Climate-induced flood inundation for the Arial Khan River of Bangladesh using open-source SWAT and HEC-RAS model for RCP8.5-SSP5 scenario

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Abstract

Bangladesh is one of the largest flood-prone deltas of the GBM (Ganges–Brahmaputra–Meghna) basins, and recently, it is categorized as the 7th worst climate-affected country in the world. Future climate change along with economic development, urbanization, and increase in population may worsen this situation manifolds. To cope with future flood situations and lessen probable flood losses, it is essential to develop flood maps of the major flood-prone rivers of Bangladesh considering climate change scenarios. In this study, the flood inundation of the Arial Khan River and its floodplain has been assessed for the predicted climate change scenario of RCP 8.5 (Representative Concentration Pathway 8.5) using open-source mathematical models. A calibrated and validated hydrologic model of GBM basins in SWAT (Soil and Water Assessment Tool) model has been used to estimate the future flow magnitudes at Bahadurabad Transit (Brahmaputra River) and Hardinge Bridge (Ganges River) using extreme emission scenario RCP 8.5. Using the flow magnitude of these two stations as the upstream boundaries, an HEC-RAS 1D model has been set up for the Brahmaputra, Ganges, and Padma rivers for generating future flow magnitude at the offtake of the Arial Khan River. Later, an HEC-RAS 1D-2D coupled model is set up for the Arial Khan River floodplain and flood maps are prepared considering flood depth, duration, and inundation extent. The flood assessment for different projections of RCP 8.5 shows that there is an increasing trend of flood in terms of depth, duration, and inundation from the 2020s to the 2080s. Hence, the floodplain becomes more hazardous by the end of this century. The climate change impact on the projected population for the RCP 8.5 scenario is assessed under SSP5 (Shared Socioeconomic Pathways 5) which indicates that the total flood-affected population will be nearly twice in the 2080s compared to the 2020s. So, future climate change is going to have a dreadful effect on the flood situation of the Arial Khan River floodplain.

Keywords Arial Khan River · Brahmaputra · Climate change · Ganges · HEC-RAS 1D-2D coupling · IPCC · RCP scenario · Shared Socioeconomic Pathways (SSPs)

1 Introduction

Climate change and its impact is a significant concern of the twenty-first century. Climate-induced changes in temperature, rainfall, and sea-level are already evident

in many parts of the world, as well as in Bangladesh [1, 2]. According to the AR5 (Fifth Assessment Report) of IPCC (International Panel on Climate Change), the global mean temperature may increase up to 4.8 °C by the end of the twenty-first century for high emission scenario RCP

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(Representative Concentration Pathway) 8.5 [3]. Concurrently, the equilateral pacific may undergo an increase in mean precipitation [3]. The increase in temperature and precipitation will increase the monsoon flows of the GBM rivers. The study of Masood et al. [4] estimated that by the end of the twenty-first century, the entire GBM basin is projected to be warmed by 4.3 °C and the changes of mean precipitation (runoff) are projected to be + 16.3% (+ 16.2%), + 19.8% (+ 33.1%), and + 29.6% (+ 39.7%) in the Brahmaputra, Ganges, and Meghna, respectively. Whitehead et al. [5] projected the GBM flow using the SRES (Special Report on Emission Scenarios) scenarios of IPCC and showed an increase in the flow of GBM basins by the end of the twenty-first century. The changes in extreme flows of the Ganges–Brahmaputra–Meghna river system under the RCP 8.5 scenario are recently modeled by Mohammed et al. [6] with SWAT (Soil and Water Assessment Tool). This study also finds that mean monthly flows and flood flows will significantly increase in the 2080s of the RCP 8.5 scenarios. All the studies predict that monsoon flows of the GBM rivers will increase manifolds by the end of the twenty-first century, and this flow will ultimately discharge into the Bay of Bengal through Bangladesh. So, it is certain that Bangladesh will face more intense and frequent floods in the near future [7, 8]. To cope with future flood situations and lessen probable flood losses, it is necessary to predict the future flood status of the flood-prone rivers of Bangladesh considering the climate change impact.

