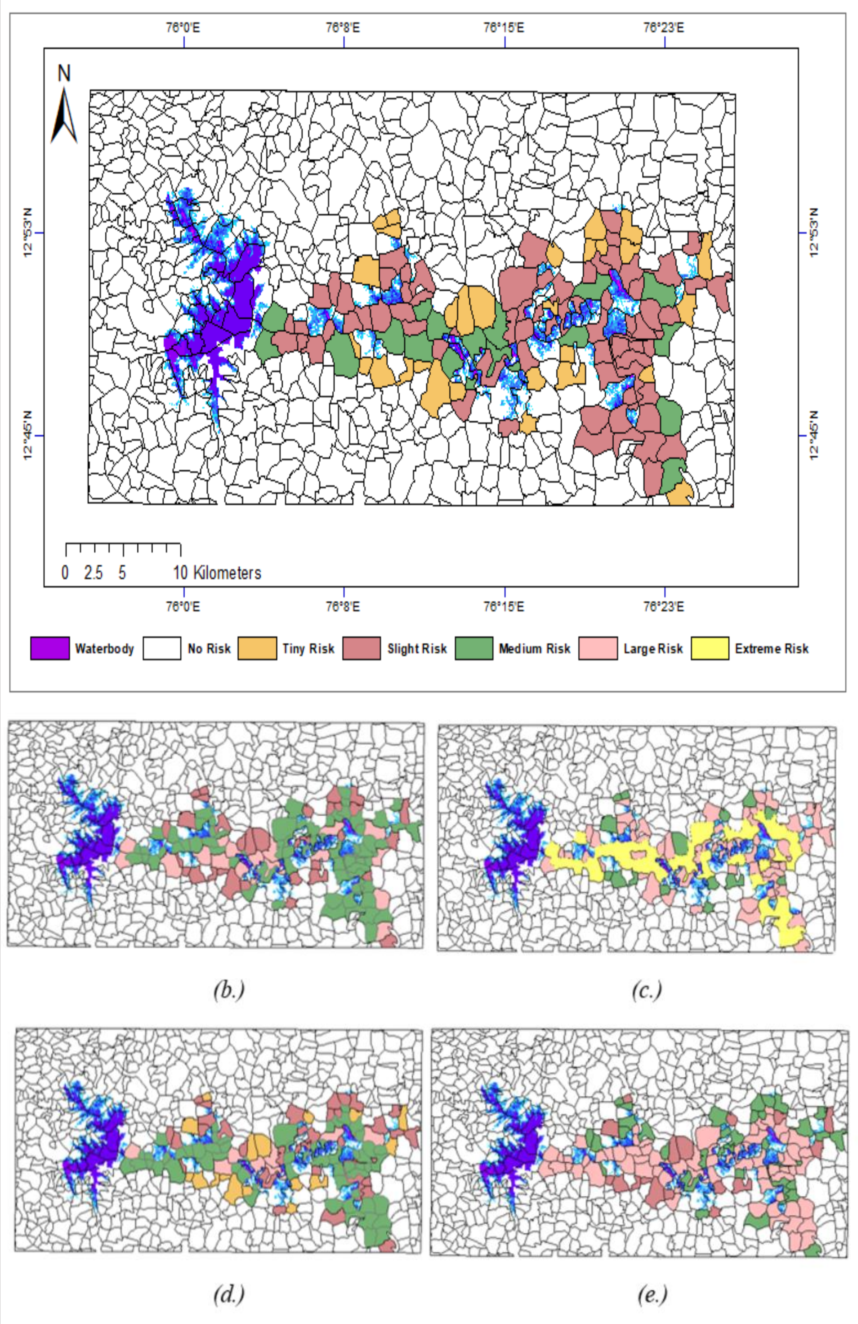




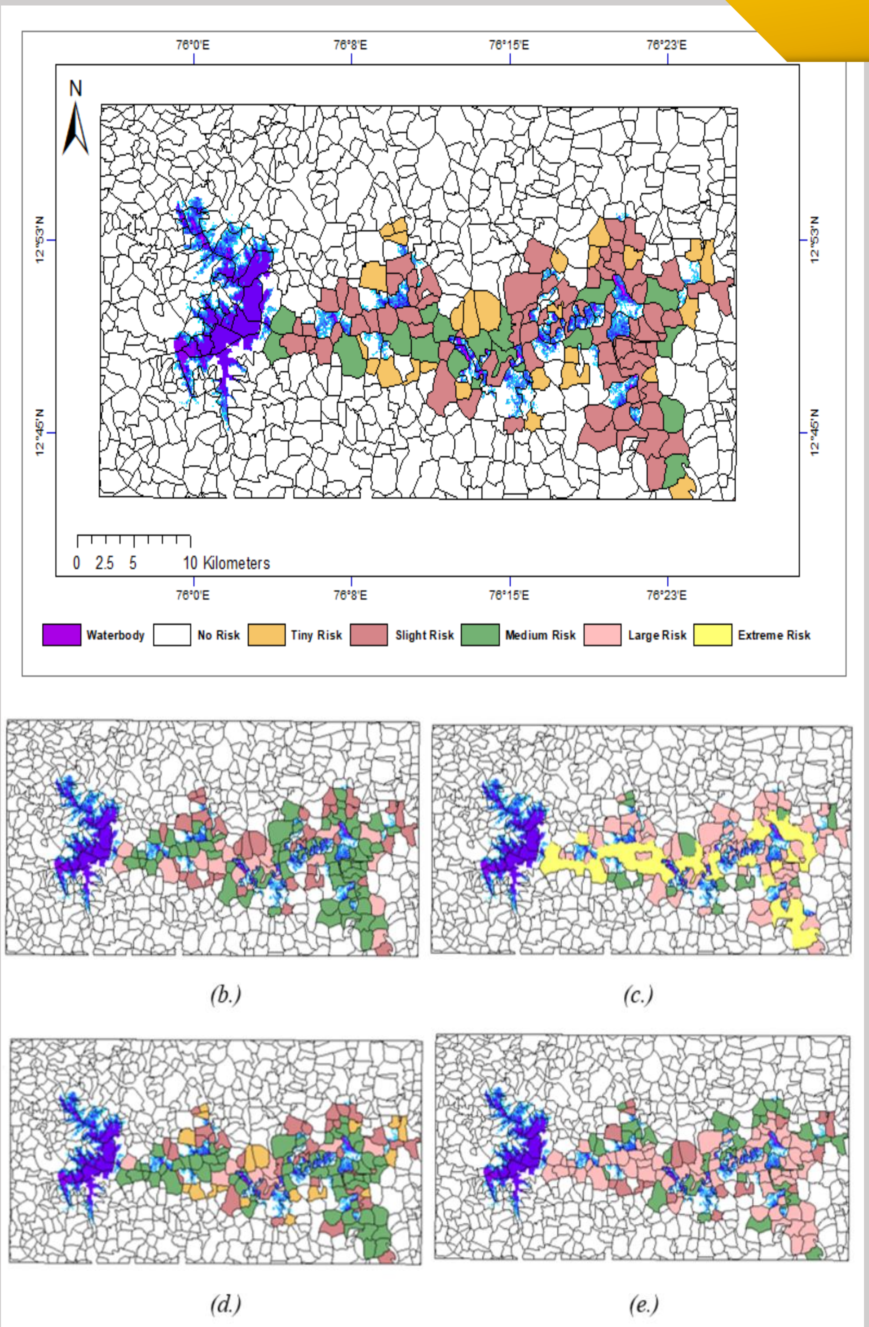
Flood inundation map showing maximum severity

Village Wise Aggregative Risk Index (VW-ARI)

No Gate Available



1 Gate Available



a) Method 1: Conventional method for estimating ARI based on SFS theory (Type 1).
b) Method 2: Modified Conventional method for estimating ARI based on SFS theory (Type 2).
c) Method 3: ARI based VFS theory.
d) Method 4: ARI based on integration of SFS and VFS theory (Type 1)
e) Method 5: ARI based on integration of SFS and VFS theory (Type 2)

Conclusions

01. ARI based solely on VFS theory results in over estimation of Risk as compared to Risk based on integration of SFS and VFS theory.

02. ARI based on Type 1 method results in under estimation of risk as compared to Risk based on Type 2 method.

03. ARI based on integration of SFS and VFS theory (Type 2) is preferred as the estimated risk is reasonable and it takes into account the influence of uncertainties / vagueness associated with linguistic classification of Risk Items.

04. Weights calculated using Fuzzy AHP are more reliable as they take into account uncertainty associated with subjective pairwise comparison matrix

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Thank You

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