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*Shringar Mishra¹, Vinod Kumar Tripathi^{*1}, R.K. Jaiswal², Samikshya Panda¹, Deepak Kumar¹*

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Research Paper

Climate Change and Hydrological Risk Assessment : Probable Maximum Precipitation Analysis in the Sindh Basin

Shringar Mishra¹, Vinod Kumar Tripathi^{*1}, R.K. Jaiswal², Samikshya Panda¹, Deepak Kumar¹

¹Department of Farm Engineering, I.Ag.Sc, BHU, Varanasi 221005

²Scientist F, National Institute of Hydrology, Bhopal

*Corresponding Author E-mail: vktripathi@bhu.ac.in

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ABSTRACT

The Probable Maximum Precipitation (PMP) is the theoretical maximum precipitation that could occur over a given area during a specified period and is commonly used in designs of hydraulic structures such as dams, spillways, weirs, barrages levees etc. Climate change affects the PMP, as warming temperatures can increase the moisture-holding capacity of the atmosphere and alter precipitation patterns. Hershfield method was applied to estimate the PMP of daily maximum rainfall data over 32 years (1991–2022) in the Sindh basin. This paper investigates the possible spatio-temporal change in PMP over the Sindh basin under changing climate. To capture this change in PMP, 1-day, 2-day and 3-day PMP maps are developed for the entire Sindh basin for four time periods, spanning over 110 years from past to future – one historical period, viz. (1991–2022) and three future periods, viz. near-future (2025–2050), future (2051–2075) and far-future (2076–2100), following four possible climate change scenarios (SSP1-2.6, SSP2-4.5, SSP3- 7.0 and SSP5-8.5). These PMP maps, especially the historical and its future projections will serve as a piece of important information for the design engineers and hydro-meteorologists for revised planning and designing various major water-energy infrastructures in the context of climate change. The performance evaluation of thirteen climatic models was done with reference to observed IMD data using three performance indices (NSE, PBIAS, R^2) for mean annual precipitation from 1991 to 2014. The comparison between different scenarios also revealed that precipitation value is decreasing in case of 1-day PMP variation for all scenarios in the near future, future and far future. SSP1-2.6 scenario shows a maximum decrease in precipitation in the case of 1-day and 2-day PMP variation for all three futures. The historical and future PMP maps were created using IMD-observed daily precipitation data. In this study, a distinct decreasing trend in PMP for all the periods in future in most of the region was found.

Keywords: Probable maximum precipitation, Climate change, GCM climate model, SSP scenario, Hershfield method, Inverse Distance weighting

Keywords: Characterization, Biophysical Parameters, GIS, Satellite images.

INTRODUCTION

In recent decades, the relationship between extreme precipitation, climate change, and variability has gained substantial attention from the scientific community. Observational evidence indicates an increase in the frequency and intensity of heavy rainfall events in various regions across the globe. These changes have been linked to shifts in atmospheric circulation patterns, altered moisture availability, and changes in convective processes. However, quantifying the extent to which human-induced climate change contributes to these observed trends remains a complex challenge, requiring advanced modelling techniques and comprehensive data analysis. One of the most significant effects of climate change is the intensification of the hydrological cycle (Jacob and Hagemann, 2007, Allen and Ingram, 2002). At both the global and local scales, this intensification increases the intensity and frequency of precipitation events (Trenberth et al., 2003; Giorgi et al., 2011). Numerous studies (Allan and Soden, 2008; Madakumbura et al., 2019) have documented an increase in intense precipitation. As a result of this intensification, probable maximum precipitation (PMP), which is defined as "the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year" (WMO, 1986), is expected to rise over time.

Impact of Climate Change

The occurrence of related extreme events, such as floods and droughts, may increase due to the unpredictability of precipitation brought on by a changing climate. The most severe climate-related dangers worldwide have reportedly been associated with extreme precipitation occurrences (Schoof and Robeson, 2016). At both the global and regional scales, there has been a noticeable rise in extreme precipitation since the 1950s (Pinskwar et al., 2019). Additionally, it is anticipated that it will intensify further in the future due to a changing climate. The literature from several places in the world has reported on the potential effects of climate change on the PMP. According to simulation results from several Global Circulation Models (GCMs) for instance, Kunkel et al. (2013) demonstrated that the PMP is anticipated to grow in the future due to a significant increase in average and maximum atmospheric moisture content. Rouhani and Leconte (2018) found a tendency to increase PMP estimates throughout various watersheds in Quebec after analyzing the downscaled climatic projections made by the Canadian Regional Climate Model (CRCM). Using a physics-based numerical weather simulation model, Rastogi et al. (2017) predicted a considerable rise in PMP estimations over the Alabama-Coosa-Tallapoosa (ACT) River Basin in the later part of the 21st century. According to Stratz and Hossain's (2014) research on nonstationary PMP recalculations at three sizable dam sites in the United States, existing PMP values will significantly rise as a result of future climatic changes. According to Chen et al. (2017), the Pacific Northwest (PNW) region of the USA would experience a rise in PMP of roughly 50% to +30% around 2099 compared to the level in 2016 under the worst possible climate scenario (RCP8.5). Afroz et al. (2015) and Lee et al. (2016) examined the effects of climate change on PMP and reported a general increasing tendency in the future throughout many parts of the world.

Climate Change Scenario

There have been four generations of emission scenarios covered by IPCC assessments in the past. Three series were created inside the IPCC including the "1990 IPCC First Scientific Assessment" (SA90) (IPCC, 1990), the "1992 IPCC Scenarios" (IS92) (Leggett et al., 1992), the 2000 "Special Report on Emissions Scenarios" (SRES) (Nakicenovic and Swart, 2000) and the additional post-SRES including intervention (IPCC, 2001a, 2001b). The "Shared Socioeconomic Pathways" (SSPs) (O'Neill et al., 2014;) and the "Representative Concentration Pathways" (RCPs) (van Vuuren et al., 2011) are the most recent emissions scenarios. While the SSP-RCP combinations informed AR6, the RCPs provided information to AR5 (IPCC, 2021). The Special Report on Emissions Scenarios (SRES) was a report developed by the Intergovernmental Panel on Climate Change (IPCC) in 2000. It presented a range of scenarios that explored different possible futures for greenhouse gas emissions and their potential impacts on climate change. The SRES scenarios included different storylines and assumptions about factors such as population growth, economic development, energy use, and technology adoption. These scenarios were used to model a range of possible emissions trajectories and associated climate change outcomes. They were labelled with various acronyms, such as A1, A2, B1 and B2 to differentiate between different narrative storylines and underlying assumptions.