Arial Khan River is one of the major rivers of the southwest region of Bangladesh. The studies so far done on the Arial Khan River are mainly focused on morphological processes, river erosion, and instability problems [9–11]. The flood inundation of the Arial Khan River has not been studied yet, let alone its impact due to climate change impact. In past, Tingsanchali and Karim [12] studied the flood risk analysis in the southwest region of Bangladesh using a commercial hydrodynamic model and satellite image using historic data assuming stationarity of the climate. Stationarity means there will be no significant shift in rainfall/temperature intensities and patterns over time. However, the stationary historic data might misinterpret the prolonged impact of climate change [13]. Moreover, the impact of upstream Brahmaputra and Ganges basins was not considered in the previous study. That is why the objective of the present research is to predict the flood situation of the Arial Khan River and its floodplain for predicted climate change scenario using open-source numerical models.

There are many numerical models both commercial and open-source available for flood inundation assessment. Among these, the open-source hydrologic model—Soil and Water Assessment Tool (SWAT) and hydrodynamic model—Hydrologic Engineering Center River's Analysis

System (HEC-RAS) are chosen to carry out this study. The SWAT is currently one of the most frequently used large-scale hydrological models for investigating rainfall-runoff relationships at regional scales [14–16]. Among the hydrodynamic models, HEC-RAS 1D is quite acceptable for one-dimensional simulation of artificial channels or simple reaches. Simultaneously, the HEC-RAS 1D-2D coupled model is highly recommended for flood inundation modeling as well [17]. The main advantage of 1D-2D coupled models is the similarity between physical behavior and model behavior as it considers floodplains as 2D simulation and river as 1D simulation [18]. For Koiliaris River of China, the combined 1D-2D HEC-RAS model performed better than the 1D HEC-RAS model for a specific study reach by using topographic data at a high spatial resolution [19]. Considering all these facts, HEC-RAS is used in this study. Among the four RCP climate projections, i.e., RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 of CMIP 5 (Coupled Model Intercomparison Project 5) mentioned in the IPCC AR5 report, the high emission scenario RCP 8.5 is only considered in this study. For global demographic-socioeconomic projection, there are five Shared Socioeconomic Pathways (SSPs), i.e., SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5 (Fossil-fueled Development), the SSP5 for Fossil-fueled Development is adopted for this study [20]. SSP5 is consistent with the United Nation's low fertility scenario.

2 Materials and methods

2.1 Study area

Arial Khan River is the major tributary of the Padma River. The historic annual maximum and minimum discharge is 5810 m³/s and 0.83 m³/s, respectively [21]. It has two distributaries from the Padma—Arial Khan Upper (AKU) and Arial Khan Lower (AKL). The upper reach of Arial Khan is vulnerable due to the monsoon flood. It has been recorded that during the historical flood events (i.e., 1987, 1988, 1998, 2004, 2007, 2010, 2011, etc.) in Bangladesh, the water level in the Upper Arial Khan River was above the danger level (4.17 mPWD¹ at Madaripur station) as shown in Fig. 1c and caused severe flooding in the floodplain [22]. Therefore, the upper reach of the Arial Khan River and nearby floodplains have been selected as the study area as shown in Fig. 1a, b. This reach is nearly 70 km long. The floodplains are comprised of eight Upazilas—Bhanga, Sadarpur, Maksudpur, Madaripur, Shibchar, Rajoir, Janjira,

¹ The PWD datum is 0.46 m higher than the MSL (Mean Sea Level).

Fig. 1 Study area: Arial Khan River and its floodplain **a** administrative boundary **b** DEM **c** Comparison of flood hydrographs at Madaripur station (SW 5) of Arial Khan River

and Shariatpur and four Districts—Faridpur, Gopalganj, Madaripur, and Shariatpur. The maximum recorded water level in the Arial Khan River was recorded as 5.80 mPWD at Madaripur station during the flood of 1998 [23]. Upazila is an important geographical boundary in the local administrative system in Bangladesh. In this study, it is considered as the land unit boundary for further zone-wise flood analysis.

2.2 Data collection

For the generation of the future RCP scenario in the SWAT model, CMIP5 daily precipitation and maximum/minimum temperature data have been collected from the EC-EARTH3 dataset for the RCP 8.5 scenario. EC-Earth is a GCM developed by the European Centre of Medium Range Weather Forecast (ECMWF). EC-Earth3 considers land surface-ocean-sea ice components, ocean biogeochemistry, dynamical vegetation, atmosphere composition, aerosol, and ice sheet components in it. Previously, it has been

applied successfully in many climate studies [24–26]. The high-resolution version of this model, the EC-Earth3 model is specially simulated by the Swedish Meteorological and Hydrological Institute (SMHI) for the high (RCP 8.5) emission scenario under the HELIX (End cLimate Impact and eXtremes) project. EC-Earth3-HR already showed satisfactory performance for studying the changes in extreme climate events such as floods [27, 28], and droughts [29]. The spatial resolution EC-Earth3-HR projection is 0.5° (~ 50 km), and it is bias-corrected. Hence, it is used in this study.

