Discharge and sediment load modeling using rating curve-based missing data management

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ABSTRACT

Hydrological models are vital for water management to determine instream flow, irrigational water, domestic water supply, and biodiversity conservation. This study formulates a hydrological model with a novel approach for streamflow and sediment load simulation in QGIS-supported Soil and Water Assessment Tool for a river catchment of Bangladesh, Halda, a unique ecological habitat for natural carp spawning and freshwater source for 10 million people. The daily simulation uses an innovative stage-discharge relationship technique from available flow data at 15-day intervals of a monitoring station located at Panchpukuria. The model evaluation parameters R^2 values 0.85 and 0.80, and NS values 0.84 and 0.79 for calibration and validation of the Panchapukuria station's streamflow suggested an excellent agreement in the seasonal cycle and most of the monsoon peak flow. The streamflow/precipitation ratio indicates a significant influence of groundwater on the streamflow through infiltration. The baseflow shows a decreasing trend, maybe due to upstream water diversion through dams or irrigation canals. Sediment load based on suspended sediment concentration at a downstream location is 1625 tons/day. In contrast, model prediction is 30 times lower at the upstream site in this river. The scattered sediment load data support the idea that the model estimate is reasonable for defining a relatively lower intervention or land use effect in its upstream than downstream area. This model provides a

baseline for daily flow and sediment load for scenario modeling (e.g., climate change, land-use change) for environmental flow estimation of the fish habitat, freshwater supply, irrigation, and salinity intrusion.

Keywords: stage-discharge, SWAT, watershed, sediment flux, land use, flow regulation

INTRODUCTION

Halda River is the only tidal river among a few river basins that lie inside the political boundary of Bangladesh and serves as a natural source of fertilized carp eggs (Saimon et al., 2016). The river is fed by several hilly streams starting from its origin. It has 20 sub-canals, 34 small hilly streams (Kibria, 2012), and 12 tributaries (Badiuzzaman, 1978; Podder et al., 2017) from which Dhurung of about 56 km length is very turbulent joined at Sundarpur, Dhurung Union (Tsai et al., 1981). The downstream of this river is well recognized as the only pure Indian carp natural spawning habitat in South Asia (Tsai et al., 1981; Azadi and Alam, 2011). The flood plain of this river is relatively stable and has reported somewhat less riverbank erosion phenomenon, though it highly braided channel characteristics throughout its course. The overall length of the river is approximately 98 km, and the total catchment area is about 1671 km^2 (Badiuzzaman, 1978). The average depth of the Halda River is 6.4 meters, and the maximum depth is 9.1 meters. Raihan et al. (2020) reported a significant increase in the number of rain days at the northern sites during the monsoon season, with an increase per decade of 3 days in Sitakunda and seven days in Rangamati. They also suggest a change in the flow and sediment load of the Halda Basin, which the anthropogenic land use change may trigger. A substantial increase in agricultural land use in its riverbank and catchment has also been reported in recent years (Mismah, 2017; Akter and Ali, 2012), which may change the river's flow and sediment load.

However, historical remotely sensed data with lower resolution cannot discrete small land use changes. As a result, a total change in the catchment did not spell out the effect on river sediment load and siltation. Since fish habitat sustainability and usability of the water, as a domestic source, heavily depends on water quality, many studies reported water quality and sediment load of this river (Azadi and Alam, 2013; Patra and Azadi, 1985; Tsai et al., 1981, Karmakar et al. 2020). Bhuyan and Bakar (2017) reported the heavy metals contaminants in surface water and sediment of the Halda River of industrial, municipal, and agricultural origin. Podder et al. (2017) recorded

34 watersheds of the Halda River, from which seven major watershed areas were identified as significant ecological habitats. However, the ecological significance within the river varies with the season, which heavily depends on flow and watershed runoff. This river supplies 180 million liter/day (MLD) freshwater to the nearby Chattogram city through two water treatment plants installed downstream of this river. Additionally, a few more proposals for the water treatment plant for fresh water supply to the nearby area are under consideration. In contrast, salinity was commonly reported to water treatment plants operating during the dry season.

The Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998), a physically-based semi-distributed, computationally efficient open source code (Yasin and Clemente 2014), is better suited for scarce data regions (Ndomba et al. 2008) compared to other commonly used models, such as MIKESHE (Refsgaard and Storm 1995), TOPMODEL (Beven and Kirkby 1979) or WASIM (Schulla and Jasper 2007). The semi-distributed model in SWAT subdivides a watershed into smaller sub-basins and hydrological response units (HRUs). SWAT has demonstrated strength in simulating catchment hydrology, considering climate and land management practices on water, sediment, and agriculture chemicals in large, complex watersheds (Neitsch et al. 2002). Badiuzzaman (1978) studied the hydrology of this river using unit hydrographs at Narayanhat, South Sunderpur, and Panchpukuria stations of this river. Habiba (2016) estimated the sediment load at Panchpukuria point in the river system using remote sensing data corresponding to suspended sediment, which is 288,850 tons/yr. Moreover, freshwater flow and environmental consequences during the dry season have been analyzed by Akter and Ali (2012). The most recent study considers that the rubber dam in this river's upper stream negatively impacts the river's downstream flow and reduces the water-holding capacity of the river (Raihan et al. 2020). Sajid (2016) also reported the sediment load and salinity intrusion to its downstream.

To date, flow simulation for this river remains a significant challenge due to the lack of continuous data and the effect of flow regulation on the observation data supplied by the Bangladesh Water Development Board (BWDB). This phenomenon is common to observe in many regional river basins in many regions of the world. Although daily water level data is available for this river at several stable cross-sections, these data were never used to validate discharge data of only measuring stations nor used for hydrological modeling. The flow model on this river carries the limitations of lack of daily flow data, inadequate data, a significant amount of missing data, and a few outliers supplied by the only monitoring agency, BWDB. Moreover, varied values for discharge with the same water level and extremely low or high discharge made the discharge data challenging to corroborate with water level and other ecological data to use in many instances. Several environmental flow modeling and discharge estimations reveal lower confidence in using them in decision support, such as integrated river management schemes for the carp breeding habitat. Developing a watershed management tool for the Halda Basin is vital for identifying key hydrological processes influencing water availability and evaluating how these may change in the future. Hence, the goals of this study are i) to reproduce hydrological conditions for the Halda Basin, using the SWAT modeling framework to provide a basis for future water resource management and monitoring, ii) to suggest a novel approach to integrating water level data using the rating curve method to estimate discharge and compare earlier model prepared by Raihan et al. (2020), iii) and finally, to estimate sediment load and dynamics in this river, which may significantly affect the flow and fish habitat.

MATERIALS AND METHODS

Halda River Catchment area

The study area includes the upper catchment of the Halda River. This river originates inside Bangladesh's political boundary (Fig. 1), at the Badnatali Hills range of Khagrachari district (Saha et al., 2019). Halda is one of the major tributaries of the Karnaphuli River, joining at about 35 km from the Bay of Bengal. The maximum water velocity during the monsoon is about 3 ms^{-1}, and the difference between the maximum daily high and low tide levels was 4.2 m (Dhar et al., 2015). Water discharge varied from 0.06 m^3/s to 548.67 m^3/s from 1983- 2012 at Panchpukuria station (Akter and Ali, 2012). The middle course of this river is well known for its carp-breeding natural habitat (Azadi, 2005; Correspondent, 2014; Saha et al., 2019). Following its critical ecological role, it was recently declared as a Fisheries Heritage site (Report, 2020) and also in the declaration process as an Ecologically Critical Area (Hussain, 2016). The river's catchment is surrounded by the Sitakunda hill range on the west and Chattogram hill tracts on the east. Chattogram hill tracts dominate the physiography of the area with a good amount of flood and the coastal plain area near the main river channel (PSU, 2011).

