MAUSAM, **77**, 2 (April 2026), 553-564

MAUSAM

DOI: https://doi.org/10.54302/mausam.v77i2.6798
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No.551.583:556.166

# Flood risk reduction in a river basin under climate change

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(*Received 8 August 2024, Accepted 19 September 2025*)

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**सार** – बाढ़ और उसका घटित होना पर्यावरणीय, सामाजिक-आर्थिक और भौतिक कारकों की जटिल परस्पर क्रिया है। जलवायु परिवर्तन चरम घटनाओं की बढ़ती आवृत्ति का प्रत्यक्ष प्रमाण है और बाढ़ हमारे समाज की प्रमुख चुनौतियों में से एक बनकर उभरी है। वर्तमान शोध अध्ययन जलवायु परिवर्तन में बाढ़ के जोखिम का आकलन करने के लिए जल विज्ञान और जल विद्युत मॉडलिंग को अपनाकर दैनिक समय पैमाने पर चरम जल प्रवाह का अनुकरण करने का प्रयास करता है। यह शोध भारत के तमिलनाडु राज्य के उत्तर-पूर्वी भाग में स्थित निचले पेन्नैयार और गदिलम उप-बेसिनों पर लागू किया गया था। निर्धारण गुणांक आर2 का उपयोग करके अंशांकन (2015, 2017, 2018, 2020 और 2023) और सत्यापन (2015, 2018 और 2020) चरणों के दौरान प्रत्येक बाढ़ घटना के लिए एचईसी-एचएमएस मॉडल की दक्षता का सटीक रूप से परीक्षण किया गया था। वर्ष 2015, 2018 और 2020 की तीन प्रमुख बाढ़ घटनाओं के लिए आर2 और एनएसई मान क्रमशः 0.88, 0.83, 0.86 और 0.85, 0.8, 0.82 पाए गए। परिणामों में आर2 और एनएसई मान दर्शाते हैं कि अंशाकित मॉडल, सत्यापन के दौरान अच्छा प्रदर्शन करता है। भविष्य में बाढ़ के अनुकरण के लिए एसएसपी2-4.5 और एसएसपी5-8.5 परिदृश्यों के तहत सीएमआईपी6 के ईसी-अर्थ 3 जलवायु मॉडल को तैनात किया गया है। विभिन्न प्रतिफल कालों से संबंधित हाइड्रोग्राफ तैयार करने के लिए ईसी-अर्थ 3 जीसीएम डेटा का उपयोग किया गया। एचईसी-आरएएस 2डी मॉडल के माध्यम से किए गए हाइड्रोलिक मॉडलिंग ने 25, 50 और 100 वर्ष की प्रतिफल अवधियों के तहत भविष्य के एसएसपी परिदृश्यों के लिए बाढ़ मानचित्रों के विकास को सक्षम बनाया। इस अध्ययन में एचईसी-आरएएस भू-भाग संशोधन उपकरण का उपयोग करके जोखिम न्यूनीकरण रणनीतियों के साथ हाइड्रोलॉजिक और हाइड्रोलिक मॉडलिंग को संयोजित करने का एक एकीकृत दृष्टिकोण अपनाया गया। बाढ़ के अनुमानों का उपयोग उपयुक्त बाढ़ नियंत्रण उपायों और बाढ़ जल संरक्षण संरचनाओं की योजना बनाने और उन्हें लागू करने के आधार के रूप में किया जाता है। इस शोध में सामने आए परिणाम, निर्णयकर्ताओं के लिए बहुमूल्य जानकारी प्रदान करते हैं।

**ABSTRACT.** A flood and its occurrence is a complex interaction between environmental, socio- economic and physical factors. climate change is an imminent witness of extreme events occurring more frequently and floods have emerged as one of the pressing challenges in our society. The current research study strives to simulate extreme streamflow on a daily time scale by adopting hydrologic and hydraulic modeling in order to assess the flood risk in a changing climate. This research was applied to the lower Pennaiyar and Gadilam sub-basins located in the state North eastern side of Tamil Nadu state, India. The efficiency of the HEC-HMS model was precisely examined for each flood events during calibration (2015, 2017, 2018, 2020, and 2023) and validation (2015, 2018, and 2020) stages using the coefficient of determination $R^2$. The $R^2$ and NSE values for the three major flood event 2015, 2018 and 2020 are found to be 0.88, 0.83, 0.86 and 0.85, 0.8, 0.82 respectively. The $R^2$ and NSE values in the results reveal that the calibrated model performs well in the validation. The EC-EARTH 3 climate model of CMIP6 under the SSP2-4.5 and SSP5-8.5 scenarios is employed for future flood simulations. The EC-EARTH 3 GCM data was utilized to generate hydrographs pertaining to different return periods. The hydraulic modeling through the HEC-RAS 2D model enabled the development of flood inundation maps for future SSP scenarios under 25, 50, 100 year return periods. An integrated approach of combining hydrologic and hydraulic modeling with risk reduction strategies using the HEC-RAS terrain modification tool was adopted in this study. The flood estimates are used as the basis for the planning and implementation of suitable flood control measures and flood water conservation structures. The results revealed in this research provide valuable insight for decision-makers.

**Key words** – Flood, Risk, Climate change, HEC-HMS, HEC-RAS, ECEARTH3

## 1. Introduction

Based on the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) documented that the surface temperature all over the globe is 1.09 ˚C higher in 2011-2020 than 1850-1900 (IPCC 2023). In previous decades, climate change footprint been identified by its serious effects on natural systems such as extreme rainfall events, heat extremes, forest fires, glacier retreat and rise in sea level (UNDESA, 2014). According to the 13$^{th}$ Sustainable Development Goal (SDG) climate action, the highly vulnerable regions affected by floods, drought and extreme storms due to climate change have 15 times more mortality rates (3.3 to 3.6 billion people approximately) between 2010 to 2020 in comparison with lower vulnerable regions (UN DESA report, 2023).

The frequency of extreme hydrological events such as flood and drought is increasing all over the world due to climate change. The cause of the occurrence of hydrological extremes is based on the modification of hydrological cycle due to global warming (Ehtasham *et al*. 2024). Hence the climate change affects the water availability, spatial distribution of water, water resources management, hydropower generation, agricultural activities and irrigation water management (Orkodjo *et al*. 2022). The future flood events, flood extent and flood water levels will increase due to the change, in climate change which in turn, emphasizing the projected climate change information is indispensable for the flood risk reduction and emergency response plans (Aryal *et al*. 2022). In view of the above the it is need of hour to understand the effects of change in climate in order to propose new strategies for adaptation and management in future vulnerable regions. Global circulation models (GCMs) are the models created to portray the intricate climate system which involves ocean, land, ice and the atmosphere. The GCMs were preferred to simulate future climate change variables such as rainfall, temperature, evaporation *etc* (Yılmaz *et al*. 2024). Because the GCMs provide the reliable future outcomes based on selected scenarios compared to other models (Kumar *et al*. 2022). The future variables so developed from the GCMs under climate change scenarios are helpful to obtain the future impacts on the hydrological condition due to changing climate (Supriya *et al*, 2018).

Coupled model Intercomparison Project 6 (CMIP6) has noteworthy improvement compared to CMIP5 is the integration of socioeconomic elements in the Representative Concentration Pathways (RCP) (Lovino *et al*. 2021; Pimonsree *et al*. 2023). The alterations in the social, economic, demographic, technological, environmental and governance factors are addressed by SSPs (O'Neill *et al*. 2017). In the present study the future climate variables are acquired from the Shared Socioeconomic Pathways (SSP) such as SSP 2-4.5 (middle of the road development) and SSP5-8.5 (fossil fuelled development). The downscaling of climate variables from GCMs to the local scale is an important step representing the hydrological condition of the basin. The bias corrected GCM climate data pertaining to rainfall and temperature on daily time scale under the CMIP6 is available for the South Asian extent of periods 1951-2014 and 2015-2100 (Mishra *et al*, 2020).

Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) is a popularly chosen model for dendritic basin drainage systems. The Soil Conservation Service Curve Number (SCS-CN) method in HEC-HMS is a widely used method for event based hydrological flow simulations for current and future scenarios (Sahu *et al*. 2023). Several studies have documented that the HEC-HMS model is a widely utilized model for the future simulation of streamflow in a river basin to evaluate the climate change impact (Li *et al*. 2022; Wang *et al*, 2022). The HEC-HMS model is used to analyse the simulated and predicted streamflow under SSP2-4.5 and SSP5-8.5 scenarios in the river basins of Changbai mountains (Li *et al*. 2022).

A Hydrologic Engineering Center - River Analysis System (HEC-RAS) 2D is the most common method for the generation of flood inundation maps for the required return periods. HEC-RAS can simulate flood inundation for both baseline and future climate change scenarios. The results from the HEC-RAS is used to analyse damage assessment, risk reduction, structural and non-structural measures (Sadiqzai *et al*. 2024; Satriagasa *et al*. 2023; Romali *et al*. 2018). Duraisekaran *et al*. (2021) investigated a flood mitigation strategy in HEC-HMS as increasing the capacity of tanks by 20% along with soil conservation measures could lead to a decrease in peak discharge. The lower sub-basins of Cuddalore district, Tamil Nadu have more drainage density, less bifurcation ratio, more stream frequency, are highly vulnerable to floods (Nithya *et al*. 2019). The lower Vellar (Cuddalore district) is ranked first in flood vulnerability based on a regression equation framed between annual maximum daily rainfall and maximum streamflow (Supriya *et al*, 2015).

Balu *et al*. (2023) analysed the impacts of changing climate on streamflow and water availability using the Soil and Water Assessment Tool (SWAT) model in the Ponnaiyar river basin. The future streamflow under SSP8.5 scenarios is higher and needs flood risk information, flood inundation details, flood management, adaptation measures and water management strategies for the Ponnaiyar river basin. The novelty of this current

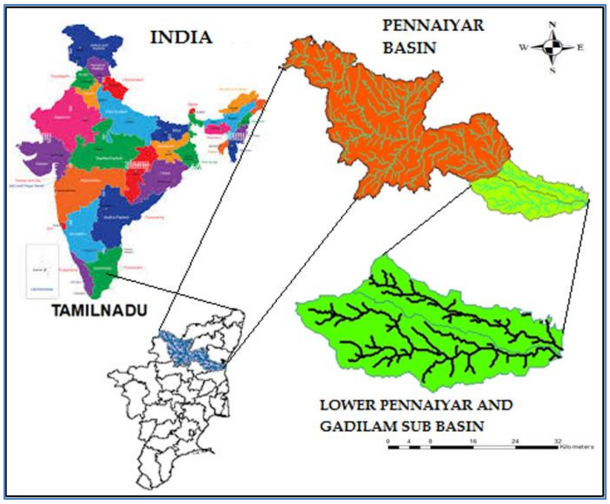


**Fig. 1**. Index map of the lower Pennaiyar and Gadilam subbasin

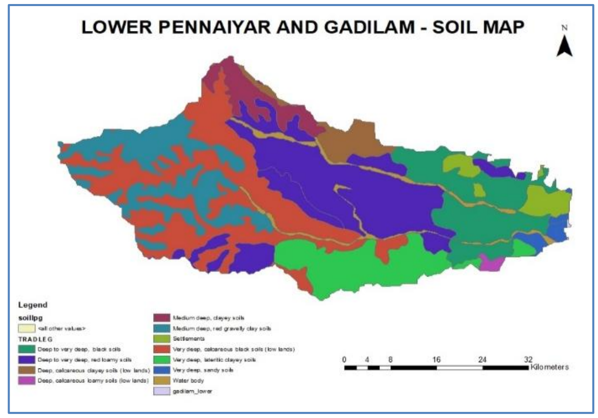


**Fig. 2**. Soil map of the lower Pennaiyar and Gadilam subbasin

research is that it explores the flood flow and flood inundation extent in baseline and future scenarios to provide in-depth investigation of implications.

This research incorporates high-resolution downscaled climate projections, enabling more precise simulation of flood events under different climate change scenarios within the river basin, offering improved accuracy compared to previous studies. EC-EARTH 3 is a fully coupled Earth system model that incorporates atmospheric, oceanic, sea ice, and land surface components, enabling more realistic simulation of climate feedbacks that influence hydrology. To enhance robustness and minimize uncertainty in flood predictions, a multi-model approach is employed. Socioeconomic pathways are integrated with key vulnerability indicators to pinpoint communities at highest risk. Going beyond traditional static risk assessments, this study also explores adaptive management strategies tailored to anticipated climate impacts, offering a more dynamic and forward-looking approach than prior research.

## 2. Data and methodology

### 2.1. *Study area description*

Pennaiyar basin is one of the major river basins among 17 basins in Tamil Nadu, India. It covers a vast area of approximately 11,595 km² and is located between a latitude of 11°38’30″ N and 12° 54’00” N and a longitude of 77°39’30” E and 79° 54’15” E. Pennaiyar river originates in Nandi Hills, Karnataka, flows through Tamil Nadu and enters the Bay of Bengal. The Pennaiyar river has 14 tributaries and 7 major anicuts. Tirukovilur, Ellis Choultry, Sornavur anicut is the major anicut located below the Sathanur reservoir. There are 19 open off takes to feed the tanks above Tirukovilur anicut and 47 open off takes to feed the tanks below Tirukovilur anicut. The Gadilam river originates in Swamymalai hills in Villupuram district and drainage from Melaphazhengoor reserve forest in Kallakurichi taluk of Villupuram district. The lower Pennaiyar and Gadilam sub-basins have a total area of 2124.86 km² and its index map is shown in Fig. 1. Average annual rainfall of the lower Pennaiyar and Gadilam sub basins is 920.79 mm. The land-use land-cover of the lower Pennaiyar and Gadilam subbasin has been classified into six categories: Agriculture (70%), Urban (11%), Vegetation (5%), Water body (4%), Barren land (10%). The majority of the area are used as agricultural land and villages is located in the Pennaiyar river basin (Balu *et al*. (2023). The Lower Pennaiyar and Gadilam sub-basins are prone to seasonal flooding, especially during the monsoon months, which results in the inundation of low-lying areas and disrupts local communities. The Gadilam and Lower Pennaiyar sub-basins are home to communities whose livelihoods rely heavily on agriculture and fishing. Socio-economic vulnerability in the region is heightened by factors such as poverty, limited access to healthcare, and inadequate disaster preparedness.