For the hydrodynamic HEC-RAS model set up, the SRTM 90 m DEM (Digital Elevation Model) has been collected from the US Geological Survey. The river cross section, discharge, and daily water level data of Brahmaputra, Ganges, Padma, and Arial Khan rivers have been collected from Bangladesh Water Development Board (BWDB) from 1985 to 2017 based on availability. The collected water level comprises data at an interval of one day. However, for the years after 2006, the discharges were measured irregularly (twice a month) and so rating curves were used

Fig. 2 Step by step model development in graphical flow chart

to generate a continuous daily time series of discharges using daily observed river stages. The equation of the rating curves developed by Kennedy [30] used in this study is shown in Eq. (1),

$$Q = C(h - a)^n \quad (1)$$

where, Q = discharge, C and n = constants, h = river stage and a = river stage at which discharge is zero.

Global 1-km downscaled projected total population data for SSP5 under Fossil-fueled development scenario is downloaded from the Socioeconomic Data and Applications Center (SEDAC) (<http://sedac.ciesin.columbia.edu/data>) by NASA's Earth Observing System Data and Information System (EOSDIS) for the year 2000–2100 [31].

2.3 Model development

In this study, the future flow hydrographs are collected from the hydrological model SWAT. Later, an HEC-RAS 1D model and a linear regression analysis are developed to generate future flow hydrographs at the Offtake of Arial Khan for RCP 8.5. Finally, an HEC-RAS 1D-2D coupled model of the Arial Khan River is set up to generate the flood maps of the study area. Figure 2 shows the steps of the model developed in this study.

2.3.1 Hydrological model SWAT

In this study, a calibrated and validated hydrologic model of GBM basins, set up by Mohammed et al. [6] in SWAT has been used to estimate the future flow magnitudes at Bahadurabad Transit (Brahmaputra River) and Hardinge Bridge (Ganges River) as shown in Fig. 3a. This model topography

has been set up using 90 m DEM from HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales) [32]. The GlobCover land-use map prepared by the European Space Agency [33] and the Digital Soil Map of the World prepared by the Food and Agricultural Organization of the United Nations has been used as land-use and soil information of the model, respectively [34]. Daily precipitation and maximum/minimum temperature data from the Princeton Global Forcing (version 2) dataset [35] of the period 2001 to 2012 are used as meteorological inputs during the development of the SWAT models. This model has been calibrated for 2001–2006 and validated for 2007–2012 using the observed discharge data of BWDB (Fig. 3b–e). Before calibrating the model, sensitivity analyses are performed on all hydrology parameters of SWAT using SWAT-CUP [36]. For more details, see Mohammed et al. [6].

For future climate simulations, the SWAT model has been simulated using the projected daily precipitation and daily maximum/minimum temperature data of the EC-EARTH3 dataset for RCP 8.5 scenarios. The simulated future flow hydrographs of Bahadurabad Transit (SW 46.9L) of Brahmaputra and Hardinge Bridge (SW 90) of Ganges show that the future flow for Brahmaputra and Ganges is found much higher nearly 200,000 m³/s and 100,000 m³/s, respectively, by the end of the twenty-first century. Later, for simulating the hydrodynamic models for RCP 8.5, 3 periods of time (each spanning thirty-year) such as the 2020s (2006–2035), the 2050s (2036–2065), and the 2080s (2066–2095) are selected. In the following step, the annual hydrograph of each of the mentioned time periods has been prepared. As this study is mainly focused on the extreme flood scenario, maximum flood hydrographs would serve better than

Fig. 3 **a** SWAT model developed for GBM basins; **b** Calibration and **c** Validation of Brahmaputra; **d** Calibration and **e** Validation of Ganges basin (Source: Mohammed et al. [6])

Fig. 4 HEC-RAS 1D **a** Model set up **b** Calibration and **c** Validation of Ganges–Brahmaputra–Padma River system at Mawa (SW 93.5L)

the mean values. However, the maximum of the climate dataset is not recommended in climate-related studies as it contains outliers. Hence, extreme flood scenarios are usually defined by 90, 95, or 99th percentile in the climate studies [37–40]. In this study, the 90th percentile annual daily flow hydrograph of Brahmaputra and Ganges is developed for each of the time periods (the 2020s, 2050s, and 2080s) for the RCP 8.5 and used as the flow input for the HEC-RAS 1D model described in 2.3.2.

