

**Competitive Research Grant**  
**Sub-Project Completion Report**

**on**

**Developing a model-based water management plan  
for haor wetlands of Bangladesh to reduce the  
vulnerability of Boro rice crop to flash floods**

**Project Duration**

**May 2016 to September 2018**

**Department of Irrigation and Water Management  
Bangladesh Agricultural University  
Mymensingh 2202**



**Submitted to**  
**Project Implementation Unit-BARC, NATP-2**  
**Bangladesh Agricultural Research Council**  
**Farmgate, Dhaka-1215**



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#### Citation

Developing a model-based water management plan for haor wetlands of Bangladesh to reduce the vulnerability of Boro rice crop to flash floods

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Bangladesh Agricultural Research Council (BARC)

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Bangladesh Agricultural Research Council (BARC)

New Airport Road, Farmgate, Dhaka – 1215

Bangladesh

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## Acronyms

BARC	Bangladesh Agricultural Research Council
BWDB	Bangladesh Water Development Board
CEGIS	Centre for Environmental and Geographic Information Services
CMIP5	Coupled Model Intercomparison Project Phase V
CRG	Competitive Research Grant
GCM	Global Climate Model
HydroSHED	Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
NATP	National Agricultural Technology Program
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Projections
PIU	Project Implementation Unit
RCP	Representative Concentration Pathways
SWAT	Soil and Water Assessment Tool
SWATrw	SWAT for riparian wetland
USGS	United States Geological Survey

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## Executive Summary

This Project Completion Report (PCR) on CRG sub-project “Developing a model-based water management plan for haor wetlands of Bangladesh to reduce the vulnerability of Boro rice crop to flash floods” illustrates various research activities and associated results obtained from the project work conducted during the period May 2017 – September 2018. Amid the burgeoning early flash flood problems in the northeastern haor region of Bangladesh during Boro rice harvesting period (April–May), this study was undertaken to formulate a better water management plan with developing a distributed hydrological model for the experimental Agolpahaor located in Itna, Kishoreganj. Since developing a distributed hydrological model requires various data (elevation, land use, soil, climate, crop etc.) with less artifacts, this study deployed different instruments/devices at the field sites in order to monitor and record different time series data. A simple, quick and cost-effective boating topographic survey technique was developed and subsequently used to generate a digital elevation map of the haor. After reviewing a number of widely used hydrological models, Soil and Water Assessment Tool for riparian wetland (SWATrw) model was finally selected for this study, and calibrated against observed daily water depths of the haor recorded during October 2017 – June 2018. With future climate forcing from five Global Climate Models (GCMs), the model was used to project future scenarios of haor’s flash floods.

From this study it was found that 16% of the Agolpahaor with cultivated Boro rice was inundated due to local rainfall within the haor catchment before overflowing of the Dhanu River on 13<sup>th</sup> May 2018. Therefore, this study stresses that any haor water management strategy must not overlook the role of local rainfall induced early floods. Without necessary workable sluice gates, dykes alone were found to be ineffective in protecting Boro rice from being damaged by early floods in the haor. Modelling results show that raising field bunds of cultivated lands could reduce local rainfall induced floods by about 46%. However, this potential of such land management practice should be further evaluated with direct field experiments which was beyond the scope of this study. The existing suffering of haor Boro rice due to flash flooding is projected to be increasing in the future due to changing climate.

## CRG Sub-Project Completion Report (PCR)

### A. Sub-project Description

#### 1. Title of the CRG sub-project:

Developing a model-based water management plan for haor wetlands of Bangladesh to reduce the vulnerability of Boro rice crop to flash floods

#### 2. Implementing organization:

Department of Irrigation and Water Management, Bangladesh Agricultural University (BAU), Mymensingh

#### 3. Name and full address with phone, cell and E-mail of PI/Co-PI (s):

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#### 4. Sub-project budget (Tk):

- 4.1 Total: 1,997,330 (Nineteen lacs ninety seven thousands three hundred thirty Taka)
- 4.2 Revised (if any):

#### 5. Duration of the sub-project:

- 5.1 Start date (based on LoA signed): 9 May 2017
- 5.2 End date: 30 September 2018