The CMIP6's embedded scenario model intercomparison project delivers multi-model climate projections based on several scenarios to show the socio-economic issues connected to climate change adaptation and mitigation (O'Neill et al., 2017). Recent climate forecasts are based on land-use scenarios and emissions from Shared Socioeconomic Pathways (SSPs) scenarios, new social development pathways and the IPCC's sixth assessment report's updated RCPs (IPCC, 2021). CMIP6 climate projections differ from CMIP5 due to its newer climate models and SSP scenarios as well as new gap scenarios that were not addressed earlier (Rogelj et al., 2016). In the sixth assessment report (IPCC, 2021), five scenarios (SSP1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) predicted 1.5 °C temperature increases in the near future (2021-2040) and 3.3–5.7 °C in the long future (2081-2100) under the highest emission scenario. Past RCP conceptions, socioeconomic transformations and climate change mitigation contributions are considered in forecasts.

In brief, the overall objective of this study is to investigate the possible spatio-temporal change in PMP over the Sindh basin under changing climate. To capture this change in PMP, 1-day, 2-day and 3-day PMP maps are developed for the entire Sind basin for four time periods, spanning over 110 years from past to future – one historical period, viz. (1991– 2022) and three future periods, viz. near-future (2025–2050), future (2051–2075) and far-future (2076–2100), following four possible climate change scenarios (SSP1-2.6, SSP2-4.5, SSP3- 7.0 and SSP5- 8.5). These PMP maps, especially the historical and its future projections will serve as an important information for the design engineers and hydro-meteorologists for revised planning and designing various major water-energy infrastructures in the context of climate change.

MATERIALS AND METHOD

Study Area

The Sindh river is located between $77^{\circ} 10' 19''\text{E}$ and $79^{\circ} 07' 32''\text{E}$ and $24^{\circ} 01' 04''\text{N}$ and $26^{\circ} 47' 01''\text{N}$ and the basin is extended in $26,207.02 \text{ km}^2$. A large part of the basin lies in Madhya Pradesh and some part in Uttar Pradesh (Fig. 1). The Sindh River flows through the 9 districts of Madhya Pradesh i.e., Vidisha, Guna, Ashok Nagar, Shivpuri, Seopur, Datia, Gwalior, Morena and Bhind and then joins the Chambal River in Etawah district of Uttar Pradesh which is close to the Bhind district of Madhya Pradesh. The Mahuar, Parbati, Pahuj and Kunwari rivers are the major tributaries of the Sindh River. The Mohini Pickup Reservoir and Madikheda (Or Atal Sagar) are the two main dams on the Sindh. The stream of the Sindh River is stretched about 470 km of which 461 km flows in Madhya Pradesh and 9 km in Uttar Pradesh. The study area has a dry tropical climate and there is less rainfall there than in Madhya Pradesh's southern parts. In the summer, the mean daily maximum temperature can reach 47°C and in the winter, the mean daily minimum temperature is about 7.9°C . The range of yearly precipitation is 800 to 1000 mm. The distribution of rainfall within the Sindh basin region can vary from year to year and within different parts of the region.

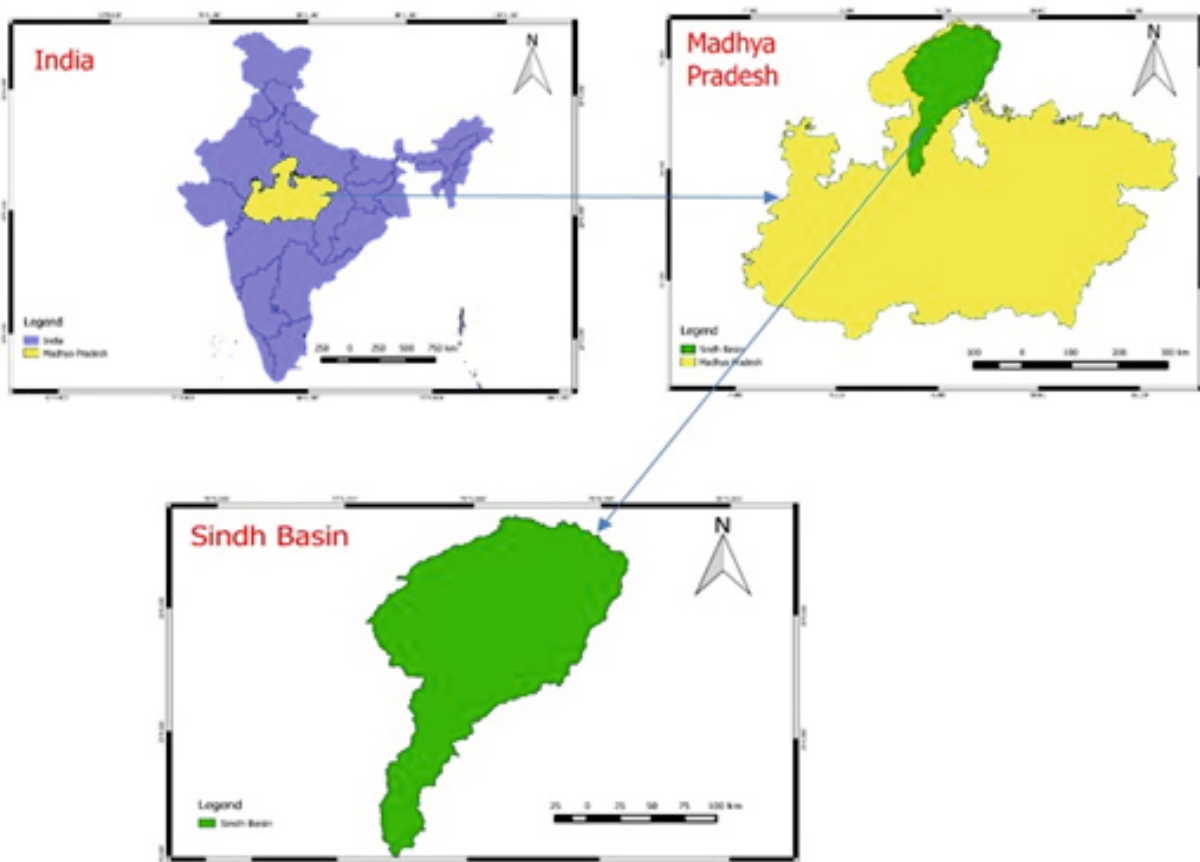


Fig. 1 Location map of the study area

Data Collection

IMD precipitation data

Daily gridded (0.25° latitude \times 0.25° longitude) rainfall data over the entire Sindh basin is procured from the India Meteorological Department (IMD) official website (www.imd.gov.in). The length of the data is 32 years i.e., from 1991 to 2022. There were 37 IMD gridded stations in entire the Sindh basin. In this study, the yearly maximum daily rainfall was used to represent extreme rainfall. A total of 37 rainfall stations were used in the analysis. Only stations with 32 years of IMD data and no missing data were chosen for this study. As a result, the annual maximum series for N years of data includes N rainfall values. To estimate the PMP of all stations, 1-day annual maximum rainfall values for each year were collected and translated into an array of annual maximum rainfall values for each station.