### 2.2. *Data*

The historical rainfall data from 1990 to 2023 span with a daily timescale is obtained from the Indian Meteorological Department (IMD) Pune website. The Theissen polygon map of lower Pennaiyar and Gadilam subbasin is given in Fig. 5. The latest soil data acquired from the Geological Survey of India (GOI) is shown in Fig. 2. The Shuttle Radar Topography Mission (SRTM) based Digital elevation model (DEM) of 30 m resolution was downloaded from an earth data website and is presented in Fig. 3. This study utilized Sentinel-2 Land Use and Land Cover data for the year 2021, obtained from the European Space Agency (ESA) website, is displayed in Fig. 4. The discharge data (1990 - 2020) is needed for

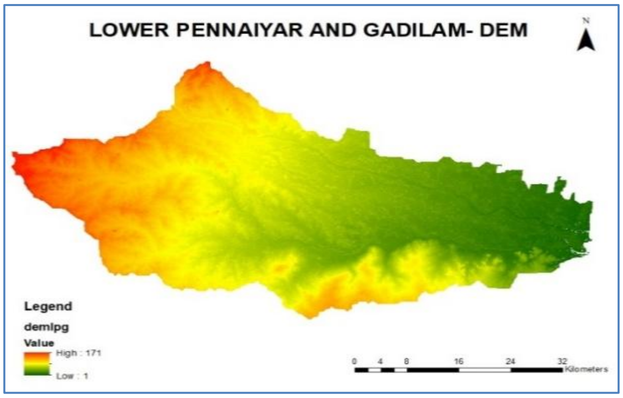


**Fig. 3**. Digital elevation map of lower Pennaiyar and Gadilam subbasin

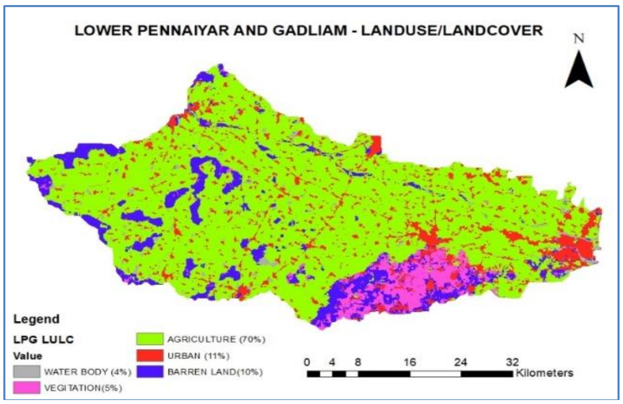


**Fig. 4**. Land use and Land cover map of lower Pennaiyar and Gadilam subbasin

calibration and validation at anicut locations were received from the India-Water Resource Information System (WRIS) website.

Based on the variation in rainfall, temperature and other climate variables, the GCMs were modelled. Hence, the CMIP6 GCM was chosen for this study and it is downloaded from http://zenedo.org/. It comprises of five socio-economic pathways (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7, SSP5-8.5) could incorporate all the GHG emission scenarios ranged from low to high).

2.3. *HEC-HMS and HEC-RAS Model set-up*

The HEC-HMS model was adopted to denote the hydrological characteristics of the Lower Pennaiyar and Gadilam river basins and to analyse the impacts due to changing climate. It is a distributed model that supports event based simulation of stream flow. The river basin is delineated in HEC-HMS using DEM is shown in Fig. 6. The physical parameters of sub-basins and reaches were computed in this step. The Land use and Land cover data, DEM, Soil data were given as input to the model. The study uses the SCS-CN unit hydrograph (UH) method to compute rainfall-runoff over the sub-basins. The runoff

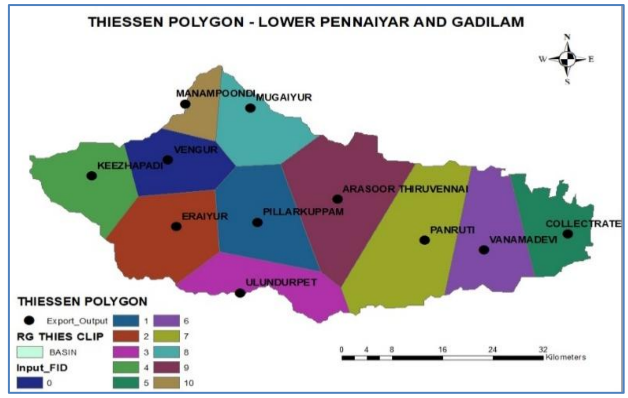


**Fig. 5.** Theissen polygon map of lower Pennaiyar and Gadilam subbasin

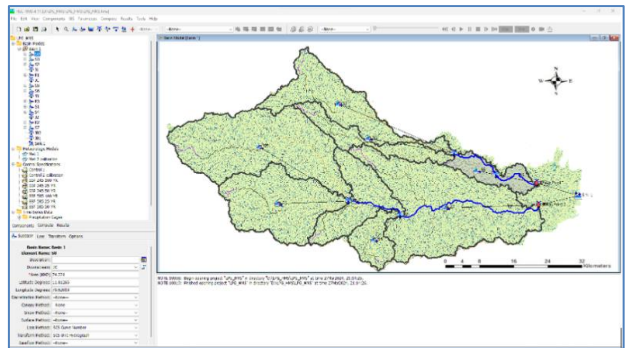

**Fig. 6.** HEC-HMS model set-up for Pennaiyar basin

volume is estimated using the SCS conceptual model which is based on equation 1.

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \tag{1}$$

Here in equation 1, Q is the runoff value in mm, P is the rainfall depth in mm, $I_a$ is the initial abstraction in mm and S is the potential maximum water retention. The relationship between S and CN is given by equation 2. The value of initial abstraction varies in the range of 0.1 and 0.3, and is taken as 0.3 for Indian conditions.

$$S = (25400/\mathrm{CN}) - 254 \tag{2}$$

The curve numbers are, 30 for areas which have more infiltration and 100 for those areas which are a wet region, specifically denotes a water body. The runoff computations were dependent upon the climate variables, LULC, soil type with Antecedent Moisture Conditions (AMC) and terrain of the basin. The SCS-UH method of HEC-HMS requires the input parameter of lag time for the calculation of infiltration excess rainfall. The lag time is calculated as 0.6 times the Time of Concentration. The lag time is calculated using the Kirpitch's formula as depicted by equation 3.

$$T_c = 0.01947 * L^{0.77} * S^{-0.358} \tag{3}$$

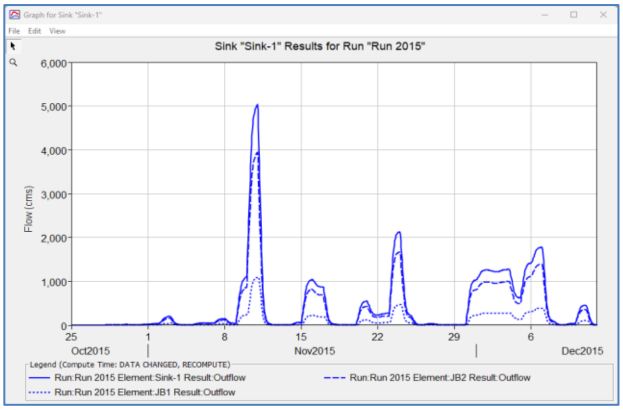


**Fig. 7.** Observed and Simulated hydrograph for the 2015 event

Here in equation 3, $T_c$ is the time of concentration in minutes, L is the Overland flow distance in m and S is the channel slope. Among the five routing methods, Muskingham's routing method was selected for this study. This method gives effective channel flow propagation. The parameters of the Muskingum method used for routing the runoff from the sub-basins to the outlet of the basin are k and x values. The weighting parameter x can be assumed a value from 0 to 0.5. The value of x typically ranges between 0 and 0.5, where 0 represents no storage effect (pure translation) and 0.5 represents maximum storage effect. The k value being the travel time of water in the reach, is calculated as the division of the length of the reach derived from GIS platform by the velocity of water in it. In this study, the velocity was assumed to be 1.5 m/s, which corresponds to the maximum permissible flow velocity in the channel. The routing parameters are shown in the Table 2.