2.3.2 Hydrodynamic HEC-RAS 1D model

A 1D HEC-RAS model has been set up for the Brahmaputra, Ganges, and Padma River using the discharge hydrographs at Bahadurabad Transit (SW 46.9L) and Hardinge Bridge (SW 90) as upstream boundary conditions and stage hydrograph of Sureswar (SW 95) as a downstream boundary (Fig. 4a). The one-dimensional model of the Ganges–Brahmaputra–Padma River system has been calibrated for the year 2016 and validated for the year 2017 at Mawa (SW 93.5L) station of Padma River. This station is selected for calibration and validation because the statistical equation of Arial Khan Offtake (Chowdhury Char SW 4A) has been developed for this station of Padma River. Flow is used as the calibration indicator because it will be later used for projecting future flow at the Offtake of Arial Khan River. Manning's n is the main calibration parameter of the HEC-RAS model. The Manning's roughness of $n = 0.025$ for the main channel and $n = 0.03$ for the right and left floodplains have been fixed for all the rivers of the system as shown in Figs. 4b, c. After calibration and validation, the model is simulated using the future flow hydrographs of the SWAT model.

2.3.3 Statistical model

The Padma being the parent river of the Arial Khan, the water level, and discharge of the Arial Khan River shows a similar trend of rising and falling as the river Padma [22]. Previously, in many studies, the hydrological data of the Mawa (SW 93.5L) station of the Padma River have been used for the offtake of the Arial Khan River as Mawa is the nearest discharge station to the offtake of Arial Khan River and there is no distributary of Padma River except Arial Khan River [9, 10]. So, a statistical equation (Eq. 2) is developed between the discharge of the Mawa (SW 93.5L) of the Padma River to the Chowdhury Para (SW 4A) of the Arial Khan River using the monsoon time series discharge data collected from BWDB for the year of 1965 to 2017.

$$Q_{\text{Arial Khan}} = 0.0358 \times Q_{\text{Padma}} - 281.03 \quad (2)$$

where $Q_{\text{Arial Khan}}$ is the discharge of Chowdhury Char (SW 4A) and Q_{Padma} is the discharge of Mawa (SW 93.5L). The equation performs reasonably well. Later, the flow outputs of the Mawa stations are used in Eq. 2 to estimate the flow of the Arial Khan River offtake. Finally, the estimated flow is used as the boundary condition of the Arial Khan 1D-2D coupled model (described in 2.3.4) to estimate flood scenario for the 2020s, 2050s, and 2080s for both RCP 8.5.

2.3.4 Hydrodynamic HEC-RAS 1D-2D coupled model

A 1D/2D coupled HEC-RAS model of the Arial Khan river basin in integration with ArcGIS and HEC-GeoRAS (an extension of ArcGIS) has been set up using the discharge and water level hydrograph as upstream and downstream boundary, respectively (Fig. 5a). Here, the

Fig. 5 HEC-RAS 1D-2D coupled **a** Model set up **b** Calibration and **c** Validation of the Arial Khan 1D model at Chowdhury Char (SW 4A)

discharge hydrograph of Chowdhury Char (SW 4A) and water level hydrograph of Madaripur (SW 5) are used as upstream and downstream boundary, respectively. A mesh of 150 m × 150 m grid resolution has been defined for each of the 2D flow areas. The left mesh contains approximately 25,000 cells, and the right one contains nearly 47,000 cells. Here, the lateral structure is used to create a connection between the 1D and 2D area, which generates flood water movement between the 1D river and the 2D flow area. There are 6 peripheral boundaries incorporated in the 2D flow area of the model. Two inflow boundaries are used on the upper left periphery to consider the effect of the Padma River. Another four boundaries are used in the lower periphery to pass out the water from the floodplain. In these boundaries, normal depth condition has been used. The threshold value used for the normal depth is 0.1 m.

The 1D simulation has been conducted for a whole year from January to December. However, the 1D-2D coupling model has been simulated for the flood season only, specifically from June to October to save time and space. The computational interval has been fixed as 1 min in all the models. However, the total computational time varies from simulation to simulation depending on flooding scenarios. For example, the 2020s has little flood inundation; hence, the total computation time has been nearly 7 h. On the other hand, the 2080s needed nearly 24 h due to its high flood and associated huge calculation.