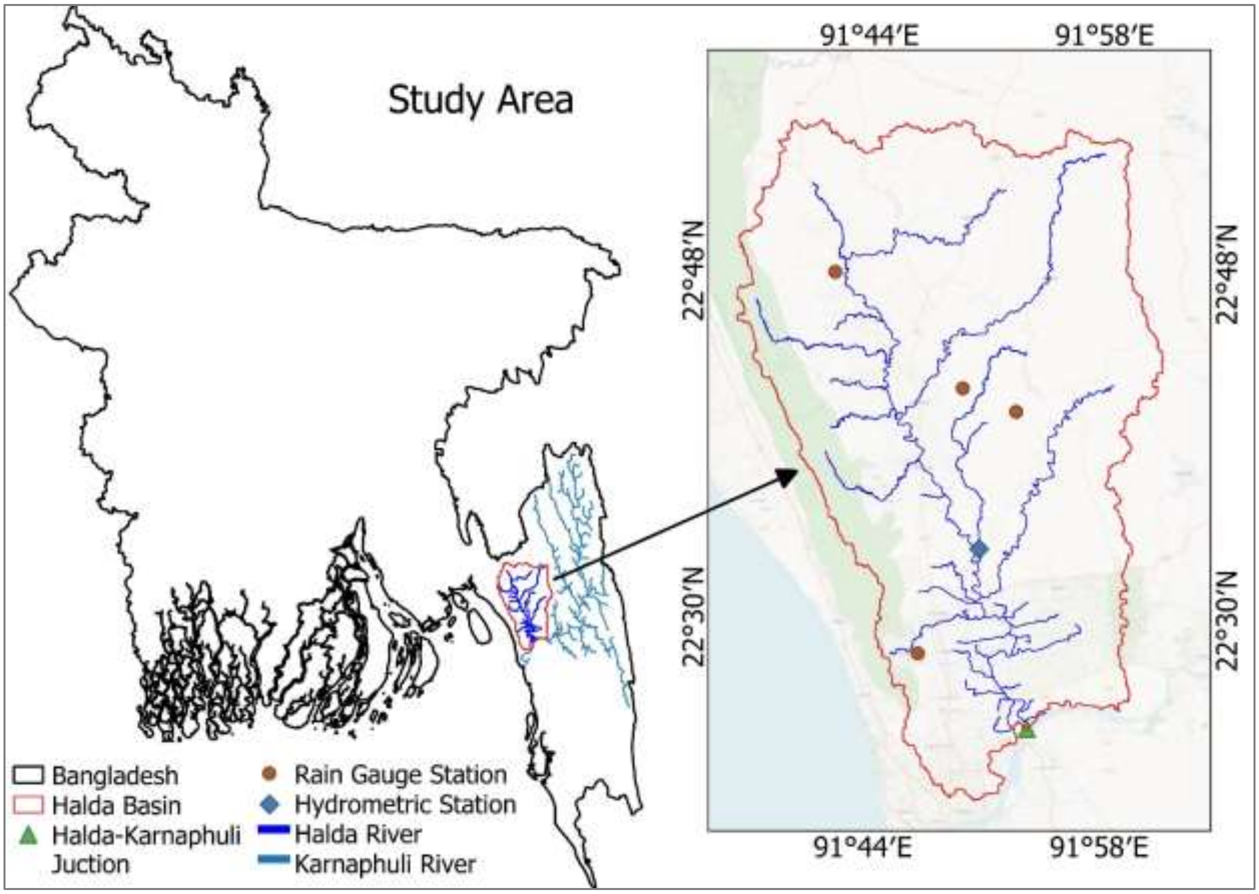

Figure 1: Halda River watershed area, the Panchpukuria hydrometric station for discharge measurement by Bangladesh Water Development Board (BWDB), and the regional drainage basin attributed to Karnaphuli River.

The SWAT model setup

The SWAT is a semi-distributed, continuous, and semi-physical based deterministic simulation model widely used in assessing hydrology and water quality (Arnold, Kiniry, et al., 2012; Arnold et al., 1998; Jha, 2009; Querner & Zanen, 2013). Here, the catchment is divided into sub-catchments and further into hydrological response units (HRUs) based on unique land use or land management, soil attributes, and slope definition (El-Nasr et al., 2005; Gassman et al., 2007; Golmohammadi et al., 2014). Hence, the input information includes climate, soil properties, topography, vegetation, and land management practices (Gassman et al., 2007; Golmohammadi et al., 2014). The SWAT uses the water balance equation for the hydrological phase, divided into land and water or routing phases (Alam, 2015; Moriasi et al., 2012; Neitsch et al., 2002; Sarwar, 2013). SWAT follows the water balance equation to all processes in a catchment (Arnold, Moriasi, et al., 2012) and routing of water through the channel network of the basin, carrying the sediment, nutrients, and pesticides to the outlet (Alam, 2015). SWAT also models the transformation of chemicals in the stream and streambed (Neitsch et al., 2009). Surface runoff is computed by modifying the soil conservation service curve number (Singh et al., 2013).

Digital Elevation Model (DEM), slope, land use, and soil data as model input

For a SWAT hydrological modeling simulation, the following datasets are needed – Digital Elevation Model (DEM), land use, soil type, slope, and slope bands (Fig. 2), existing stream network, location of outlets, weather generation (WGEN), and precipitation data (Fig. 1).

Digital Elevation Model (DEM): The MERIT (Multi-Error-Removed Improved-Terrain) DEM version 1.0.3, published on 15 October 2018, is used for this study. It was developed at 3 arc-sec resolution (about 90 m) by removing multiple error components from the DEMs like SRTM-90, v. 2.1 and AW3D30, v.1, with a varied temporal extent and 2 m global vertical accuracy (Yamazaki et al., 2017). It covers land areas between 90N-60S and is projected to WGS84 and EGM96. From DEM during the HRU creation process, five quantile slope classes were derived, viz. flat to nearly level, very gentle, gentle slope, sloping, and moderately steep, covering 23.61, 11.11%, 13.79%, 14.43%, and 37.06% of the total area, respectively.

Land use: This study used the GlobCover, a European Space Agency (ESA) initiative to serve a 300-m global land cover map, produced from an automated classification based on the ENVISAT's (ESA Environmental Satellite) Medium Resolution Imaging Spectrometer (ESA & UCLouvain, 2011). The GlobCover image of Dec -Jan 2009 with 13 land use classes reclassified to 11 categories, projected to WGS84 ellipsoid, according to the SWAT land cover/plant growth and urban growth database (Fig. 2).