GCMs data from CMIP6

The World Climate Research Programme (WCRP) supported Coupled Model Intercomparison Project (CMIP) webpage provides simulation outputs of numerous climatic variables over historical and future time periods at the regional scale (Nikulin et al., 2011). In this study, daily predicted precipitation values for the future time period 2025–2100 i.e., 75 years are collected from the CMIP database for one Regional Climate Model (RCM) for four emission scenarios denoted by Share Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5). To analyse the change in PMP estimations through time, the length of future simulated data of 75 years is separated into three portions, namely near-future (2025-50), future (2051-75) and far-future (2076-2100). To use any future climate model output, however, bias with respect to observed data must be rectified. Historical simulated daily precipitation values for the relevant climate model are required for bias correction. As a result, in addition to future data, historical data (1991-2014) are received for the model.

Selection of Climate Model

Thirteen GCMs from CMIP6 were first chosen using precipitation data with a 100-km resolution in order to explore future changes in precipitation. The model's precipitation data were downloaded from the ESGF centre at <https://esgf-node.llnl.gov/search/cmip6/>. For each meteorological station, the observational and historical precipitation values were available for South Asia and Mishra et al. (2020) have already downscaled the data of thirteen GCM models which are suitable for South Asia and selected based on the availability of daily precipitation for the historical and four scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5)

The CMIP6 models only have historical data up to 2014, so that should be used for comparison. From 2015 to 2100, the models are projected using this data. The Nash-Sutcliffe Efficiency, Percentage Bias (PBIAS) and

Coefficient of Determination (R^2) indices were used to assess the variation between observational and historical precipitation measurements. The Coefficient of Determination is a dimensionless criterion with 1 being the optimal value (Houshyar et al., 2018). NSE can range from $-\infty$ to 1 for excellent performance. For hydrological modelling, PBIAS values of less than or equal to 10% are deemed acceptable.

The top model was chosen after analysing the 13 GCMs. Precipitation changes were predicted using four SSPs for the future period (2025–2100) based on the best GCM. The historical period (1991–2014) was then used to compare these changes. According to O'Neill et al. (2016), the scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 represent the low, low to medium, medium to high and high ends of the range of future forcing pathways respectively. The flow chart of model selection is shown in Fig. 2.

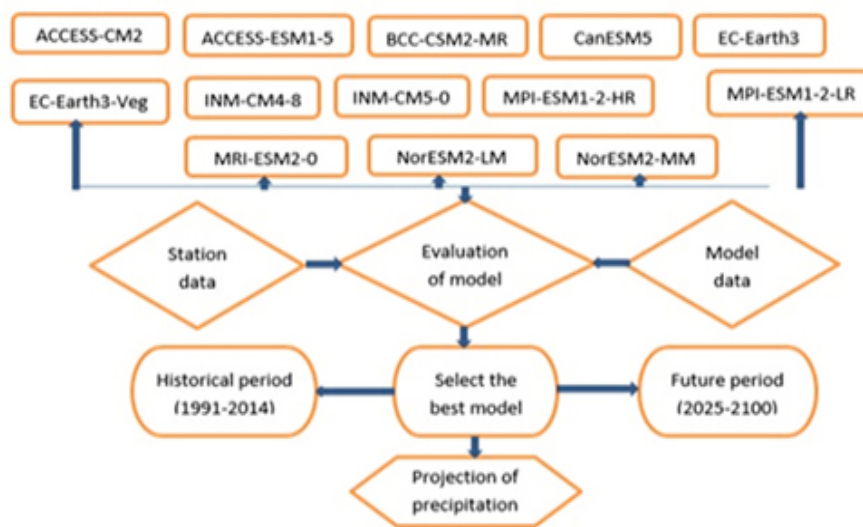


Fig. 2 Flow chart of model selection

Performance Evaluation Indices

Climate models are complex sets of equations and parameterizations that generate various forecasts for different places and variables. It is critical to evaluate the dependability and correctness of these models by comparing their outputs with observable data which may be done using statistical equations classified as frequency-based or time-series-based metrics. Mean, median, standard deviation, and the 10th and 90th percentiles are examples of frequency-based metrics whereas time-series-based metrics include Nash-Sutcliffe efficiency (NSE), percentage bias (PBIAS), mean absolute error (MAE), coefficient of determination (R^2) and root mean square error (RMSE).

Estimation of Probable Maximum Precipitation

In order to estimate PMP, the World Meteorological Organization has actively advocated the use of statistical and hydro-meteorological (physics-based) techniques (WMO, 2009). A statistical technique is a probabilistic method that calls for statistical analysis based on past exceptional precipitation at

meteorological stations where at least 30 years of daily data are available. The Hershfield method (Koutsoyiannis, 1999) is regarded as a practical and effective tool for the estimation of PMP, particularly for those locations where sufficiently long precipitation records are available but other meteorological data (e.g., dew point temperature, wind speed, relative humidity etc.) are lacking. These meteorological data are necessary for other physical techniques such as moisture maximization and storm transposition methodology (Singh et al., 2018). Based on Chow's general frequency equation, Hershfield provided the following fundamental equation for estimating PMP:

$$X_{PMP} = \bar{X}_N + K_M \times S_N \quad \dots (1)$$

where, K_M is the frequency factor for estimating PMP at that location, X_{PMP} is the PMP estimate for that location, \bar{X}_N is the mean of the AMDP series for N years at that location, and S_N is the standard deviation of the AMDP series at that location. Geographic Information System software i.e., ArcGIS was utilized to spatially analyse the PMP data in to study area map. IDW (Inverse Distance Weighting) technique was used to interpolate the data collected from scattered monitoring stations, generating detailed maps that showcase the distribution of the variable of interest (Jeong, 2020).

RESULTS AND DISCUSSION

The accuracy of PMP estimates also depends on the quality of the rainfall data and the statistical methods used for analysis. After the PMP was calculated for 1-day, 2-day, and 3-day duration, its spatial variation is plotted with the help of ARC Map using IDW technique.