Hydraulic modelling: HEC-RAS incorporates two-dimensional (2D) flow modeling capabilities using the Saint-Venant equations to solve for water surface profiles, velocity, and depth distributions under various flow conditions. The present study uses unsteady flow analyses, making it suitable for both routine water surface profile calculations and complex, time-varying flood simulations. Additionally, HEC-RAS includes tools for evaluating the performance of hydraulic structures such as bridges, culverts, and levees, and it supports flood risk reduction studies.

## 3. Results and discussion

### 3.1. *EC-EARTH 3*

EC-EARTH 3 (European Community Earth-System Model) is used for a wide range of climate studies, including simulations of past, present, and future climates, as well as assessments of climate change impacts and mitigation strategies. EC – Earth3 integrates various components representing different parts of the Earth system, including the atmosphere, ocean, sea ice, land surface, and biogeochemical cycles (Meucci *et al*. 2023). It plays a valuable role in advancing the understanding of the Earth's climate system and informing climate policy decisions at regional and global scales. Based on the study conducted in the Ponnaiyar river basin, EC-EARTH 3 GCM model can be efficiently adopted in the river basins to semi-arid regions to generate the best streamflow discharge. EC-EARTH 3 is the best model selected out of 13 different GCM models (Balu *et al*. 2023). In view of the best results, the present study chose EC-EARTH 3 GCM for the future streamflow discharge generation.

As part of CMIP6, EC-EARTH 3 benefits from the latest improvements in climate modeling frameworks, including better physical parameterizations and representation of greenhouse gas forcing scenarios. Therefore, the model produces more reliable projections under SSP scenarios. Previous studies have demonstrated that EC-EARTH 3 performs well over South Asia, especially in capturing seasonal patterns and extreme events. While a comprehensive inter-comparison of all available CMIP6 models was not conducted within the scope of this study. Based on the previous study conducted on Pennaiyar basin, EC-EARTH 3 is the best model selected out of 13 different GCM models (Balu *et al*. 2023). It was chosen based on its spatial resolution, data availability, and alignment with observed historical trends in the basin.

The EC-EARTH 3 model GCM data utilized in this study were sourced from a downscaled dataset available on ZENODO, which includes statistical downscaling to achieve higher spatial resolution. This dataset had already undergone preprocessing to correct large-scale biases and improve spatial detail. However, the effectiveness of the bias correction was assessed by comparing the model's precipitation data with observed precipitation during flood events occurring in the same timeframe.

### 3.2. *Calibration and Validation of HEC-HMS*

In this HEC-HMS hydrological model underwent calibration of flood events 2015, 2017, 2018, 2020, and 2023 is depicted in Fig. 7, Fig. 8, Fig. 9, Fig. 10 and Fig. 11. Further, the flood events were validated with the semi-seasonal data of the North East Monsoon (NEM) by the three selected major flood events 2015, 2018 and 2020 is given in Fig. 12, Fig. 13 and Fig. 14. The parameters CN has an effect on volume of flow and lag time influences flow peak values (Roy *et al*. 2013). The CN was computed for all the sub basins and the values obtained are shown in the Table 1. The Muskingham's routing parameters were calculated and represented in Table 2.

**TABLE 1**

**Composite curve number for sub basins**

| Sub basins | Curve Number | Lag time in (minutes) |
|---|---|---|
| Subbasin-1 | 77.308052 | 201.14 |
| Subbasin-2 | 78.055859 | 269.45 |
| Subbasin-3 | 76.900684 | 287.41 |
| Subbasin-4 | 76.836794 | 283.71 |
| Subbasin-5 | 77.043019 | 219.94 |
| Subbasin-6 | 76.496788 | 187.63 |
| Subbasin-7 | 77.844421 | 120.59 |
| Subbasin-8 | 77.329932 | 366.55 |

**TABLE 2**

**Routing parameters**

| Reach No | K (hours) | X Assumed |
|---|---|---|
| R1 | 3.465 | 0.25 |
| R2 | 5.104 | 0.25 |
| R3 | 1.883 | 0.25 |