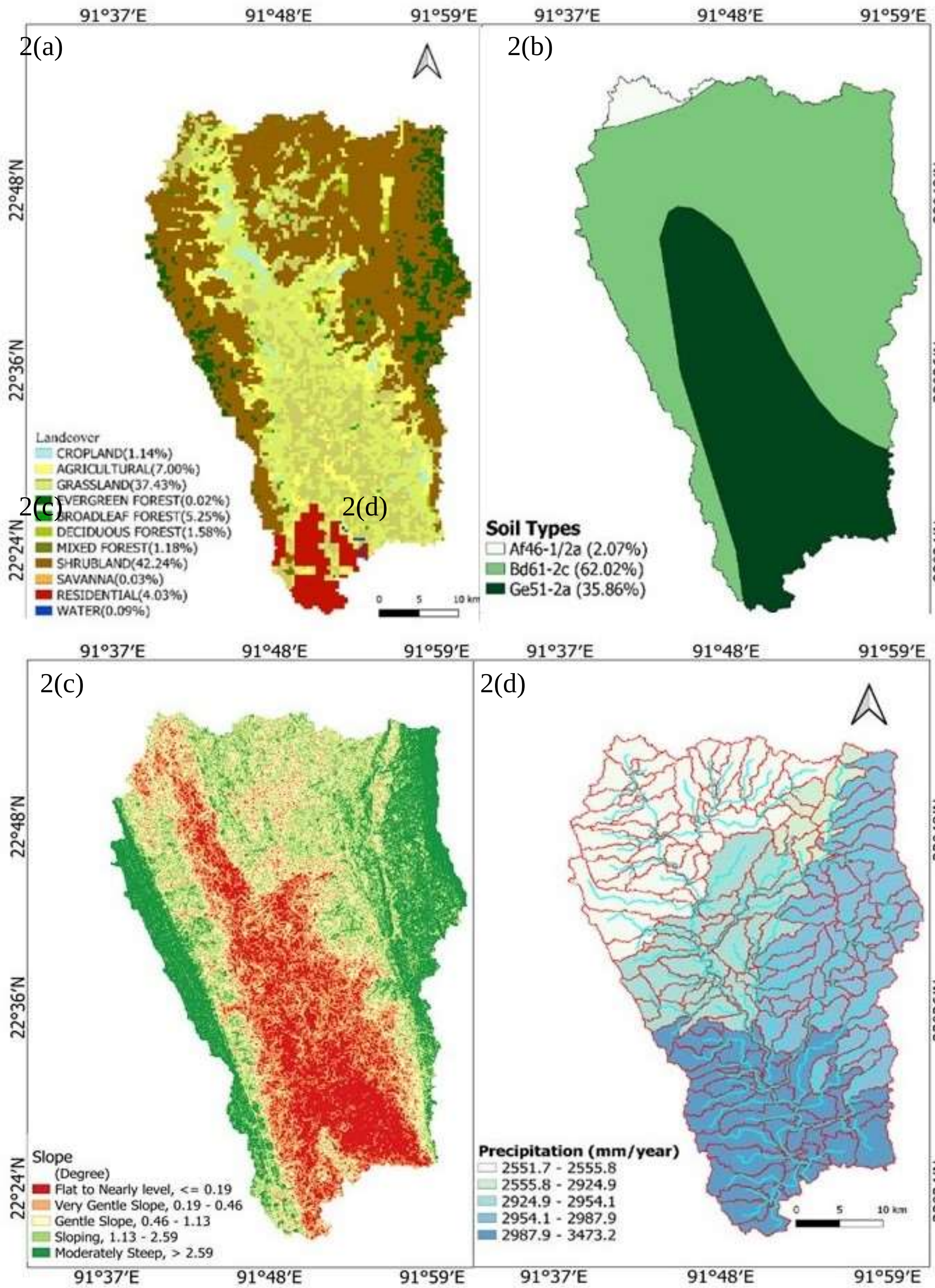

Figure 2: Halda catchment map shows the 2(a) land use, 2(b) soil, 2(c) slope class, and 2(d) precipitation inputs used in SWAT runoff and nutrient load simulation.

Soil data: The Harmonized World Soil Database is used in this study, which combines existing regional and national updates of soil information worldwide with the information of FAO-UNESCO World Soil (1995) Map (FAO et al., 2009). Three major soil classes - Ferric Acrisols (2.07%), Dystric Cambisols (62.05%, weakly to moderately developed soils in steep hilly slope), and Eutric Gleysols (35.87%, permanent or temporary wetness near the surface or the stream networks) are present in the Halda Basin (Fig. 2).

Weather Generator (WGEN) and observed precipitation data

Climate data is considered one of the primary inputs for hydrological process simulation in SWAT. Climate data includes precipitation, maximum and minimum temperature, solar radiation, wind speed, relative humidity, and the weather generator file. We have used climate data from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) to prepare the WGEN user database using two applications, 'dewpoint' and 'pcpSTAT' as described by Dile & Srinivasan (2014) as weather generator data. Moreover, daily rainfall data from 1967 to 2017 for Narayanhat, Fatikchari, Nazirhat, and Hathazari stations of this river catchment were collected from the Bangladesh Water Development Board (BWDB) (Fig. 2).

Hydrological Model setup in QSWAT

The open-source QGIS 3.16 and QSWAT 3.1, SWAT 2012 editor, were used to develop the hydrological model. For automatic watershed delineation, the DEM raster MERIT 90m was used. Stream networks may differ (Reddy & Reddy, 2015) from the observation corrected for the drainage network by digitizing and georeferencing from the Google Earth and outlet points of 'khals' from field survey verification, respectively. A 10 km^2 area threshold value was used for stream network creation in this river catchment, as suggested by Datta et al. (2022). During the HRUs creation process, land use, soil, and slope bands data were added using only the dominant proportion, assuming a negligible influence from these parameters to streamflow to reduce processing time (Her et al., 2015). Then WGEN and rainfall data were added to the SWAT editor. Here, we defined the rainfall distribution as skewed normal. The model was run daily from January 1990 to June 2015, with the first three years of simulation as a warm-up period to stabilize the model. For model calibration, 1993-1997 and validation, 1997–2005 period was used. The simulation was extended for an additional 10 years as an extended validation and prediction period to understand performance of the model.

Water level and discharge data

The time series of water levels from 1967 to 2017 (2.12 % missing data) and discharge data from 1983 to 2017 of the Halda River were collected from the Bangladesh Water Development Board (BWDB) for this study. Monthly flow data from the Panchpukaria Hydrometric Station (Station ID: 119.1) were used for model calibration and validation. These data were incomplete and inconsistent. As daily discharge data is not continuous, measured discharge and water level (twice per month) data are used to construct a stage-discharge relationship to generate daily discharge data after filtering outliers.

Stage-discharge relationship formulation for stream discharge estimation

Streamflow measurements are required to plan and design diverse structures and projects (Mirza, 2003; Muzzammil et al., 2015; Sivapragasam & Muttil, 2005). However, flow measurement requires proper instrumentation, a skilled workforce, and time and sometimes faces practical difficulties (Muzzammil et al., 2015; Schmidt & Yen, 2001; Sivapragasam & Muttil, 2005). But instead, maintaining a record of a stream's stage or water level is relatively easy and flawless (Muzzammil et al., 2015). Generally, in the SCS-CN method, the maximum water stage is of primary interest. The stage-discharge relationship for flow can simulate daily discharge from the daily water level data (Kumar, 2011; Sivapragasam & Muttil, 2005). However, water-surface slope, cross-sectional area, and unsteady flow create discontinuities or loops in measurement-based rating curves (BV & Hydraulics, 1999; Schmidt & Yen, 2001). The stage-discharge relationship is generally treated as a power function (BV & Hydraulics, 1999; Herschy, 1998; Lambie, 1978; Mirza, 2003; Mosley & McKerchar, 1993; Reitan & Petersen-Øverleir, 2005; Sankhua, 2015; Schmidt & Yen, 2001) as follows:

$$Q = C \times (H + a)^b \quad \ldots\ldots\ldots (1)$$

Where Q = discharge; C and b = constant; H = stage; a = stage at which discharge is zero.

To achieve a single-line rating curve relationship, a compound rating curve of two or more similar equations (often referred to as segments), each relating to a portion of the head range, can be applied (Reitan & Petersen-Øverleir, 2005). A satisfactory stage-discharge relation determines the quality of computed streamflow data in surface hydrology (Mosley & McKerchar, 1993; Reitan & Petersen-Øverleir, 2005). We used the generalized reduced gradient (GRG) nonlinear solver for optimization of the function embedded within Microsoft Excel (Muzzammil et al., 2015; Smith & Lasdon, 1992) and found it to be more reliable than the conventional trial and error (BV &

Hydraulics, 1999; Muzzammil et al., 2015). From the observed discharge data, the relationship between stage and discharge was found the following

$$Q = 0.0034 \times H^{5.5217} \quad \ldots (2)$$

From the rating curve relationship of observed discharge data with stage, the value for C is 0.0034, a is 0, b is 4.007696, and model R^2 value is 0.69.