## **6. Justification of undertaking the sub-project:**

Haor wetlands in the northeast part of Bangladesh (Sylhet, Sunamganj, Habiganj, Mouvibazar, Netrokona, Kishoreganj and Brahmanbaria districts) are of a great importance in maintaining country's food security through producing about 18% of country's total rice (mainly Boro) production (CEGIS, 2012a). The haor region represents about 11% of the country's total population. Majority of people in haor areas are directly/indirectly engaged in agriculture. This area remains completely under water during the wet period of June–October because of its depressional landforms in physiographical settings and of receiving huge runoff from the upper hilly Indian state Meghalaya. After receding flood water in December haor areas become cultivable for Boro rice. Although the estimated rice production potential of haor areas is very high, flash floods often destroy the nearly ripen boro rice during the harvesting time (April/May) which directly affects the livelihood of local people thereby national economy. On average haor flooding damages 2.44 million tons of rice (CEGIS, 2012b). Recent field surveys reveal that haor areas are now more exposed to flash floods than that of past decades (Ahmed, 2014; CEGIS, 2012b). Despite evidence of such risk, it is understandable that Asian wetlands will be experiencing more pressure from agricultural conversion due to burgeoning food demand by increasing population (Gopal, 2013; Molla et al., 2018; Quan et al., 2018). This situation may further be exacerbated by changing climate (Greenberg et al., 2015; Thompson et al., 2016). For instance, Vietnamese farmers are adopting a shorter rice cultivation system called 'ratoon' where tillers are re-generated from previous cut-stalks in order to escape the damage to low-lying rice from early floods (Sen and Bond, 2017).

Proper management of haor areas including its water resources can boost its current 2% contribution to GDP to tenfold. In order to combat the existing haor flooding problems, currently two measures are prescribed: (i) planting short duration rice variety (e.g. BRR1 dhan 28) so that it can be reaped before next flooding and (ii) isolating haors by erecting temporary submersible earthen dykes from adjacent flashy rivers which is mainly promoted by the Bangladesh Water Development Board (BWDB). However, none of the approaches is yet to be proved as a reliable measure due to some major limitations experienced over the past years. The main objection to the former approach is its low yield potential unlike long duration high yielding rice varieties (e.g. BRR1 dhan 29), although recent records indicate that even shorter duration BRR1 dhan 28 cannot avert the risk of early floods. The latter has three major limitations: (i) causing flash floods due to

restricted drainage of runoff generated from heavy rainfall within a haor catchment rather than overflows from adjacent rivers, (ii) short life span of submergible earthen dykes (1–2 years) due to lack of maintenance works; their breaching during harvesting time most often causes serious havocs and (iii) financial constraints to build and manage earthen dykes. Therefore, this research proposes a modelling study of haor hydrology, with real-time hydro-meteorological observations for some instrumented representative haors, that can explore better but economical water resource management plans for haors. Such a model can be used to simulate haor flooding responses for different WHAT IF scenarios, for instance, how likely a Boro crop in a haor can escape flash floods if the haor is dyked. As such, from numerous combinations of those simulated scenarios an affordable and adaptable water management strategy for the haor region could be identified. Moreover, such models can be further employed to formulate future water management plans under different climate change scenarios.

#### **7. Sub-project goal:**

Adapting the developed prototype of haor water management approach across the entire haor region for attaining optimum rice production under the risk of future climate change

#### **8. Sub-project objective (s):**

- (i) Instrumenting some representative haors for monitoring real time hydro-meteorological data,
- (ii) Developing a distributed physics-based model for simulating haor hydrology, and
- (iii) Developing haor water management scenarios for different climate change induced hydrological alternations.

#### **9. Implementing location (s):**

Agolpahaor at Shimul Buck Village in Itna under Kishoreganj district

#### **10. Methodology**

This project was undertaken to develop a hydrological model for haor wetlands of Bangladesh in order to critically diagnose the cause of flash floods in haors and also to develop a better water management plan for haor agriculture. The project was accomplished under four major sub-tasks that are described in the following sections.