The one-dimensional model of Arial Khan River 1D-2D coupled model has been calibrated and validated at the station of Chowdhury Char (SW 4A) for the years 2015 and 2017, respectively (Fig. 5b, c). The model has been calibrated and validated for the Manning's roughness

$n = 0.015$ and $n = 0.02$ for the main channel and the floodplains, respectively. Two widely known statistical indicators—Nash Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2), are used for evaluating the performance of the model. The R^2 and NSE values are found 0.9974 and 0.892 for calibration, and 0.989 and 0.882 for validation. After the calibration and validation of the 1D model, a 1D-2D coupled model is set up to simulate the flood inundation in the floodplain.

2.4 Flood analysis

Generally, flood hazard assessment is the calculation of adverse effects of flooding in terms of flood depth, flood duration, flood wave velocity, and rate of rising of water level, etc., for a particular area. The selection of the hazard parameters mainly depends on the characteristics of the study area and flood [41]. In this study, the flood depth, duration, and extent are considered as the hazard parameters. These parameters are selected based on previous studies, geographical, and basin characteristics of the study area. The intensity of flood hazard is generally given by a relative scale, which is called a hazard index (HI). Every hazard category is given a hazard index like 1, 2, 3, 4, and 5. A smaller hazard index was assigned for a lower hazard and vice versa. The hazard index values for different categories of flood depth, duration, and inundation extent are summarized in Table 1. The hazard classification has been fixed based on similar literatures [42–44].

The Mean Hazard Index (MHI) was calculated separately for depth and duration using Eq. 3:

Table 1 Hazard Index for the selected Hazard Indicators

Depth of flooding (m)	Category	Duration of flooding (day)	Category	Area inundated (%)	Category	HI
$D \leq 0.3$	Very low	$T \leq 3$	Short	$0 < A \leq 20$	Very low	1
$0.3 < D \leq 0.9$	Low	$3 < T \leq 7$	Medium	$20 < A \leq 40$	Low	2
$0.9 < D \leq 1.8$	Medium	$7 < T \leq 25$	Long	$40 < A \leq 60$	Medium	3
$1.8 < D \leq 3.6$	High	$25 < T$	Very long	$60 < A \leq 80$	High	4
$D > 3.6$	Very high			$80 < A \leq 100$	Very high	5

Table 2 Projected mean population density (per km²) under SSP5 Scenario

Upazila	Population density (per km ²)									
	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Bhanga	1075	1169	1216	1217	1178	1108	1022	930	836	744
Sadarapur	769	827	850	841	805	750	688	623	557	494
Muksudpur	844	922	965	972	946	895	830	758	684	610
Madaripur	1134	1233	1279	1277	1231	1153	1060	962	863	766
Rajoir	912	993	1031	1029	991	927	850	770	689	611
Shibchar	1013	1094	1126	1114	1064	988	901	812	724	640
Shariatpur	1171	1285	1354	1378	1358	1300	1219	1125	1022	917
Janjira	995	1074	1105	1093	1044	970	884	797	710	628

$$MHI = \left(\sum_{i=1}^n HI_i A_i \right) / \sum_{i=1}^n A_i \quad (3)$$

where HI_i is the hazard index of land area A_i of hazard category, i and n is the total number of land areas in the land unit. Finally, the resultant hazard factor (HF) was calculated as a summation of MHI for depth, duration, and inundation extent. Three trials of weighting factors for depth, duration, and area weights were performed three sets as (0.4, 0.3, 0.3); (0.3, 0.4, 0.3) and (0.333, 0.333, 0.333). In each of the cases, the variation of HF was insignificant. Therefore, for simplicity, equal weightage (0.333) is adopted for all the hazard parameters.

2.5 SSP5 population data processing

The SSP5 population projection downloaded for 2010–2100 at the 10-year interval (w.r.t. the base year 2000) is processed for the study area in ArcGIS (Table 2). The population density gets peaks in 2040 and then starts to decline till the end of 2100 which is consistent with the global population projection by SSP5 [20].