Calibration and validation

Calibration and validation play important roles in decreasing uncertainty and increasing the predictive abilities to make the model effective. For the calibration period (1993-1997), values were adjusted by inputting the fitted values. Once the model is calibrated with soil and vegetation parameters, the model is validated with modified parameters. The model has been validated from 1997 to 2005.

Global Sensitivity Analysis and Statistical Evaluation of uncertainty

The sensitivity of the flow simulation in SWAT is usually defined by using p-factor, r-factor, and t-statistic as global estimates. The p-factor denotes the proportion of observed data within the 95% prediction uncertainty (95PPU), and the r-factor defines the average width of the 95PPU band divided by the standard deviation of the corresponding measured variable (Abbaspour et al., 2015). The 95PPU is estimated at 2.5 and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling (multiple regression system) by omitting 5% of the worst simulations against the selected objective function values (Van Griensven et al. 2006, Abbaspour 2007). The t-stat is the coefficient of a parameter divided by its standard error, used to identify the relative significance of each parameter. In this analysis, the larger the absolute value, the value of the t-stat, and the smaller the p-value, the more sensitive the parameter. Though the r factor ranges from 0 to infinity, $p > 0.70$ and $r < 1.5$ were recommended for discharge (Abbaspour, 2007).

Model performance evaluation

Calibration and validation performance was further assessed using performance ratings (Moriasi et al., 2007; Moriasi et al., 2015) of the coefficient of determination (R^2), the Nash-Sutcliffe efficiency (NS), percent bias (PBIAS), and the ratio of the root mean square error (RMSE) to the standard deviation of measured data (RSR) (Table 1).

Table 1: List of model performance evaluators and their characteristics.

Model Name	Performance evaluator Equation	Description of the variables	Qualitative range	Reference
Root mean square error	$RSR = \frac{\sqrt{\sum (qm - qs)^2}}{\sqrt{\sum (qm - Qm)^2}}$	q is a variable (discharge). m and s are measured and simulated data. Q is the arithmetic mean for respective observations.	0.0 ≤ RSR ≤ 0.50	Moriasi et al., (2007)
Coefficient of determination	$R^2 = \frac{[\sum (qm - Qm)(qs - Qs)]^2}{\sum (qm - Qm)^2 \sum (qs - Qs)^2}$		0.75 ≤R2 ≤1.0	Moriasi et al., (2007, 2015)
Percent Bias	$PBIAS = \frac{\sum (qm - qs)}{\sum qm} \times 100$		PBIAS ≤ ±10	Gupta et al. (1999)
Nash-Sutcliffe efficiency	$NS = 1 - \frac{\sum (qm - qs)^2}{\sum (qm - Qm)^2}$		0.75 ≤NSE ≤1.0	Nash and Sutcliffe, (1970)

The **coefficient of determination, denoted $\mathbf{R^2}$**, is the proportion of the variance of the dependent variable to the predicated independent variable(s). The **Nash-Sutcliffe efficiency (NS)** is a normalised statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). The NS efficiency indicates how well the plot of observed versus simulated data fits the 1:1 line. The NS = 1 means a perfect match, and the NS = 0 corresponds to the model data is as accurate as the observed mean. The Inf < NS < 0 represents that the observed mean is a better predictor than the model data. **Percent bias (PBIAS)** measures the average tendency of the simulated data to be larger or smaller than the observations. The optimum value is zero; low magnitude values indicate a better simulation. Positive values indicate model underestimation, and negative values indicate overestimation (Gupta et al., 1999). **Root Mean Square Error (RMSE)** is the standard deviation of the residuals (prediction errors), which measures the distance from the regression line data points. The ratio of the RMSE to the standard deviation of estimated data gives a standardized RMSE value as RSR that varies from zero to positive values. The lower the RSR, the better the model fit (Moriasi et al., 2007).

RESULTS AND DISCUSSIONS

Discharge estimation using an innovative mixed rating curve method

A mixed rating curve combining power function (lean flow phase) and Microsoft Excel solver (peak flow phase) data was formulated for daily discharge estimation to calibrate and validate flow simulation. The rate of discharge change for a given portion of the stage-discharge curves differs in a hydrograph's rising and falling limbs. Low flow discharge occupies a relatively small part of channels, and overflows occur through the vast flood plains during flood flow in this river. As a result, a highly variable discharge with distance from the main channel was common throughout this river. Again, after the flood peak, the recession stage, water re-enters the stream and causes an unsteady flow, producing a stream slope more diminutive than that for a constant discharge.

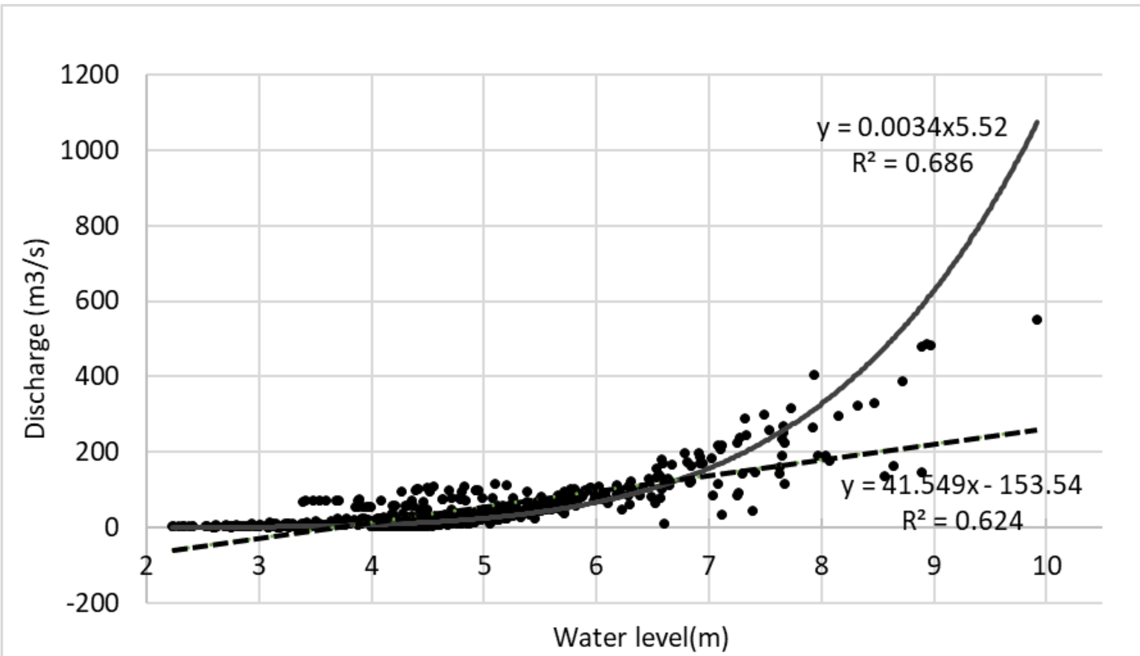

Figure 3: Halda river flow characteristics and derivation of discharge data from water level at the Panchpukuria monitoring station.

Flow simulation using SWAT

The model was run daily from January 1990 to December 2015, with the first three years of simulation as a warm-up period to stabilize the model. For model calibration, 1993-1997 and validation, the 1997–2005 period was used. This period included one major flood year (1991) and one drought year (1994), which allowed us to evaluate the model's ability to simulate extreme flow events associated with the monsoon-driven climate.