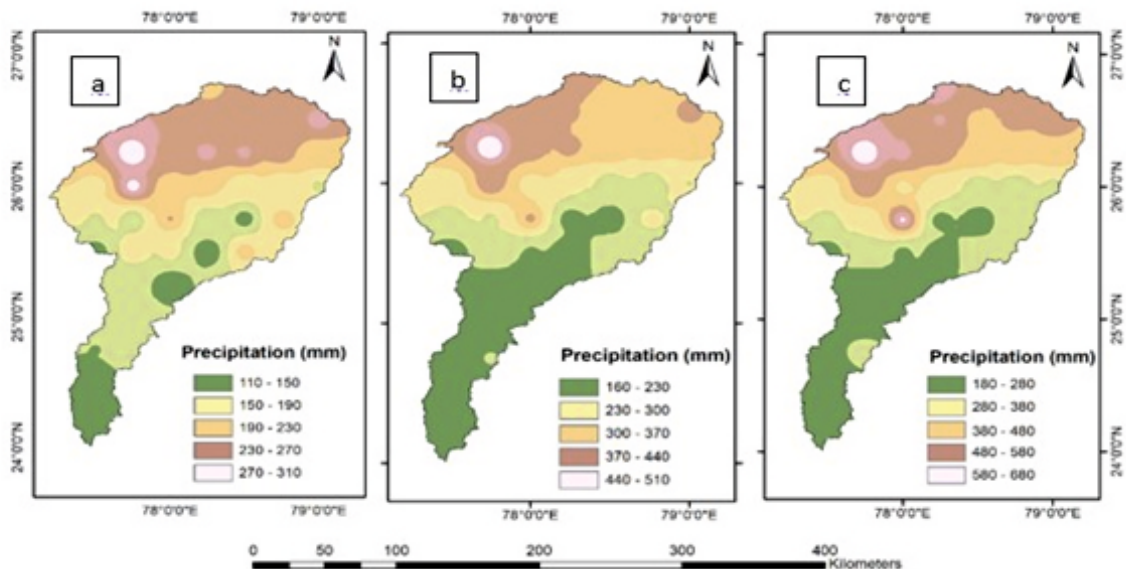


Fig. 3 Variation of probable maximum precipitation (a) IMD 1-day, (b) IMD 2-day, (c) IMD 3-day

Fig. 3 shows the variation in PMP for rainfall of 1Day, 2Day and 3Day duration over the Sindh basin for the period of 1991-2022. It could be seen that PMP increases with rainfall duration as the PMP value for 1-day, 2-day and 3-day rainfall duration increases as 203, 301 and 338 mm respectively.

Performance Evaluation of Climate Models

The thirteen climate models (namely ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, CanESM, EC-Earth3, EC-Earth3-Veg, INM-CM4-8, INM-CM5-0, MPI-ESM1-2-HR, MPI-ESM1 2-LR, MRI-ESM2-0, NorESM2-LM and NorESM2-MM) were evaluated with reference to observed IMD data using three performance indices (NSE, PBIAS, and R^2) for the period of 1991 to 2014. The values of performance indices for climate model parameters are shown in Table 1. MPI-ESM1-2-LR provided satisfactory results in all the cases where NSE is 0.53, PBIAS is -9.64% and R^2 is 0.66. Overall, the performance evaluation findings of the CMIP6 models verified the resilience of the MPI-ESM1-2-LR model for precipitation projection in the Sindh region.

Table 1 Comparison of Model based on R^2 , PBIAS (%) and NSE

Model	R^2	PBIAS (%)	NSE
ACCESS-CM2	0.18	-18.09	-0.37
ACCESS-ESM1-5	0.01	-15.60	-0.74
BCC-CSM2-MR	0.45	-10.12	0.39
CanESM5	0.003	-4.82	-0.86
EC-Earth3	0.44	-14.13	0.11
EC-Earth3-Veg	0.52	-8.61	0.28
INM-CM4-8	0.50	-17.09	-0.19
INM-CM5-0	0.39	-13.51	-0.65
MPI-ESM1-2-HR	0.48	-11.55	0.09
MPI-ESM1-2-LR	0.66	-9.64	0.53
MRI-ESM2-0	0.32	-13.84	-0.21
NorESM2-LM	0.35	-30.33	-0.29
NorESM2-MM	0.36	-30.75	-0.12

Probable Maximum Precipitation Map using Future Data and Comparison with Recent Past

The PMP maps for the Sindh basin were created utilizing future projected GCM data for four scenarios (SSP1, SSP2, SSP3 and SSP5) and three future time periods: near-future (2025–2050), future (2051–2075) and far-future (2076-2100).

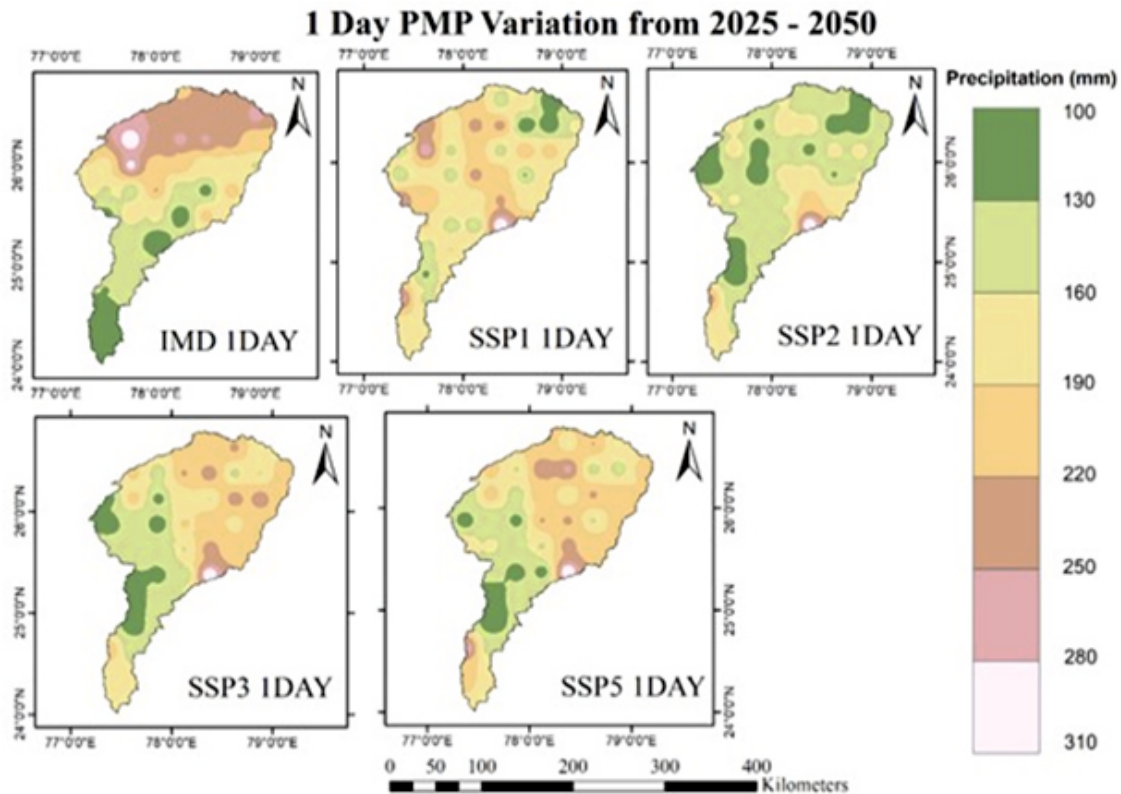


Fig. 4 PMP Variation from 2025-2050

Fig. 4 shows the variation of 1Day PMP over the Sindh basin in which it is clearly seen that there is a decrease in PMP all over the region. According to different scenarios, from the spatial distribution, we can see that the precipitation will be decreased by 10.09% in SSP1-2.6, 0.21% in SSP2-4.5, 12.93% in SSP3-7.0 and 19.49% in SSP5-8.5 scenario in the study area compared to IMD historical rainfall data (Table 2). Except in SSP5 in which rainfall is decreasing in the south-west region compared to IMD data for all scenarios extreme events of rainfall shifted in the region of Datia district. There is an overall decrease in PMP compared to IMD data in the near future (2025-2050). According to the Intergovernmental Panel on Climate Change (IPCC) 2013, Climate models project alterations in atmospheric circulation patterns due to climate change. These changes can lead to a decrease in the transport of moisture into a region which may reduce PMP. According to Trenberth et al. 2011, increasing temperatures can affect the moisture-holding capacity of the atmosphere. Warmer air can hold more water vapor, potentially leading to increased rainfall efficiency but not necessarily an increase in PMP.