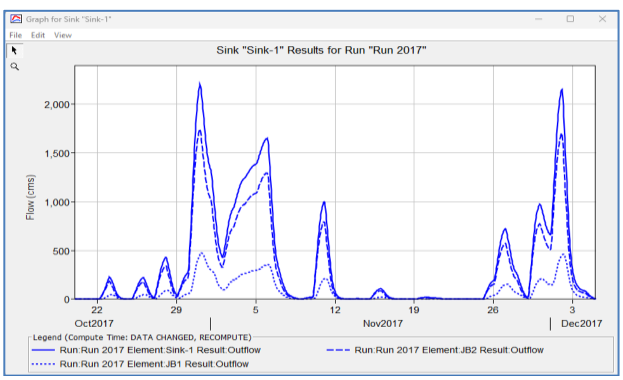


**Fig. 8**. Observed and Simulated hydrograph for the 2017 event

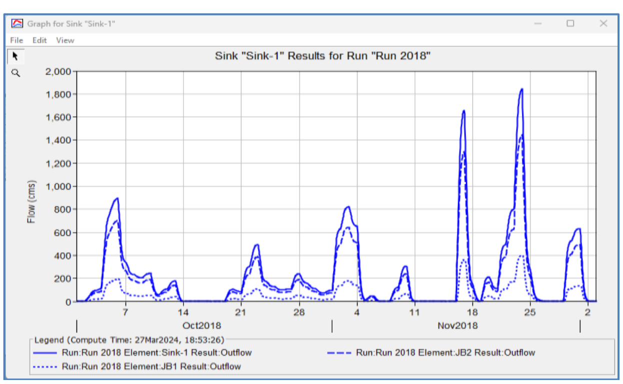


**Fig. 9**. Observed and Simulated hydrograph for the 2018 event

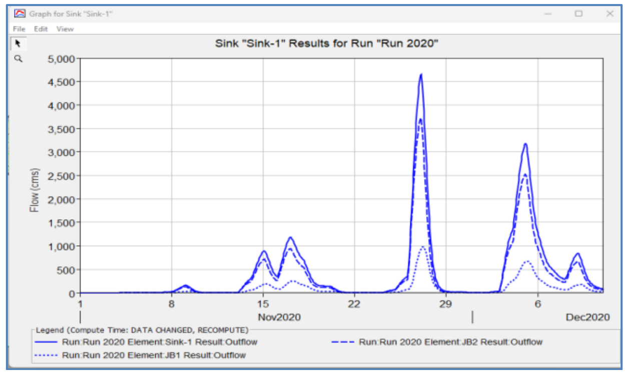


**Fig. 10.** Observed and Simulated hydrograph for the 2020 event

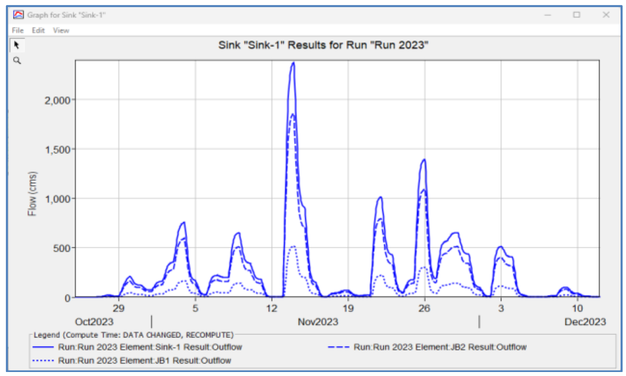


**Fig. 11**. Observed and Simulated hydrograph for the 2023 event

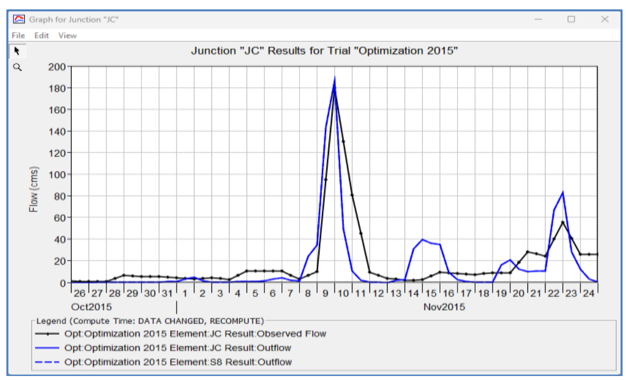


**Fig. 12**. Observed and Simulated hydrograph of 2015 event

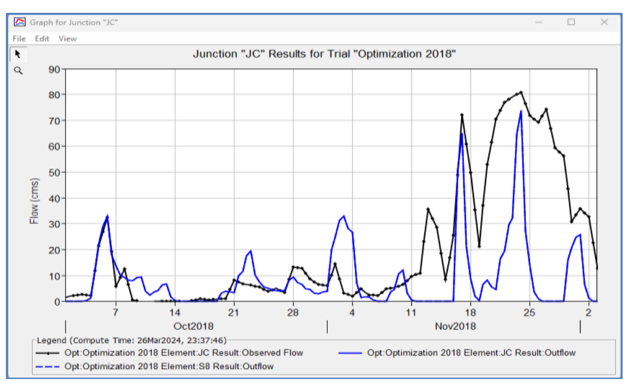


**Fig. 13**. Observed and Simulated hydrograph of 2018 event

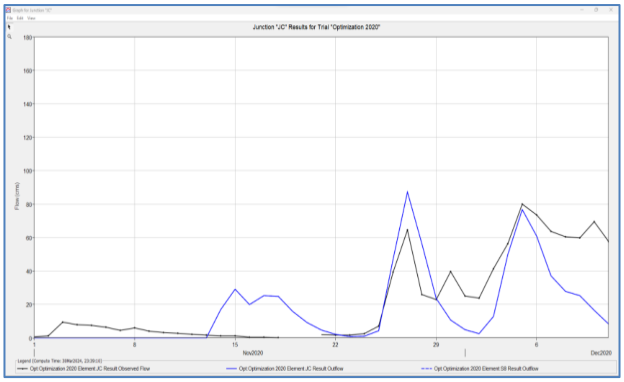


**Fig. 14**. Observed and Simulated hydrograph of 2020 event

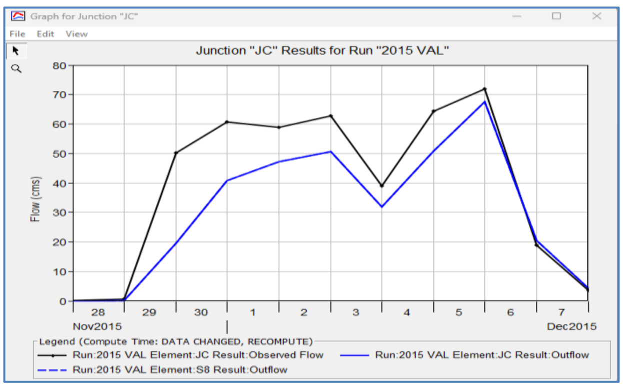


**Fig. 15**. Validation plot of 2015 event

The sensitivity analysis of most influential parameters such as CN, lag time, initial abstraction and Muskingham's routing were carried out by modifying their value ranges between ±10%, ±15%, ±20% and ±25%. The best fit values of the parameters with respect to the runoff volume and peak discharge were determined as 9.7%, 5%, 2.8% and 1.7% for the CN, routing, lag time and initial abstraction in the calibration step. To simulate the hydrological processes accurately, the calibrated model with the best fitting parameters is used for validation of the selected flood events. The observed and simulated flow has the best match in the calibration flood events 2015, 2017, 2018, 2020, and 2023. The validation results are presented in Fig. 15, Fig. 16 and Fig. 17.

The scatter plot in Fig. 18, Fig. 19 and Fig. 20 of validation shows the match between observed and simulated flow for the semi-seasonal flood events 2015, 2018 and 2020 with a $R^2$ value of 0.88, 0.83 and 0.86 respectively. The $R^2$ values in the results reveal that the calibrated model performs well in the validation. The Nash–Sutcliffe Efficiency (NSE) is a widely used statistical metric to evaluate the predictive skill of hydrological models by comparing simulated data to observed data. The NSE values found to be 0.85, 0.8 and 0.82 respectively for the flood events 2015, 2018 & 2020.

### 3.3. *Hydrologic and hydraulic modeling*

The hydrologic modeling using HEC-HMS and hydraulic modeling by HEC-RAS 2D was adopted for both the baseline observed data and EC-EARTH 3 under SSP 2-4.5 and SSP 5-8.5 model data. The HEC-HMS results for future climate change scenarios indicate significant variations in peak discharge rates under different SSPs. The hydrographs were developed for the return periods 25, 50 and 100 years and are shown in Fig. 21, Fig. 22 and Fig. 23 for the SSP 2-4.5 scenario. For the SSP5-8.5 scenario, the hydrographs were generated for the return periods 25, 50 and 100 years and are shown in Fig. 24, Fig. 25 and Fig. 26. For SSP245, the peak discharges for the 25-year, 50-year, and 100-year return periods are 4089, 5570, and 5782 m³/s, respectively. In contrast, for SSP585, the peak discharges for the 25-year, 50-year, and 100-year return periods were 2792, 4844, and 6442 m³/s respectively. These results highlight the potential impacts of different climate change scenarios on flood risk.

Under the SSP5-8.5 scenario, rainfall events may become more intense but shorter in duration, or exhibit shifts in seasonal patterns, resulting in different runoff generation dynamics compared to SSP2-4.5. Flood volume is strongly influenced by the initial moisture conditions of the catchment. In SSP5-8.5, soils may be drier prior to key rainfall events, which can enhance