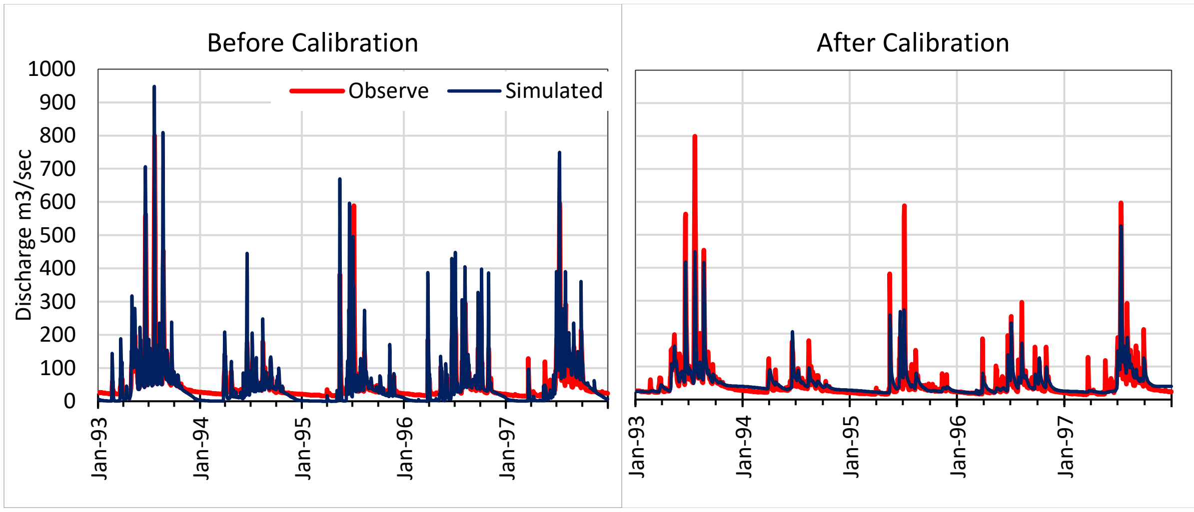

Figure 4: Halda River flow simulated and observed for 1993-1997. Before calibration, the base flow is overestimated, whereas the peak flow shows a low estimate. The calibrated model shows higher sensitivity to the baseflow and peak discharge to observation.

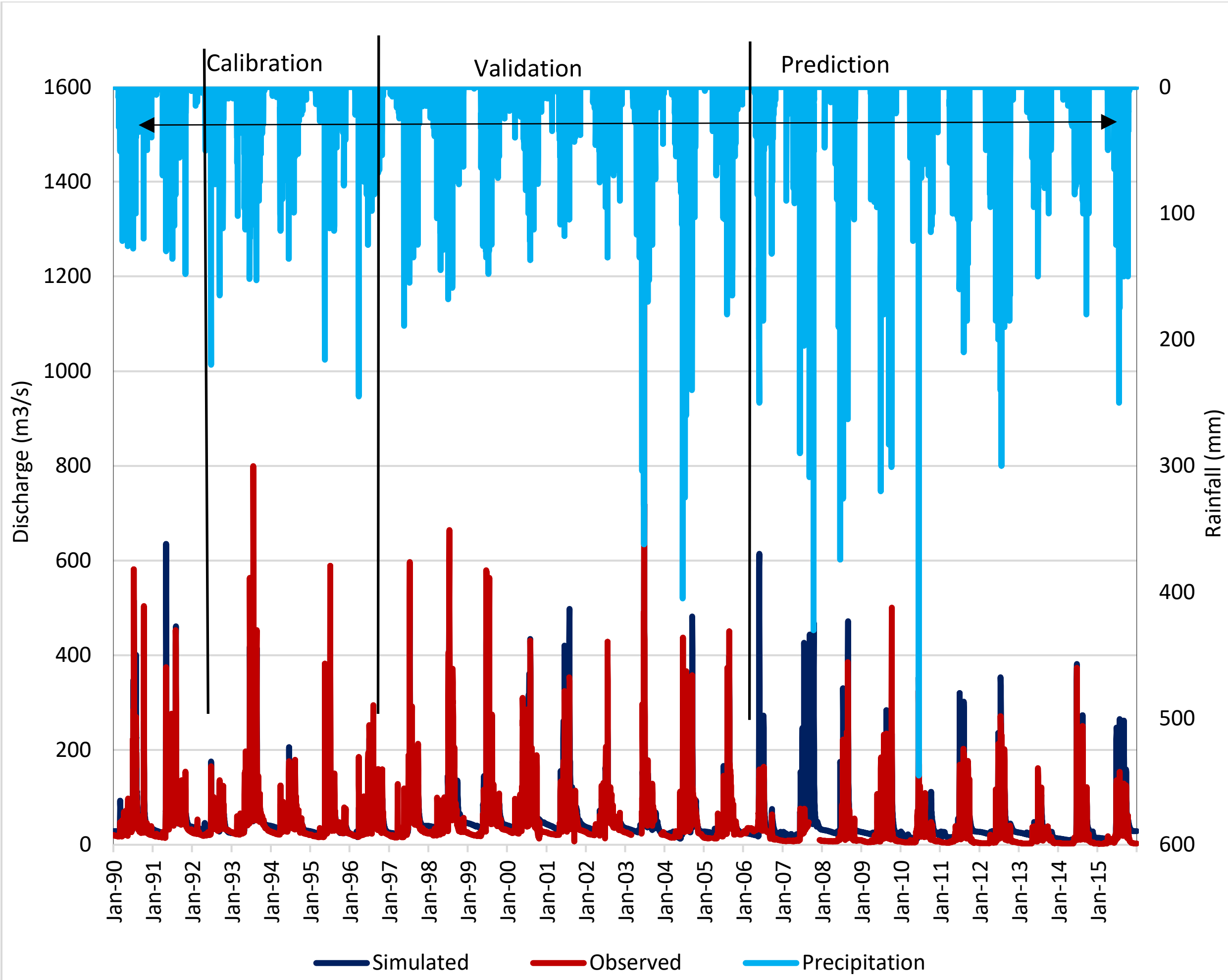

Figure 5: Halda River flow simulated and observed for 1990-2015. The seasonal variation was perfectly captured in the simulated flow, though some peaks showed higher discharge compared to observation, while after calibration, peaks showed lower river discharge than observation; however, the calibration error matrix performance enhanced.

Table 2: Statistical evaluation of model performance

Model Performance	**Calibration**		**Validation**	**Preferred value range**
	Before	After		
NSE	0.45	0.86	0.66	0.75 ≤NSE ≤1.0
R^2	0.73	0.82	0.670	0.75 ≤R^2 ≤1.0
RSR	0.74	0.37	0.58	0.0 ≤ RSR ≤ 0.50
PBIAS	+0.5	+1.6	+9.5	PBIAS ≤ ±10

Table 3: Parameter analysis and fitted value for the calibrating model.