Similar to flood analysis of the 2020s, 2050s, and 2080s, the projected population data of the corresponding years are calculated for each of the Upazilas. In this case, the mean population density of 2010, 2020, and 2030 are considered as the 2020s, mean population of 2040, 2050, and 2060 are considered as 2050s and mean population of 2070, 2080, and 2090 are considered as 2080s. Finally,

the Upazilla-wise flooded area is multiplied with the corresponding mean population density to calculate the potentially affected population of each of the 2020s, 2050s, and 2080s.

3 Results

After simulating the series of models as described in Sect. 2.3.1, 2.3.2, 2.3.3, and 2.3.4, the maximum flood depth, flood duration, and inundation extent are extracted from HEC-RAS RasMapper and processed in ArcGIS. The flood depth, duration, and area maps of different periods—2020s, 2050s, and 2080s of RCP 8.5, are shown in Fig. 6a–i. The figures from the 2020s to 2080s of RCP 8.5 clearly show that there is an increase in flood depth, duration, and area from 2020 to 2080s.

A detailed summary of the inundation areas for eight Upazilas under each of the projections of the RCP 8.5 scenario is presented in Table 3. It is observed that the total flood inundated area in the 2020s of RCP 8.5 is nearly 330 km² which is 17% of the study area. On the other hand, the total flood inundated area in the 2080s of RCP 8.5 is almost 800 km² which is nearly 44% of the whole study area. Table 3 further shows that 5 (Sadarapur, Madaripur, Rajoir, Shibchar, and Zanjira) Upazilas are flooded in the 2020s. During this time, the flood in Shariatpur is insignificant. There is no flood in Bhanga and Maksudpur as well. On the other hand, the inundated area increased significantly after the 2050s. The total flood inundated

Fig. 6 Flood depth for different projections of RCP 8.5 **a** 2020s **b** 2050s **c** 2080s; Flood duration for different projections of RCP 8.5 **d** 2020s **e** 2050s **f** 2080s; Flood area for different projections of RCP

8.5 **g** 2020s **h** 2050s **i** 2080s; Flood hazard maps for different projections of RCP 8.5 **j** 2020s **k** 2050s **l** 2080s

areas under Bhanga, Sadarpur, Maksudpur, Madaripur, Rajoir, Shibchar, Shariatpur, and Zanjira are 100, 81, 109, 131, 84, 94, 60, and 139 km², respectively, at the end of the century. The area under each flood depth and duration categories (as categorized in Table 1) are given in Table 4. It is observed that the flood-affected area under the High and Very High depth category and Long and Very Long duration category increase manifolds by the end of 2100.

Finally, the Upazila-wise hazard maps are prepared on three hazard indicators—flood depth, duration, and extent. For this purpose, resultant hazard factors are calculated and the study area is categorized into five hazard zones—Very Low (0–20%), Low (20.01–40%), Medium (40.01–60%), High (60.01–80%), and Very High (80.01–100%) hazard zone. The flood hazard maps of the 2020s, 2050s, and 2080s are shown in Fig. 6j–l.

Table 3 Upazila-wise flood inundated area (km²) for RCP 8.5 Scenario

District name	Upazilla name	Area inundated (km ²)		
		2020s	2050s	2080s
Faridpur	Bhanga	0	2	100
	Sadarpur	52	73	81
Gopalganj	Maksudpur	0	7	109
Madaripur	Madaripur	70	104	131
	Rajoir	30	48	84
	Shibchar	50	69	94
Shariatpur	Shariatpur	14	33	60
	Zanjira	114	137	139
Total		330	473	798

Figure 6j shows that Maksudpur is in the very low hazard zone, Bhanga is in the medium hazard zone, Sadarpur, Madaripur, Shibchar, Rajoir, and Shariatpur are in the high hazard zone, and Zanjira is in the very high hazard zone at the 2020s of RCP 8.5. In the 2080s of RCP 8.5, Rojoir, Maksudpur, and Shariatpur are in the high hazard zone and Bhanga, Madaripur, Sadarpur, Shibchar, and Janjira are in the very High Hazard zone. These maps show that most of the Upazilas (Bhanga, Sadarpur, Maksudpur, Madaripur, and Shibchar) have become more hazardous from the start of this century to the end under climate change impact. At the end of the 2080s of RCP 8.5, there will be no low and very low hazard zone. On the other hand, high and very high hazard zone will increase too.