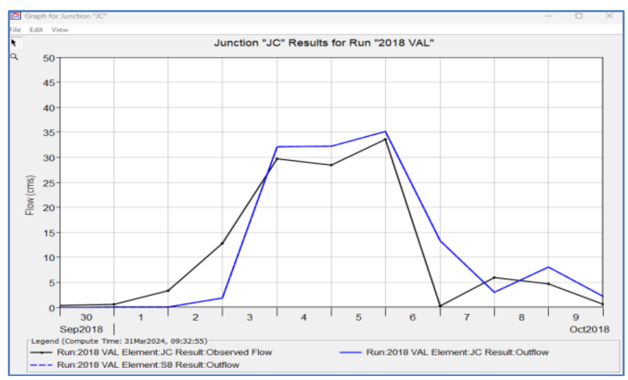


**Fig. 16**. Validation plot of 2018 event

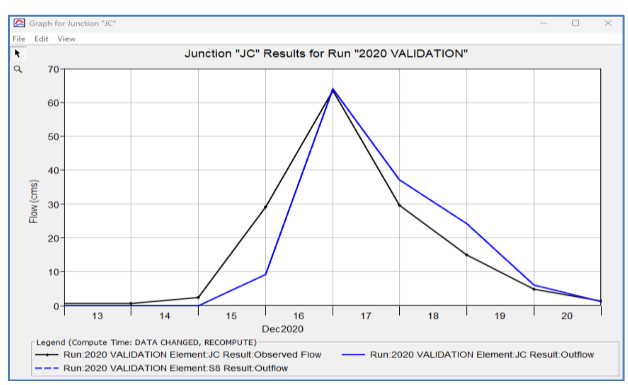


**Fig. 17**. Validation plot of 2020 event

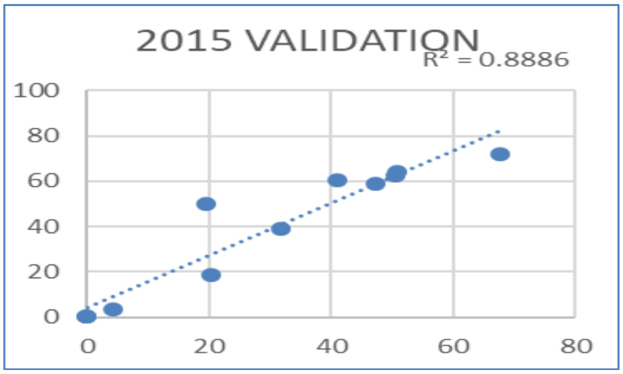


**Fig. 18.** Validation scatter plot of 2015 event

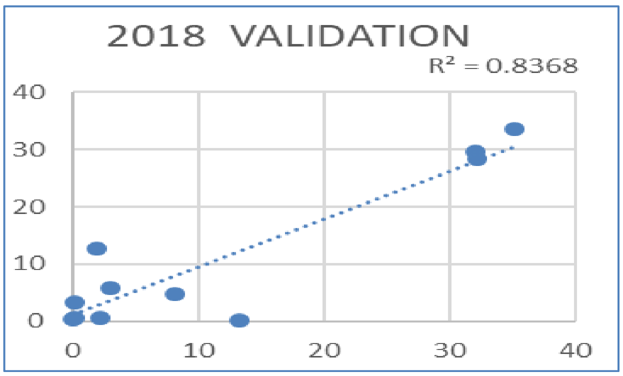


**Fig. 19.** Validation scatter plot of 2018 event

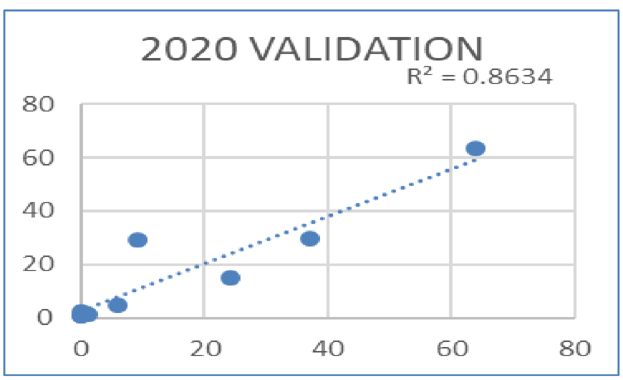


**Fig. 20.** Validation scatter plot of 2020 event

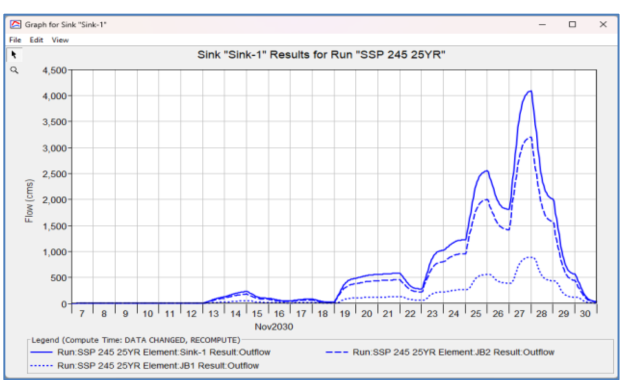


**Fig. 21**. Flow hydrograph for SSP2-4.5 scenario for 25 year return period

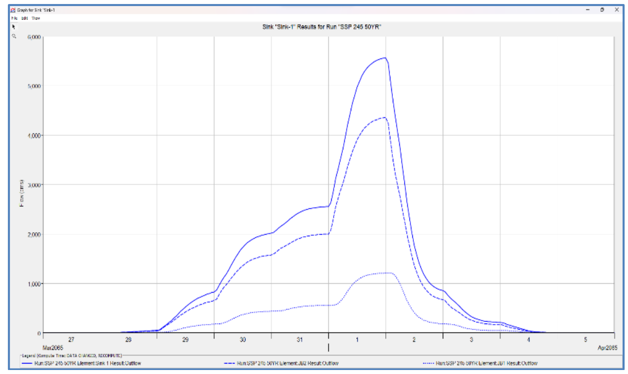


**Fig. 22.** Flow hydrograph for SSP2-4.5 scenario for 50 year return period

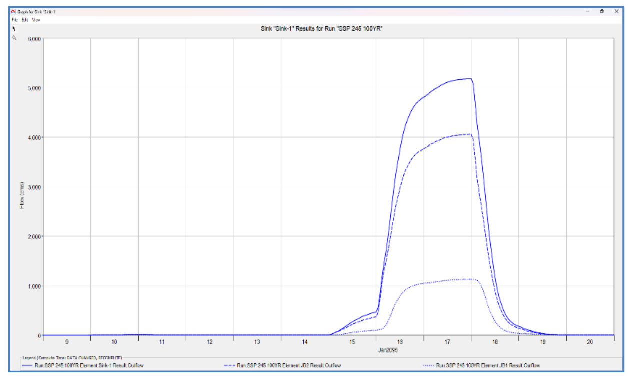


**Fig. 23.** Flow hydrograph for SSP2-4.5 scenario for 100 year return period

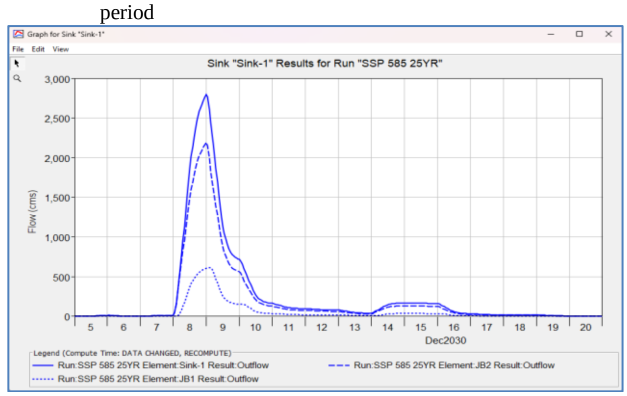


**Fig. 24**. Flow hydrograph for SSP5-8.5 scenario for 25 year return period

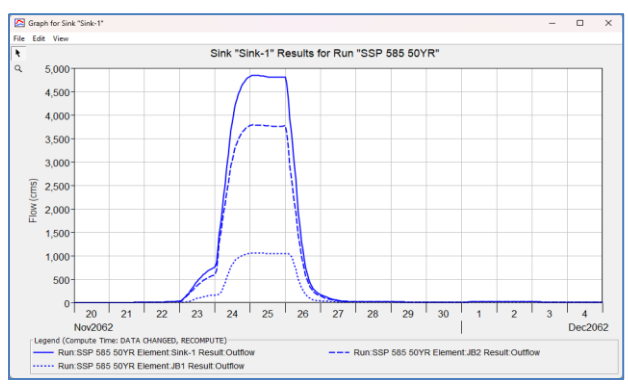


**Fig. 25.** Flow hydrograph for SSP5-8.5 scenario for 50 year return period

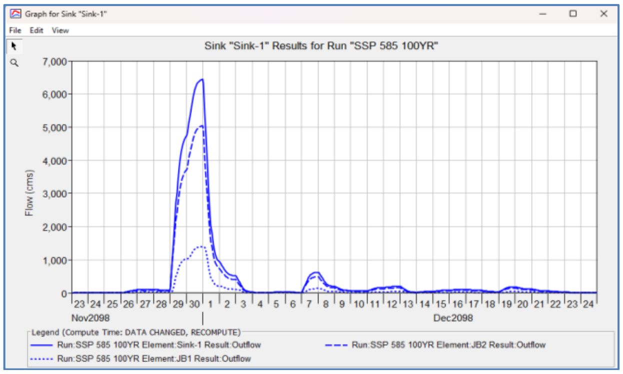


**Fig. 26.** Flow hydrograph for SSP5-8.5 scenario for 100 year return period

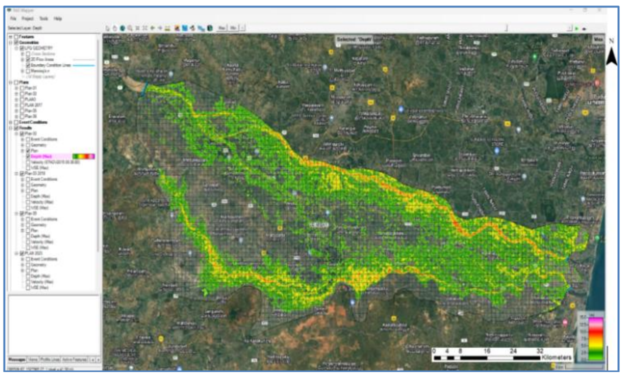

**Fig. 27**. Flood inundation map of Pennaiyar basin in the year 2015

infiltration and consequently reduce runoff volumes relative to SSP2-4.5. Hydrological models incorporate complex nonlinear processes—such as infiltration, storage, and routing—that do not respond linearly to changes in climate inputs. Therefore, despite more intense rainfall under SSP5-8.5, runoff may decrease due to thresholds related to soil saturation, vegetation responses, and channel capacity. Furthermore, uncertainties inherent in climate projections, particularly concerning regional precipitation extremes, mean that SSP5-8.5 does not consistently produce higher flood volumes. Some modeled return periods may instead reflect internal climate variability or scenario-specific regional dynamics, which can temporarily suppress flood magnitudes.