Parameter	Fitted value	t-Stat	p - factor value
R__CN2.mgt	-0.08	-1.319	0.244
V__GWQMN.gw	5.00	-1.070	0.334
V__GW_DELAY.gw	150.00	0.563	0.598
V__ALPHA_BF.gw	0.80	1.210	0.280
V__REVAPMN.gw	34.70	-0.300	0.776
R__SOL_AWC(..).sol	0.10	-1.142	0.305
R__SOL_K(..).sol	0.32	1.007	0.360
V__ESCO.hru	2.00	0.191	0.856
R__SLSUBBSN.hru	0.02	-0.477	0.653
R__HRU_SLP.hru	3.20	3.883	0.012
V__ALPHA_BNK.rte	5.50	0.384	0.717
V__CH_N2.rte	0.10	-2.141	0.085
V__CH_K2.rte	90.70	0.408	0.700

For discharge, the p-factor and r-factor recommended a value of 0.7 or 0.75 and a value of 1.5 to be adequate (Abbaspour et al., 2015). Hence, this study acquired acceptable values for both factors (Table 2 and 3). The simulation performance matrix comparing the monthly flow model developed by Raihan et al. (2020) performed better, except for the PBIAS value for the calibration period. However, the relative improvement in the daily flow simulation compared to the monthly flow simulation done by Raihan et al. (2020) was insignificant. The lag time to the rainfall peak to the discharge point (time of concentration) in the Halda River catchment is less than a day. Since the rainfall-runoff relationship cannot be evaluated for a half-month or monthly simulation for this catchment, the runoff generated by a single storm may fall in an early or late phase of the observation, which limits the application of flow simulation for river management. Additionally, variation applies to DEM uses, land use change, and discharge data of BWDB (observation error). The BWDB data reports every 15 days, a reliable interpolation method was required to comprehend the daily discharge. However, the lack of regular flow monitoring data did not affect the quality of flow simulation using water level data from a nearby station using the adapted rating curve method used in this study.

Multiple simulation iterations were executed with 300 simulations each run to achieve the best model efficiency between the observed and simulated flows.

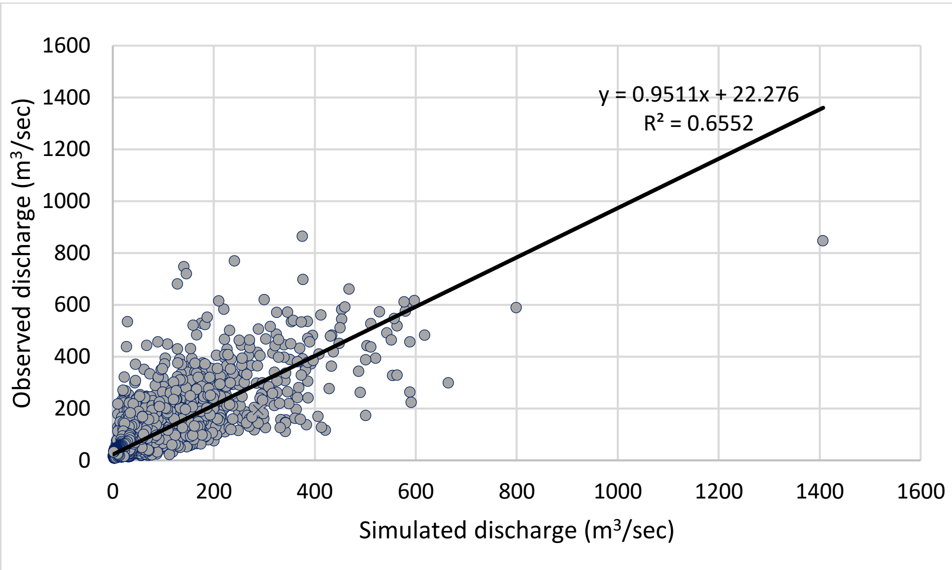

Figure 6: Simulated vs observed discharge data and linear fit model for the calibration and validation period.

The calibrated model reasonably reproduced the observed discharge quantity and monthly trends, except for 2007, 2009, and 2011, when the simulated discharge failed to capture the extreme peak flow (Figure 6). During these years, the model underestimated extreme events and peak flows, which may cause uncertainties associated with the rainfall data and the runoff generation process (Conan et al., 2003). This uncertainty was likely because of missing rainfall data during devastating floods, tropical cyclones, and other missing rainfall data at different rain gauge stations in the study area. Though the model had the above limitations, it was reliable to examine the hydrological responses of the Halda basin using the calibrated models with optimized parameters.

Baseflow flow characteristics

Following the rubber dam project operation just 5 km upstream of the monitoring station, Panchpukuria, since 2011, the stream's low-flow water was significantly affected. Raihan et al. (2020), Saha et al. (2019), and Aktar and Ali (2012) and field observation reported a lower base flow to the downstream and a reservoir due to the rubber dam being operational during dry months (January to May). However, low flow simulation is still a significant challenge in SWAT (Sudheer et al. 2007, Leisenring and Moradkhani 2012) due to higher uncertainty in groundwater flow in SWAT (Rostamian et al. (2008), which is affected mainly by not only the surface process but also subsurface process and characteristics such as hydraulic conductivity, porosity, and geological formation. Considering the catchment characteristics of the Halda River following several field visits to the area, we find that the groundwater system would represent a complex one to correctly represent the recharge process in SWAT (Shao et al. 2019). This could be attributed to the prolonged baseflow recession in its wide floodplain's thick soil layer on both riverbanks at some sub-catchments, which could not be measured by the gauge station. This limitation can be overcome by coupling groundwater flow (e.g., MODFLOW) modules or similar. The rainfall streamflow ratio is significantly higher, indicating a limited role of groundwater storage in the river flow. The influence of the soil layer on the groundwater flow has been articulated adequately in Raihan et al. (2020) study of this basin. We have observed a similar fitting parameter value for groundwater flow (Table 2).

Effect of Landuse on stream flow and sediment load

Numerous studies suggested that hydrological responses to deforestation are very inconstant and often hard to comprehend. The evapotranspiration changes are regarded as the main effect of deforestation since they influence soil water holding capacity and the interception of precipitation (Zhang et al. 2014). Deforestation generally increases, and reforestation decreases the annual flow (Ma et al. 2009; Hlásny et al. 2015). Usually, vegetation removal intensifies shallower root distribution and reduces soil porosity and soil moisture capacity (Zhang et al. 2014). Hlásny et al. (2015) specified that deforestation alters the pathways and the timing of runoff, thereby changing the volume and timing of flood peaks. Afforestation has a greater infiltration rate, which may reduce runoff peak and total runoff volume (Zhang et al. 2014), and a new approach in rainfall-runoff simulation may enhance the simulation performance (Esmaeili-Gisavandani et al. 2019). However, we have considered a minor effect on stream flow in this watershed due to the large proportion of its lowland covered with agricultural land or shrub vegetation, which would primarily affect the sediment load and nutrient flow rather than the fluid.