Fig. 5 shows the variation of 1-day PMP over the Sindh basin in which it is seen that there is a decrease in PMP over the region. According to the SSP1-2.6 scenario, the spatial distribution of precipitation values showed that the precipitation will be decreased by 15.66%, 20.69% in SSP2-4.5, 25.44% in SSP3-7.0 and 2.89% in SSP5-8.5 respectively (Table 2). Except in SSP2 in which rainfall is drastically decreasing in the northern region as compared to IMD historical rainfall data for all scenarios extreme events of rainfall shifted

in the region of Vidisha district in SSP3 and SSP5 scenario. There is an overall decrease of PMP compared to IMD data in future (2051-2075). According to Giorgi et al. 2009, the topography of the Sindh river basin including the presence of mountains or other geographical features, can influence local precipitation patterns. Changes in these factors could lead to decreases in PMP.

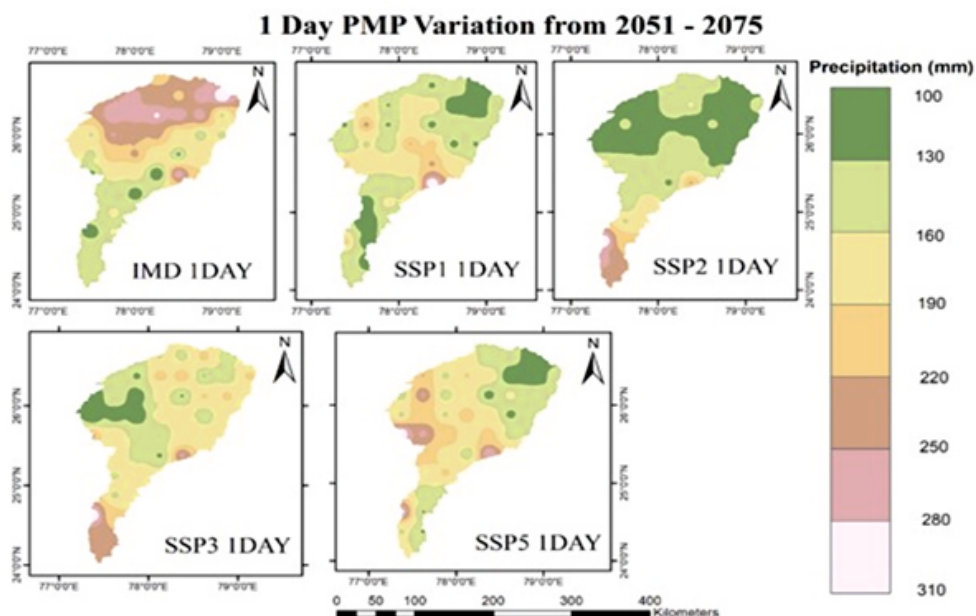


Fig. 5 1 Day PMP Variation from 2051-2075

The variation of 1-day PMP over the Sindh basin is shown in Fig. 6. It is seen that there is a decrease in PMP over the region. From the spatial distribution of precipitation, according to different scenarios, precipitation will decrease by 21.03% in SSP1-2.6, 5.87% in SSP2-4.5, 2.55% in SSP3-7.0 and 18.59% in SSP5-8.5 respectively (Table 2). Except in SSP1, in which, rainfall is drastically decreasing the entire region compared to IMD historical rainfall data for all scenarios but extreme events of rainfall shifted in the region of Datia district in all the scenarios. There is an overall decrease in PMP compared to IMD data in the far future (2076-2100). According to Trenberth et al. 2003, Climate change can lead to shifts in weather systems including monsoon patterns. These shifts can result in changes in the distribution and intensity of rainfall events. According to IPCC 2013, Natural climate variability can also influence PMP. Multi-decadal climate oscillations such as the El Niño-Southern Oscillation (ENSO) can have a substantial impact on regional precipitation patterns.

For rainfall of 2 days duration, the maximum chances of PMP in different regions change for all scenarios. However, there is a decrease PMP in all over the region except in the SSP2 scenario. According to different scenarios, the spatial distribution of precipitation values showed that the precipitation will be decreased by 16.16% in SSP1-2.6, 11.58 % in SSP3-7.0, and 7.28% in SSP5-8.5 but increased by 34.39% in SSP2-4.5 scenario in the study area compare to IMD historical data (Table 3). Except in SSP3 in which rainfall is increasing in the East region compared to all scenarios but the extreme event of rainfall shifted in the region

of Sheopur district in all the scenarios (Fig. 7). There is an overall decrease of PMP except SSP3 compared to IMD data in near future (2025-2050). This happened because these data rely on the 1-day precipitation data and increase due to the sum of two consecutive days and the magnitude of precipitation data also increases with increasing the duration of precipitation.