### 3.4. *Flood inundation map for different return periods under ssp scenarios*

The HEC-HMS time series for the selected return periods was given as input data to the HEC-RAS in order to analyze the unsteady flow. In HEC-RAS, the Manning's coefficient value is given as input based on previous studies (Phillips & Tadayon 2006). The flood inundation maps for 2015 and 2018 events are depicted in Fig. 27 and Fig. 28. The model develops different flood inundation maps for return periods under consideration for SSP2-4.5 and SSP5-8.5, are represented in Fig. 29, Fig. 30, Fig. 31, Fig. 32, Fig. 33 and Fig. 34. The HEC-RAS results for future climate change scenarios reveal notable differences in flood volumes under SSP2-4.5 and SSP5-8.5. For SSP2-4.5, the flood volumes for the 25-year, 50-year, and 100-year return periods were 1,272,194 m³, 890,288 m³, and 916,936 m³ respectively. In comparison, under SSP5-8.5, the flood volumes for the 25-year, 50-year, and 100-year return periods are 550,879 m³, 990,028 m³, and 938,226 m³ respectively. Additionally, the HEC-RAS river modeling results indicate that the peak flood depth under the SSP2-4.5 scenario is 18.8m, whereas under the SSP5-8.5 scenario, the peak flood depth reaches 21.6m. The inundation depth is increasing at the rate of 12.96% with respect to SSP5-8.5 compared to SSP2-4.5 scenario.

### 3.5. *Structural measures for flood risk reduction*

The HEC-RAS 2D results under SSP scenarios indicate that the need to focus on major flood inundated areas and requires flood risk reduction in those vulnerable regions. Severe flood damage will be significant in the future and it was predicted to the 100 year return period based on the SSP scenarios. Consequently, it is essential to implement strategies to mitigate flood risks for these resulting conditions. To address this condition, the study proposes three structural methods such as pond creation, channel modification and levee construction.

On the upstream side of the Gadilam and Lower Pennaiyar sub-basins, four ponds were created as a flood risk reduction strategy. Two ponds are created upstream of the Gadilam River with a depth of 8.5 m and two ponds