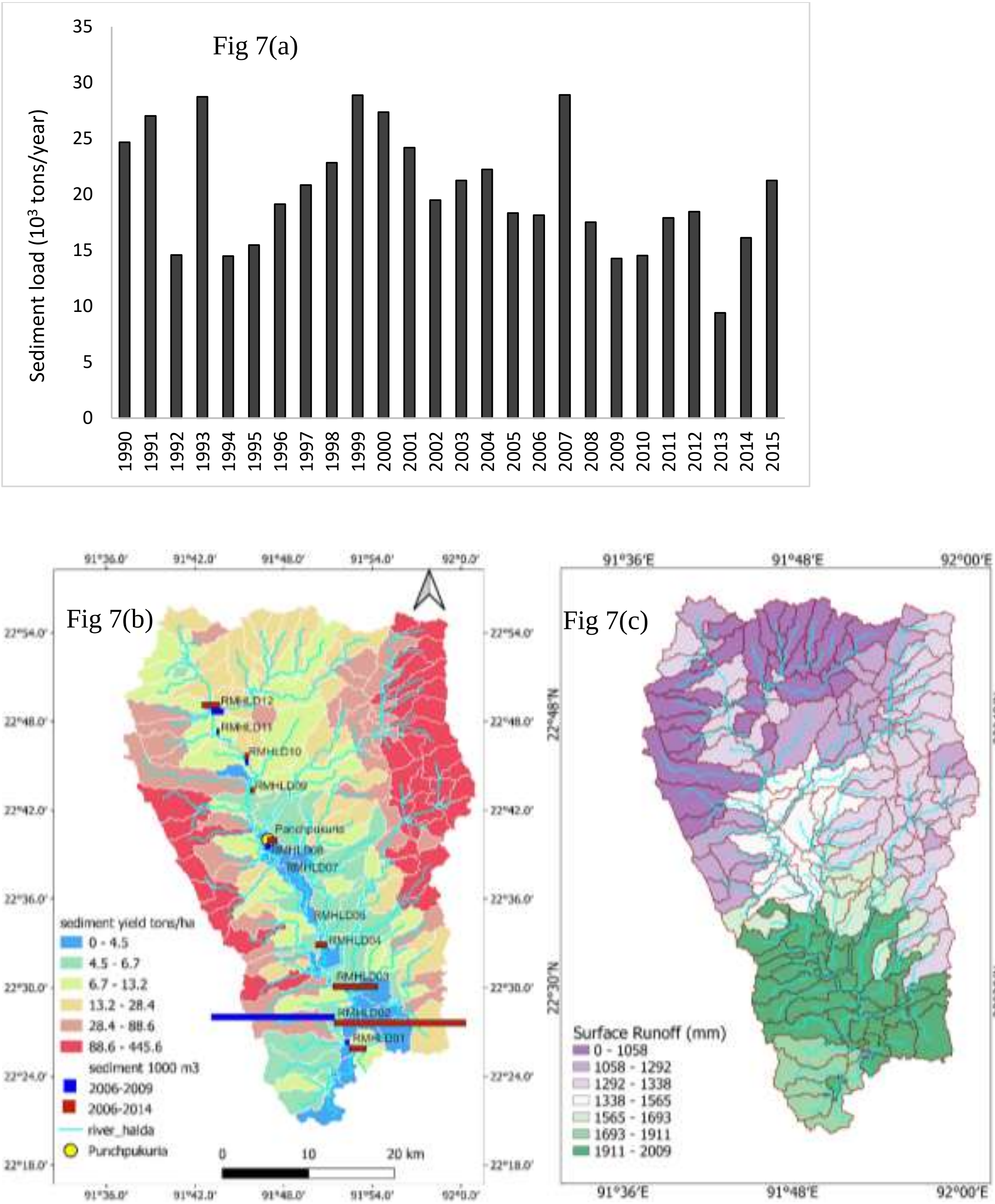

Figure 7: SWAT estimated daily yearly sediment load (Fig. 7a), the spatial distribution of mean sediment yield and surface runoff are shown in Figs. (b) and (c), respectively.

A significant limitation of the water quality simulation of this river watershed is the lack of daily water quality observation at the upstream location. Though the water quality is routinely monitored at a downstream location, low tide data at 40km downstream of discharge monitoring site near Mohora Water Treatment Plant, only partly represent the upstream geochemical and land use effect on sediment (John et al. 2023). Downstream of this river, Chattogram Water Supply and Sewerage Authority (CWASA) estimated a sediment load >1643 ± 924 tons/day (after Aktar and Ali 2012) with an yearly load 600×10^3 ton and a minimum value of 46.1×10^3 tons . The observation point located close to its mouth with Karnaphuli River is significantly affected by the resuspension and turbulence due to tidal water flow, and river flow. Hence, the sediment load reported at Panchpukuria station (Fig. 7b) is assumed to be higher than the river's actual sediment load at the downstream where runoff characteristics would be different due to tidal inflow and flow contribution multiple tributaries. However, the silt load approximated as 4063 tons/ day between 2006 to 2014 period based on the siltation survey report by BWDB (Fig. 8) while assuming a uniform cross-section condition between two consecutive sections. Both of the estimate exceed our simulation result of 55 tons/day (30 times and 95 times lower than the concentration and siltation survey-based estimate, respectively). The model estimate is conservative but reasonable for an upstream location. The landcover data revealed a lower disturbance in the hilly catchments during several field campaigns, landcover study (Chowdhury et al 2020) and other streams catchments in the regions (Karmakar et al. 2019, Haque et al. 2010). However, for a better estimate on sediment load and sediment characterization, typical sediment transport model were suggested (John et al 2023 and Wallwork et al. 2021)

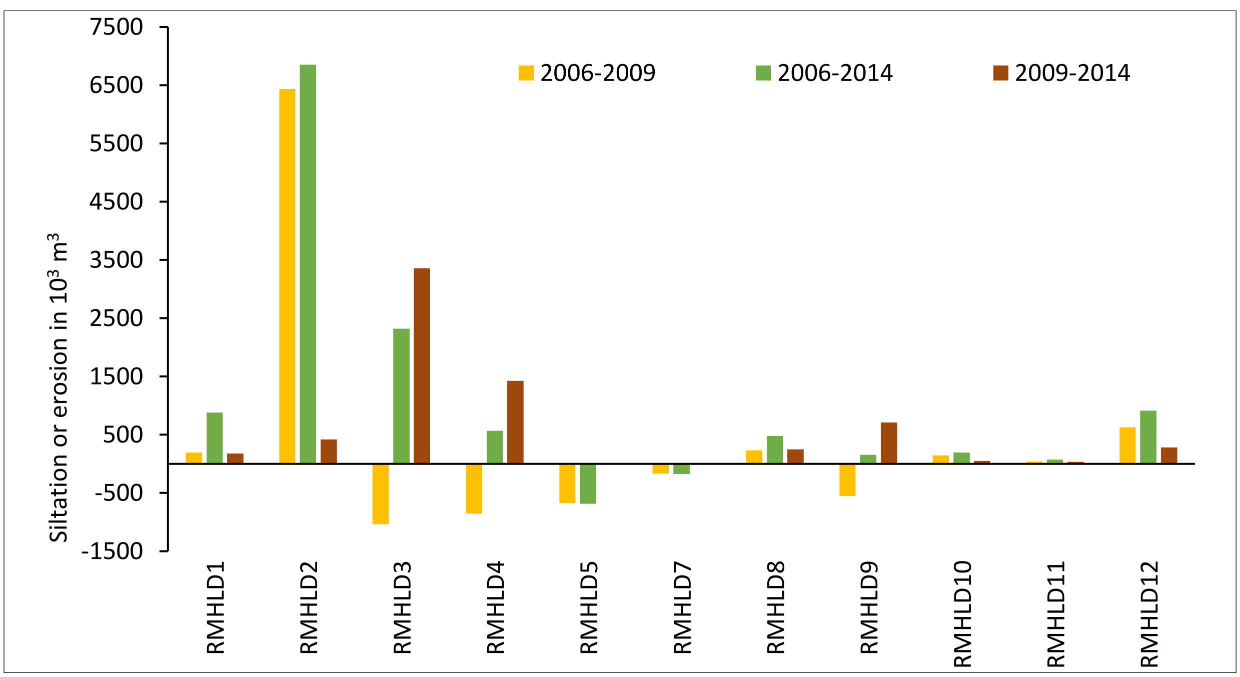

Figure 8: Siltation and erosion of the riverbed estimated during siltation survey by Bangladesh Water Development Board. The RMHLD01 denoted for a survey section located at the downstream near the mouth, RMHLD12 denotes the most upstream section and Panchpukuria station located at RMHLD08 survey station of this river.