The Upazila-wise potential flood-affected population for each of the projected time periods is tabulated in Table 5. It is observed that the total flood-affected population has increased from 349,134 to 671,036, i.e., become almost twice by the end of the century. Even though the projected population has decreased in the future (Table 2), the affected population has highly increased because the flood-affected area has been greatly expanded in the future. So, it can be interpreted that future climate change will have a dreadful effect on the flood situation of the

Table 5 Upazila-wise affected population for RCP 8.5-SSP5 Scenario

District name	Upazila name	Affected population		
		2020s	2050s	2080s
Faridpur	Bhanga	0	2335	92,934
	Sadarpur	42,403	58,291	50,425
Gopalganj	Maksudpur	0	6565	82,545
Madaripur	Madaripur	85,070	126,908	125,969
	Rajoir	29,360	47,167	64,653
	Shibchar	53,891	72,817	76,380
Shariatpur	Shariatpur	17,779	44,404	67,331
	Zanjira	120,631	141,874	110,798
Total		349,134	500,360	671,036

Arial Khan River floodplain and corresponding loss and damage will increase to a large extent too.

4 Discussion

This flood study provides a qualitative flood comparison among the 8 Upazilas of the Arial Khan River. The flood maps of different periods of the 2020s, 2050s, and 2080s denote the worst flood scenario in each of the 30 years' time periods. It is found that the depth, duration, and inundation extent are increasing with time for the RCP 8.5 scenario. The flood increases manifolds for the 2080s compared to 2020s for RCP 8.5. These findings show consistency with the recent IPCC report which states that global surface temperature is likely to increase by 2 °C at the end of the twenty-first century relative to 1850 to 1900 for high emission scenario RCP 8.5 [3]. Simultaneously, CO₂ concentration, north hemisphere sea-ice extent, and sea-level rise are going to increase as well. Hence, the impact of climate change can be extreme by the end of this century for RCP 8.5. Therefore, in this study, flood depth, duration, inundation extent, and inundated area are found highest in the 2080s. Keeping consistency with these findings, the resultant flood maps also show that the high hazard zone

Table 4 Flood-affected area (km²) under each flooding classification

Indicator	Classification	Category	Area (km ²)		
			2020s	2050s	2080s
Depth of flooding (m)	D ≤ 0.3	Very low	21.4	82.9	57.3
	0.3 < D ≤ 0.9	Low	92.6	68.4	188.1
	0.9 < D ≤ 1.8	Medium	127.6	175.9	277.1
	1.8 < D ≤ 3.6	High	175.0	237.1	383.4
	D > 3.6	Very high	31.1	37.7	80.7
Duration of flooding (day)	T ≤ 3	Short	5.78	9.0	23.1
	3 < T ≤ 7	Medium	75.8	12.2	46.3
	7 < T ≤ 25	Long	17.2	91.1	18.1
	25 < T	Very long	279.7	372.4	738.7

will increase and the low hazard zone will decrease in the 2080s compared to the 2020s. These results match with many flood studies conducted considering future climate change. Tu and Tingsanchali [44] studied the flood hazard of the Hoang Long River basin of Vietnam using the rainfall-runoff model MIKE-NAM and hydrodynamic model MIKE 11 based on two flood parameters—flood depth and duration. They found that the high and very high floods in terms of both depth and duration are expected to be more intense in the future. Another study on the Yang Basin of Thailand found that flood inundation depth and flood inundated area are the highest in the 2080s under RCP 8.5 [45]. The studies by Nishat [46] and Das et al. [47] on the Brahmaputra and Surma-Kusiyara floodplain of Bangladesh also show a prominent increase in flood inundation by the end of the 2100 century.

Tingsanchali and Karim [12] conducted the flood hazard study for the entire southwest region of Bangladesh and considered the flooding of major Ganges, Gorai, Arial Khan rivers, and other minor rivers of that region. It is observed that the Upazilas nearby the Arial Khan falls into high and very high hazard zone for a 100-year return period's flood event. The current study also found a similar flood and hazard pattern for the Upazilas near the Arial Khan River for the 2080s of the RCP 8.5 scenario. However, hazard maps are qualitative comparisons among the considered land units. Hence, such studies are not accurately comparable if the considered area or zone is not the same. Moreover, the previous study was less informative for the current study area since the whole southwest part has been considered and flooding of Ganges, Gorai, and Arial Khan River is included as well. The current study is conducted solely on the Arial Khan River floodplain and counted the upstream basin flow for the RCP high emission scenario considering three important flood parameters—depth, duration, and area. Hence, focusing on the floodplain of the Arial Khan, the current study should be more reliable.