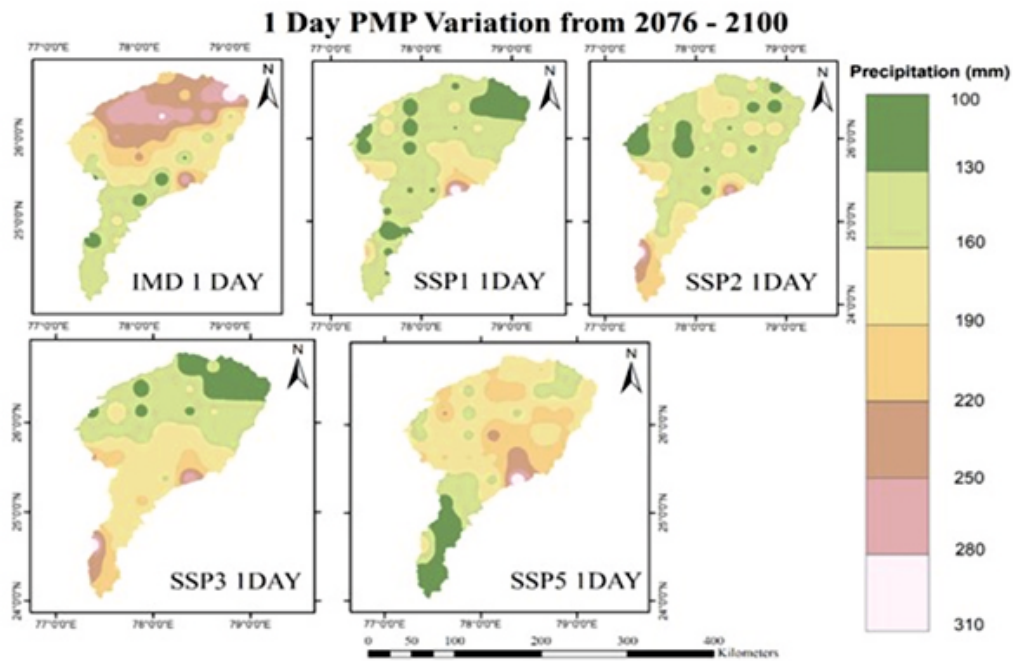


Fig. 6 1Day PMP Variation from 2076-2100

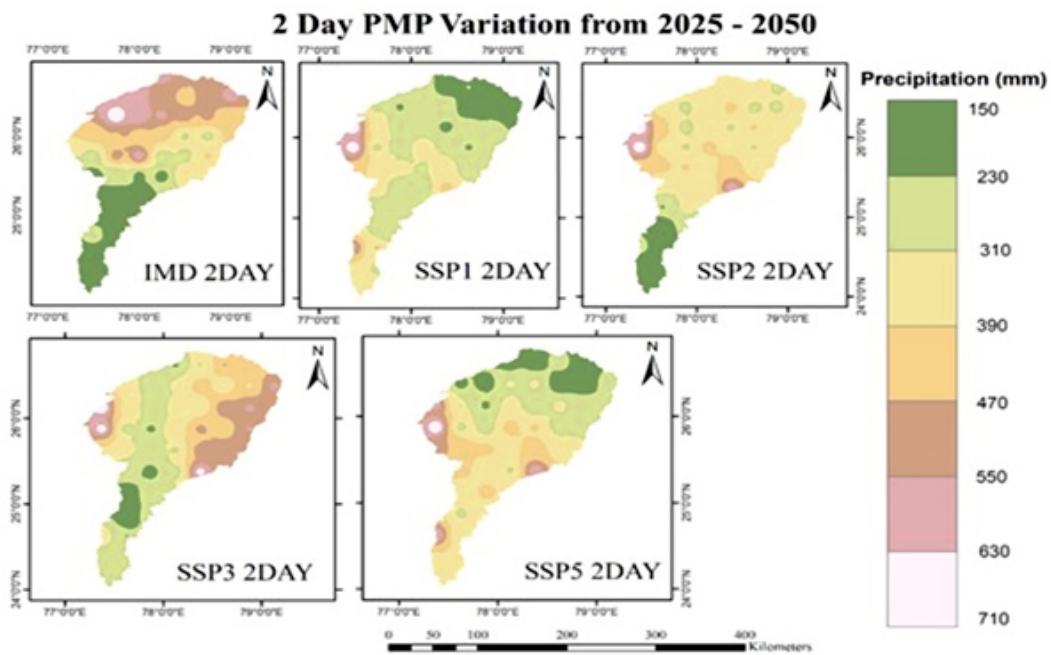


Fig. 7 2Day PMP Variation from 2025-2050

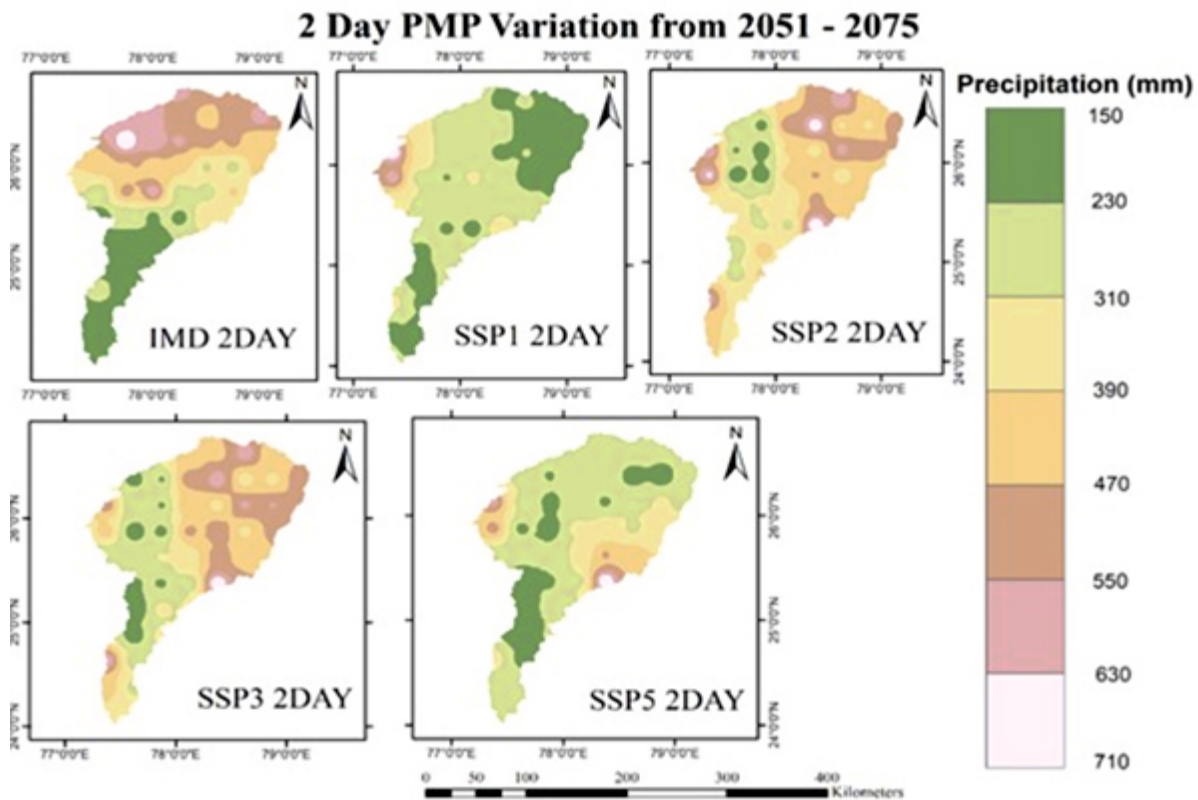


Fig. 8 2 Day PMP Variation from 2051-2075

Fig. 8 shows the variation of 2-day PMP over the Sindh basin in which it is seen that there is a decrease in PMP in the region. According to the SSP1-2.6 scenario, the spatial distribution of precipitation values showed that the precipitation will be decreased by 9.64%, 9.90% in SSP2-4.5, 12.03% in SSP3-7.0 and 7.28% in SSP5-8.5 scenario in the study area compare to IMD historical rainfall data (Table 3). Except in SSP1 in which rainfall is drastically decreasing entire the region compared to IMD historical rainfall data for all scenarios but extreme event of rainfall in SSP2 and SSP3 is increased in the north portion and shifted in the region of Datia district in all the scenarios. There is an overall decrease of PMP compared to IMD data in future (2051-2075).