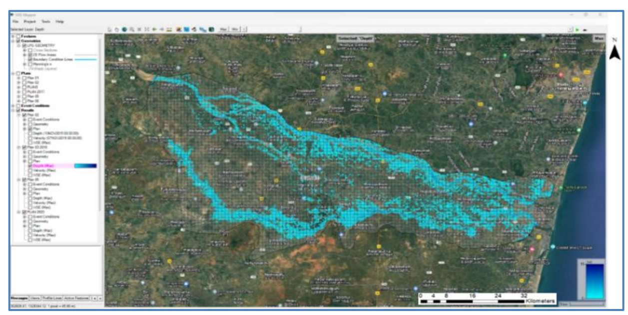

**Fig. 28.** Flood inundation map of Pennaiyar basin in the year 2018

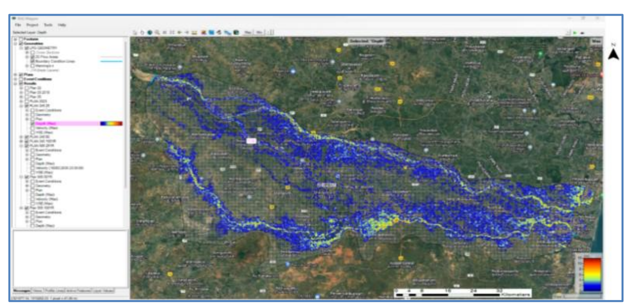

**Fig. 29**. Flood Inundation map for 25 year return period under SSP 245 Scenario

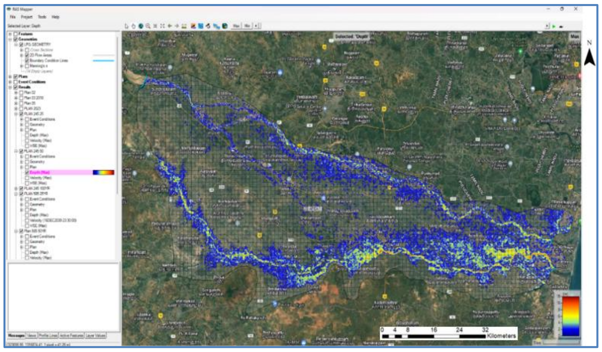

**Fig. 30.** Flood Inundation map for 50 year return period under SSP 245 Scenario

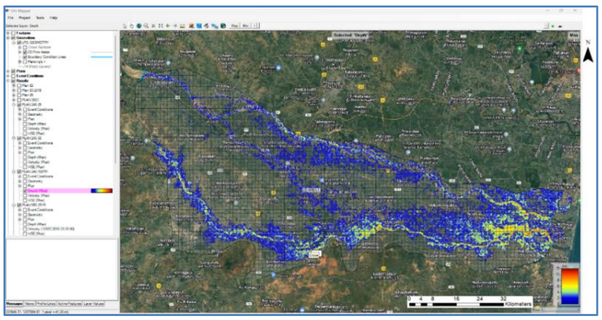

**Fig. 31**. Flood Inundation map for 100 year return period under SSP 245 Scenario

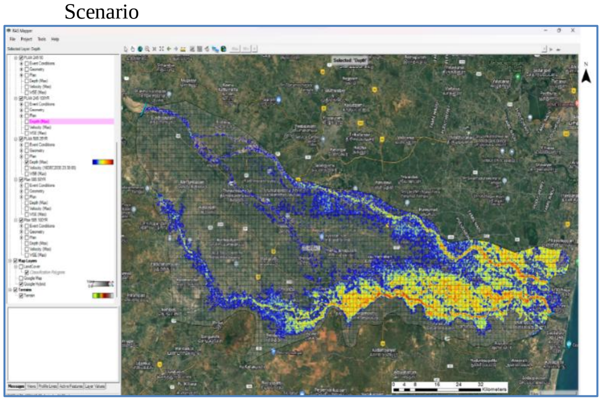

**Fig. 32**. Flood Inundation map for 25 year return period under SSP 585 Scenario

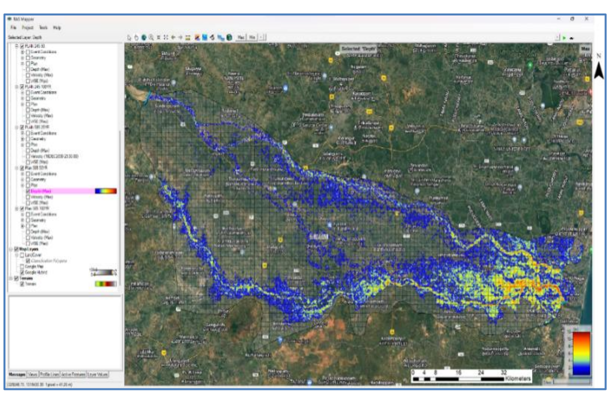

**Fig. 33**. Flood Inundation map for 50year return period under SSP 585 Scenario

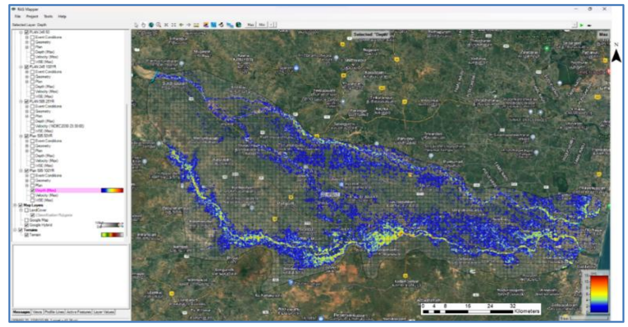

**Fig. 34**. Flood Inundation map for 100 year return period under SSP 585 Scenario

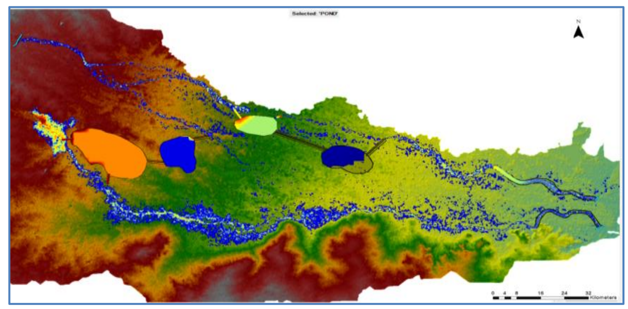

**Fig. 35**. Flood Inundation map after the creation of structures

are created on the Lower Pennaiyar River with a depth of 7.2 m, it is directly connected with the river. The channels and levee structures essential for flood mitigation were engineered using terrain modification tools available in HEC - RAS. Modifications to the Gadilam and Lower Pennaiyar Rivers included adjusted depths to range between 3 to 7 meters and levee structures extending up to 18 m in residential areas near Cuddalore city. The flood inundation map after the introduction of structures is clearly shown in Fig. 35. During the simulation of HEC-RAS 2D, the structures effectively reduced the flood flow. Demonstrating their effectiveness in enhancing flood resilience in the region.

## 4. Conclusions

The present research integrates hydrologic and hydraulic modeling along with the introduction of structures to analyze the upcoming flood risk in changing climate in the lower Pennaiyar and Gadilam sub-basin. The EC-EARTH 3 climate model of CMIP6 shows excellent ability in representing the rainfall extremes, especially in short return periods needed for the new settlement planning. The results revealed that future flood events impose higher damage to the lower elevated downstream coastal areas. The sub-basin is having major land use for agriculture and the intensity of flooding under different climate change scenarios affects the livelihood of those population. Every NEM season, the lower stretch of this sub-basin undergoes infrastructure damage in settlements and also increasing mortality. Proper flood water harvesting is necessary to sustain the agricultural activities. This study analyses the change in the streamflow and flood inundation under the different SSP scenarios. The results obtained is helpful in understanding the spatial and temporal variation of peak rainfall and peak flood discharges. The ponds created in the upstream regions reduces peak floods. The floodwater stored temporarily can significantly lower downstream flood risks. This upstream intervention will help in attenuating flood peaks before they reach vulnerable areas. The channel modification of altering the river channel to enhance its capacity to convey floodwater of an effective strategy. This method is particularly useful in urban areas where space limited. Channel modifications can include widening, deepening, or re-routing sections of the river in order to improve flow and reduce the risk of overflow. The construction of levees and other flood control structures along riverbanks can protect residential areas of Cuddalore City, from floodwater. These proposed structures will act as barriers, preventing floodwater from inundating vulnerable areas and thus, safeguarding lives and property.

Effective implementation of robust flood early warning systems can substantially reduce flood-related damages. Installing real-time monitoring stations, such as rain gauges and stream gauges, in vulnerable areas enhances early detection. Flood forecast information derived from remote sensing data integrated into hydrological models plays a crucial role in informed decision-making. Combining these flood alerts with local communication networks facilitates faster evacuation and response. Historical flood records and Digital Elevation Models (DEMs) are used to delineate flood-prone zones. High-risk areas should be restricted from encroachment and construction, while flood-resilient land uses—such as agriculture and parks-can be encouraged within floodplains. Establishing flood buffer zones along rivers and tanks further mitigates flood risk. Long-term flood resilience depends on comprehensive planning frameworks and strengthened governance. Stakeholders from the Lower Pennaiyar and Gadilam sub-basins can be ngaged in forming basin-level water user associations to promote participatory water budgeting. Institutional coordination can be improved by enhancing communication among state disaster management authorities, public works, water resources, meteorological, agricultural, rural development departments, and local panchayats. Policy reforms and incentives should focus on promoting water-efficient practices, climate resilience, and crop diversification. Regular training programs, community-based disaster management strategies, and mock drills can further build capacity and raise awareness.

The hydrological and hydraulic models used in this study are open-source and applicable to all terrain types across India. The baseline condition assessment protocol is designed to be adaptable to any basin. Rainfall, discharge, land use/land cover (LULC), and soil data were sourced from national datasets. For basins with similar characteristics, the model's input parameters can be derived accordingly. Input parameter modification and model calibration are guided by the basin's climate, topography, geology, and water availability. Additionally, the adoption of advanced technologies such as cloud-based decision support systems, mobile applications, and dashboards for real-time data dissemination, along with artificial intelligence and machine learning for prediction and anomaly detection is encouraged.

Overlaying socio-economic indicators with flood hazard maps helps identify multi-dimensional vulnerabilities, enabling targeted interventions, equitable disaster response, and efficient resource allocation. Nature-based solutions such as watershed restoration, green infrastructure, and river corridor rehabilitation are urgently needed. Flood models can be improved by integrating emerging technologies like AI, machine learning, and deep learning. Climate-resilient solutions are essential for supporting the most vulnerable communities. Moreover, participatory approaches and governance-focused research strengthen the legitimacy and sustainability of these interventions.

*Data Availability*

The manuscript incorporates rainfall, soil, DEM, Sentinel 2 Land use and Land cover, discharge and GCM datasets were collected from their respective websites and incorporated into the analysis.

*Funding*

The author received no financial grant or funding during the course of this research.

*Acknowledgement*

The author acknowledges the vital help from the Centre for Water resources, Anna University for infrastructure support.

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*Disclaimer*: The contents and views expressed in this research article are those of the authors and do not necessarily reflect the views of their affiliated organizations.

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