In addition to the total sediment estimate, the siltation survey data present river siltation-erosion dynamics and upstream-downstream balance. Fig 8 shows that the upstream locations, RHMLD10, to RHMLD12 experiences small volume of siltation between the siltation survey 2003 to 2006; however, the river course remain stable until it meets a tributary before RHMLD05. The sediment load estimate at the Panchpukuria location using SWAT lies between siltation survey station RMHLD08 and RMHLD 09. Here the daily estimate 50 ton/day in the SWAT simulation supports the siltation survey estimate in this location during 2003-2014 period. However, erosion continued at RMHLD05 survey section throughout the siltation survey period, 2003-2014, possibly due to higher flow from the tributary (Saha et al 2019) but lower sediment load in river water causes higher riverbank erosion. The downstream cross-section data shows an accretion trend. In contrast, the middle and mid-downstream showed the most soil erosion during the study period 2006-2009. This river hypsometry depicts this river catchment mainly as plain-land; consequently, the regulation or recession of flow affects most downstream compared to the upstream area. However, this river's accretion and bank erosion were not very intense (Figure 8) compared to other regional and transboundary streams in Bangladesh (Karmakar et al., 2009). From this river dynamics, it is also noticeable that flow regulation in the upstream region poses a more significant impact downstream than a very intimate part of the regulation point. From the hydrological data, we cannot univocally articulate the impact of flow regulation on the siltation or erosion, as well as effects of any other land use measures that may since some changes, such as channel modification and sand quarry in the riverbed concurrent on this river (Saha et al 2019). The flow regulations for irrigation and diversion canals also become a regular phenomenon in the last two decades to boost agricultural production in the eastern part of this catchment. Since sediment data is unavailable at the discharge monitoring station, sediment estimate using SWAT provides a management implication and the importance of monitoring the data. Since this river provides many ecosystem services and freshwater supply to the city, conserving the downstream habitat and riverbank would best serve for flow and siltation dynamics and vice-versa.

CONCLUSIONS

Despite medium confidence with the error matrix of the discharge estimation for calibration and validation periods, the daily flow simulation results agree very well with previous simulation results. Moreover, this study shows that the rating curve of flow-water level with adaptive approach for low and peak flow regimes can be used in data-poor or low temporal resolution data regions for watershed management. The hydrological water balance analysis revealed that groundwater flow is an essential element of the total discharge within the study area. Sediment load downstream was attributed to settlement, land use change, higher precipitation, sediment movement along the channel (Singh et al, 2019) and tidal resuspension of the river sediment. Effect of climate, landuse and watershed management such as afforestation, soil conservative can be integrated in this flow model to understand river hydrology in this region. Eventually that would leads to water quality modeling research for nutrient transport in a data-poor catchment of Bangladesh to ensure sustainable and integrated river water management in a critical water habitats.

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Supplementary Information

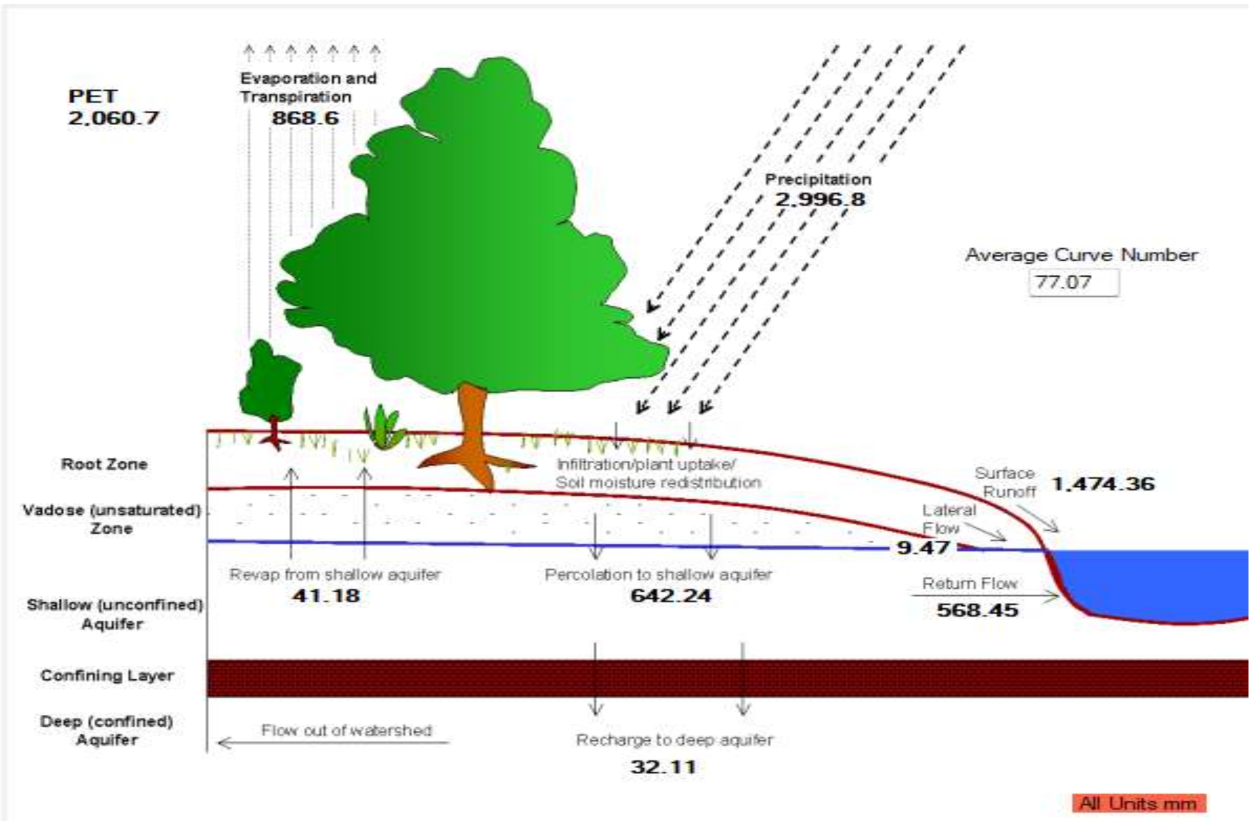

Table S2: Siltation/erosion at different Halda River cross-sections in respective years (after BWDB)

Cross sections	Distance from mouth	Stream position	Amount of Erosion/siltation (m^2)			Amount of Erosion/siltation (m3)		
			2006-2009	2006-2014	2009-2014	2006-2009	2006-2014	2009-2014
RMHLD1	3.922	DS	49.86	224.67	44.65	195550.9	881156	175118
RMHLD2	9.7	DS	663.55	706.63	43.08	6436435	6854311	417876
RMHLD3	7.76	DS	-133.77	298.94	432.71	-1038055	2319774	3357830

RMHLD4	14.03	DS	-60.87	40.49	101.36	-854006	568074.7	1422081
RMHLD5	6.53	MS	-103.38	-104.76	-1.38	-675071	-684083	-9011
RMHLD7	19.75	MS/ T	-8.56	-8.88	-0.32	-169060	-175380	-6320
RMHLD8	10.7	MS	21.98	45	23.02	235186	481500	246314
RMHLD9	6.4	US	-86.36	24.41	110.77	-552704	156224	708928
RMHLD10	5.71	US	25.48	34	8.52	145491	194140	48649
RMHLD11	5.42	US	7.45	13.75	6.3	40379	74525	34146
RMHLD12	19.75	US	31.91	46.28	14.37	630223	914030	283808
Siltation over the period in (m3)						4394368	11584272	6679417
Siltation volume (in tons)						5932396	15638767	9017213
Siltation (in tons/year)						1977465	1954846	1502869

Note: DS-Downstream, MS-Middlestream, US-Upstream, T-Tributary, RMHLD is the BWDB notation for river monitoring station, the (+) sign represents siltation, and the (-) sign represents erosion amount. Sediment bulk density approximated as 1.35 ton/m3