Fig. 8 shows the variation of 2-day PMP over the study area. It is seen that the maximum chances of PMP in different regions change for all scenarios. There is a decrease in probable maximum precipitation all over the region except in the SSP2 scenario. According to the SSP1-2.6 scenario, the spatial distribution of precipitation values showed that the precipitation will be decreased by 3.71%, 12.38 % in SSP2-4.5, 21.52% in SSP5-8.5, but increased by 29.65% in SSP3-7.0 scenario in the study area compare to IMD historical rainfall data (Table 3). Extreme event of rainfall shifted in the region of Sheopur district in all the scenarios. There is an overall decrease of PMP except in the SSP3 scenario, compared to IMD data in the far future (2076-2100).

Fig. 9 shows the variation of 3-day PMP over the Sindh basin in which it is seen that there is a decrease of PMP in SSP1 and SSP3 and an increase in SSP2 and SSP5 scenarios. According to the SSP1-2.6 scenario, the spatial distribution of precipitation values showed that the precipitation will be decreased by 23.19%, 12.13 % in SSP3-7.0, whereas precipitation will be increased by 32.16% in SSP2-4.5 and 1.96% in SSP5-8.5 scenario in the study area compare to IMD historical rainfall data (Table 4). Extreme event of rainfall shifts in the region of Sheopur district in all the scenarios in the near future (2025-2050).

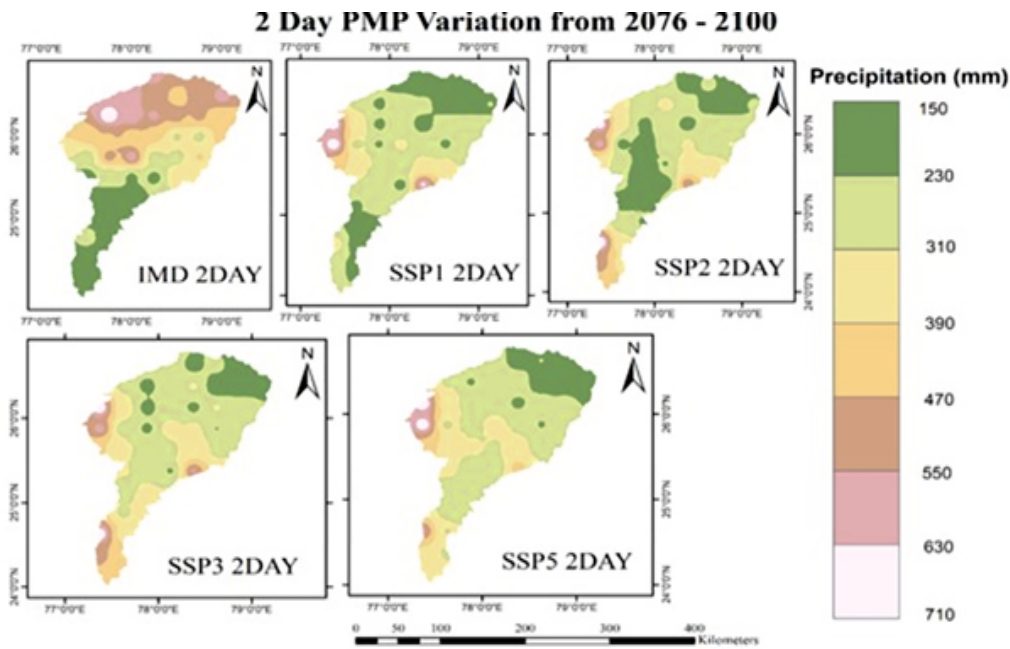


Fig. 8 2Day PMP Variation from 2076-2100

Fig. 10 shows the variation of 3-day PMP over the studied basin in which it is seen that the maximum chances of probable maximum precipitation in different regions change for all scenarios. There is a decrease PMP in all over the region except in the SSP2 scenario. According to the SSP1-2.6 scenario, the spatial distribution of precipitation values showed that the precipitation will decrease by 6.28%, 6.25% in SSP3-7.0, 6.08% in SSP5-8.5, whereas it will increase by 18.53% in SSP2-4.5 scenario in the study area compare to IMD historical rainfall data (Table 4). Except in the SSP1 scenario, rainfall is increasing in the East region compared to all scenarios but extreme events of rainfall shifted in the region of Datia district in all the scenarios. There is an overall decrease of PMP except in SSP2 compared to IMD data in future (2051-2075). Fig. 10 shows the variation of 3-day PMP over the Sindh basin in different scenarios. According to the SSP1-2.6 scenario, the spatial distribution of precipitation values showed that the precipitation will be increased by 20.47%, 56.09% in SSP3-7.0, whereas it will decrease by 5.97 % in SSP2-4.5 and 9.23% in SSP5-8.5 scenario in the study area compare to IMD historical rainfall data (Table 4). Extreme event of rainfall shifted in the region of Sheopur district in all the scenarios but shifted in Datia district in SSP2 in the far future (2076-2100).