One limitation of the flood maps prepared in this study is that the actual magnitude at the downstream boundary of the HEC-RAS coupled model due to sea-level rise is not considered here. Rather it is fixed incorporating the future sea-level rise projections of the RCP 8.5 scenario by IPCC [3]. It can be reduced by simulating any hydrodynamic model covering the southern coastal part of Bangladesh (including Arial Khan River) and extending up to the Bay of Bengal and incorporating future sea-level rise projections in the Bay of Bengal as downstream boundaries conditions in HEC-RAS coupled model. A similar study is done by Mondal et al. [48] which states that the flood peaks might increase by 25–72 cm by the end of this century for the RCP 8.5 scenario depending on the river, its location, increase in rainfall in the upstream areas and sea-level rise in the downstream Bay of Bengal. As this modeling

approach is not applied at the downstream boundary, rather IPCC AR5 sea-level rise projections are directly used instead, the flood maps may overestimate flooding a little bit. Besides, for the statistical model, a simple linear equation is developed between the Padma and Arial Khan River. Nonlinear equations such as exponential or polynomial or power might be used as well. However, such complex equations are avoided to keep it simple. The applicability of nonlinear equations in such cases can be studied in the future. Besides, the number of affected populations for each of the projections has been reported only. Other exposure and vulnerability indicators such as poverty, education, cropped land, male–female ratio, polder, flood-forecasting warning center, etc., could be considered for precise socioeconomic risk assessment.

Despite such limitations, this study attempts to develop flood maps of the Arial Khan River floodplain for the RCP 8.5 scenario. In the past, structural measures such as flood embankment, dredging, etc., were primarily adopted for flood management in Bangladesh. Nevertheless, such measures cause bed level rise, drainage obstruction, ecological imbalance, etc., in river systems. Hence, the importance of non-structural flood measures like flood hazard zoning and forecasting and warning system increasing nowadays). Therefore, the flood maps developed in this study might be useful for planners in identifying the higher flood-prone zones along the Arial Khan River and thereby planning a sustainable flood management strategy in the adjacent floodplains.

5 Conclusion

In this study, an HEC-RAS 1D-2D coupled model of Arial Khan has been set up for assessing the flood hazard of Arial Khan River floodplains for different projections of RCP 8.5. A calibrated and validated SWAT model has been used to generate the future flow at Brahmaputra and Ganges for different projections of the RCP scenario. A 1D model of Ganges–Brahmaputra–Padma has been set up to generate the future flow of Padma for that scenario. Later, the upstream discharge at the offtake of Arial Khan has been calculated establishing a linear regression equation between the offtake of Arial Khan and Mawa of Padma. Finally, Arial Khan 1D-2D coupled model is simulated for different time slices: 2020s (2006–2035), 2050s (2036–2065), and 2080s (2066–2095) of RCP 8.5. These developed flood maps of different periods of the 2020s, 2050s, and 2080s denote the worst flood scenario in each of the 30 years' time periods. Hence, such a scenario can be observed at any time during the 30 years' time period. The flood maps of different projections of RCP 8.5 show that there is an increasing trend of flood area from the

2020s to 2080s. In the 2020s, the flood inundated area is only 17% of the study area. The total flood inundated area in the 2080s of RCP 8.5 is nearly 44% of the whole study area. Additionally, the flood-affected area under the High and Very High depth category and Long and Very Long duration category increase manifolds by the end of 2100. The analysis of Upazila-wise flood maps further shows that there will be no very low and low hazard zone in the 2080s. On the other hand, high and very high hazard zones will increase too. Additionally, the total flood-affected population will be nearly twice in the 2080s compared to the 2020s. It is expected that zone-wise flood maps will help the planners, and policymakers to priorities the flood vulnerable Upazila of Arial Khan River and thereby help in taking pre-caution, distributing relief, and allocating resources in case of future flood events.

Some recommendations are made based on the results and the experiences gained during the study. This study has been done using 1D-2D coupling. For the comparison or better understanding, pure 2D analysis can be performed in the future, if fine resolution bathymetry of the Arial Khan River is surveyed. Socioeconomic risk analysis can be done based on the obtained flood results as well. Moreover, one RCP scenario—high emission scenario RCP 8.5, has been considered in this study. For a full view of climate change impact, the other RCP scenarios—RCP 2.6, RCP 4.5, and RCP 6—can be simulated in future studies as well.

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Declaration

Conflict of interest The authors declare that they have no conflict of interest.

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