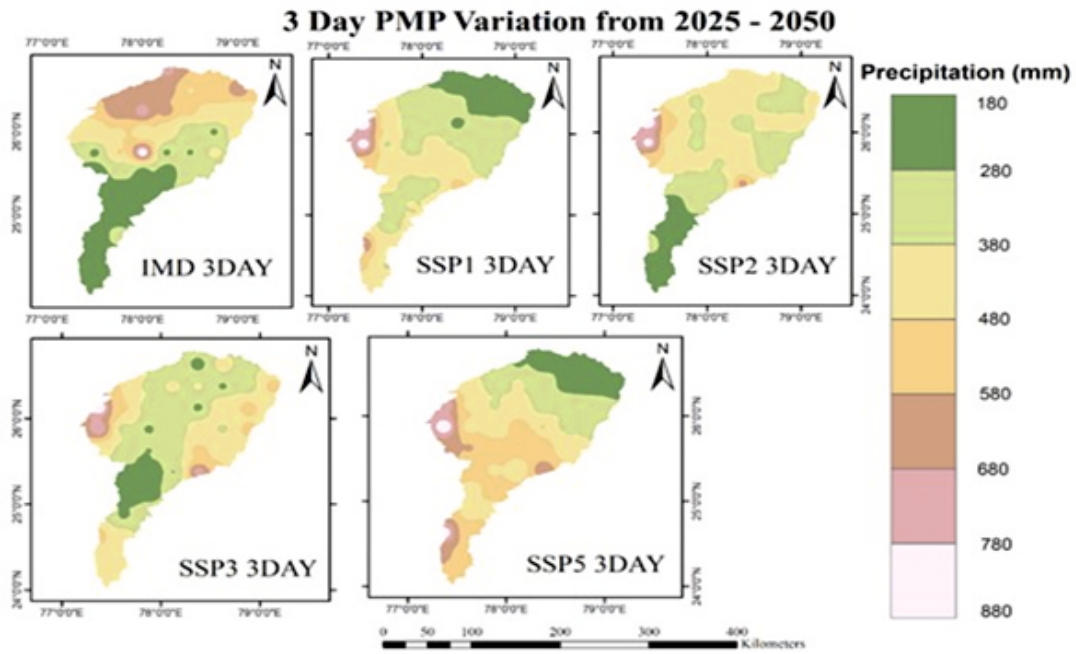


Fig. 9 3Day PMP Variation from 2025-2050

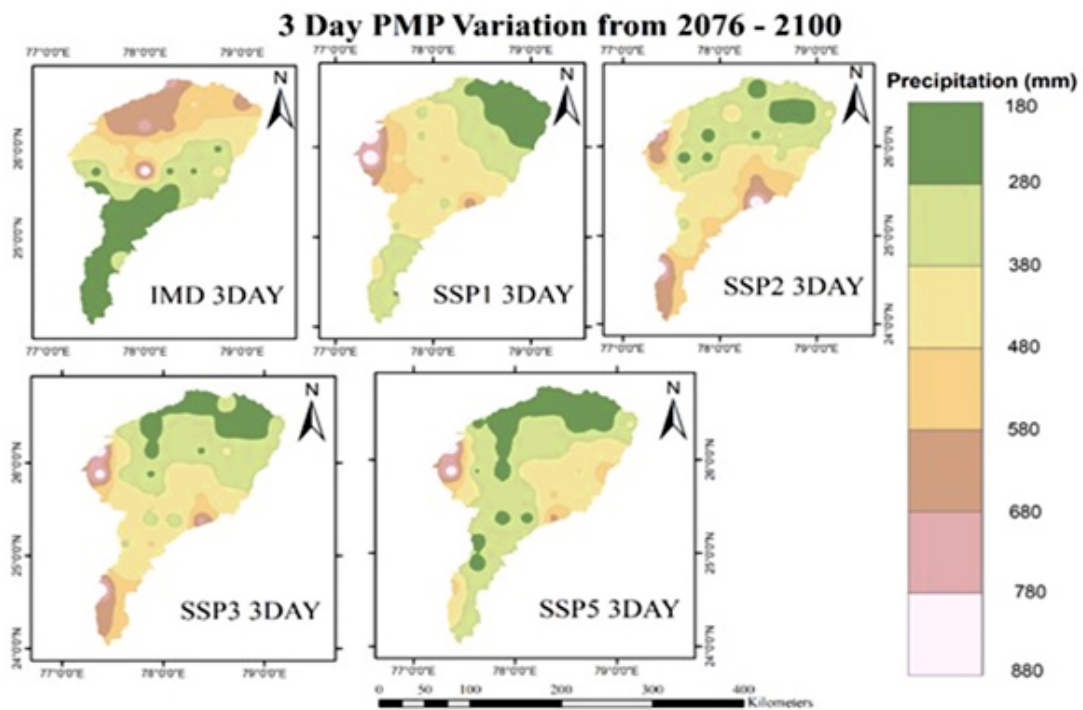


Fig. 10 3Day PMP Variation from 2051-2075

Table 2 Average percentage variation in 1-day PMP estimates

Base Period (1991-2022)	Time Periods	Average percentage variation in 1 day PMP			
		SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Precipitation(mm)	(2025-2050)	-10.09	- 0.21	- 12.93	- 19.49
203	(2051-2075)	- 15.66	- 20.69	- 25.44	- 2.89
	(2076-2100)	- 21.03	- 15.87	- 2.55	- 18.59

Table 3 Average percentage variation in 2-day PMP estimates

Base Period (1991-2022)	Time Periods	Average percentage variation in 2day PMP			
		SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Precipitation (mm)	(2025-2050)	- 16.16	34.39	- 11.58	- 7.3
301	(2051-2075)	- 9.64	- 9.90	- 12.03	- 7.28
	(2076-2100)	- 3.71	- 12.38	29.65	- 21.52

Table 4 Average percentage variation in 3-day PMP estimates

Base Period (1991-2022)	Time Periods	Average percentage variation in 3day PMP			
		SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Precipitation (mm)	(2025-2050)	- 23.19	32.16	- 12.13	1.96
338	(2051-2075)	- 6.28	18.53	- 6.25	- 6.08
	(2076-2100)	20.47	- 5.97	56.09	- 9.23

In general, based on the outcomes of various scenarios, precipitation will increase or decrease in most regions with the majority of the changes being associated with stations with higher precipitation levels than the historical period. Reduced changes in some research areas could be due to closeness to water resources such as the Madikheda dam and Mohini Pickup reservoir (with higher humidity) or mountainous and high-altitude regions. Climate change may be causing slowing changes in some areas of the research region. The comparison between different scenarios also revealed that precipitation value is decreasing in case of 1-day PMP variation for all scenarios in the near future, future and far future. SSP1-2.6 scenario shows a maximum decrease in precipitation in the case of 1-day and 2-day PMP variation for all three futures. There is also an increase in rainfall in all the remaining scenarios in some parts of the basin compared to IMD rainfall variation. Due to the nature of the scenarios and climate change, some scenarios showed greater changes than others while others showed fewer changes.

CONCLUSIONS

Probable maximum precipitation serves as a valuable tool for designing the infrastructure of reservoirs, dams, and other water management systems to ensure they can withstand the worst situations. This paper estimates the PMP using Hershfield's statistical approach in which it was calculated for 1-day, 2-day and 3-day rainfall duration. PMP increases with rainfall duration as the PMP values for 1-day, 2-day and 3-day rainfall duration were increasing as 203, 301 and 338 mm respectively. 13 climatic models were evaluated based on statistical performance indices. MPI-ESM1-2-LR model provided satisfactory results in all the cases with NSE at 0.53, PBIAS of -9.64% and R^2 at 0.66 respectively. Overall, the performance evaluation findings of the CMIP6 models verified the resilience of the MPI-ESM1-2-LR model for precipitation projection in the Sindh basin. The projection of precipitation decreases in areas for three future periods 1 day, 2 day, and 3 day. The SSP1-2.6 scenario predicted maximum changes (decreases) of 3.71% to 23.19%, while the SSP3-7.0 scenario predicted maximum increases of 56.09% in 3-day PMP. However, precipitation will decrease in most places in the future period (relative to the baseline period) with the shifting of extreme events in the western and eastern parts of the research area. By comparing three PMP maps from the past scenario, the duration of rainfall increases which implies the decreasing trend in the Sindh basin in upcoming years. There will be a dip in 2-day and 3-day PMP in some portions of the Sindh basin as the intensity of rainfall decreases with increasing time length. This result is supported by the models that were examined in this study, all of which depict an overall decreasing trend in PMP to varying degrees and in different geographic locations.

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