##### **10.1 Site selection and instrument deployment**

After conducting several reconnaissance surveys, Agolpahaor at Shimul Buck village of ItnaUpazila, Kishoreganj district was selected for the study (Figure 1). This haor is often flooded by overflowing

of adjacent Dhanu River whose catchment area mainly lies in the upper hilly Meghalaya state of India. In fact, Surma River takes the name of river Dhanu at its downstream near Itna. It was learned that the Dhanu River is also recognized as Ghorautra river in some places of the region. In order to avoid any confusion while referencing this river we hereafter will use Dhanu River. The catchment area of Agolpahaor is about 10.5 km<sup>2</sup> (1050 ha) and its elevation ranges from 0.06 m below mean sea level (msl) at its deepest point (i.e. beel) to 7.10 m above msl mainly along the bank (please see Section 10.2). There are two villages namely Shimul Buck and Elonjuri stretching along the river bank as shown in Figure 1. The entire haor is cultivated with Boro rice during the dry period December–April. However, the beel retaining a portion of receding flood water is used as an important habitat for many fish species. A small channel connects the haor with the river system. This channel is the crucial means in establishing hydraulic interactions between the river and haor specifically outside the monsoon season (June–September) when the entire haor including its peripheral bank remains under water. Although a sluice gate exists across the connecting channel but it is out of order since the associated approach dykes have been remained broken for many years (Figure 2).

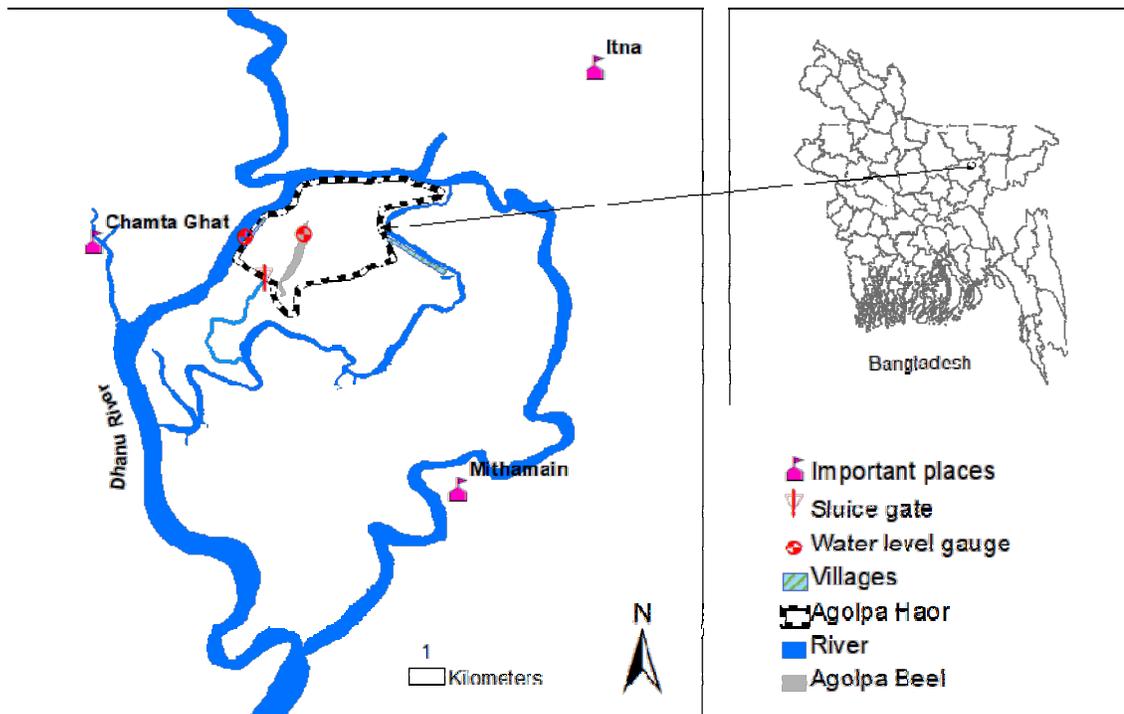


Figure 1. Location of the Agolpahaor.



Figure 2. Damaged approach dyke at the sluice gate location (PI and Co-PI along with the MS student and local field assistant).

In order to monitor and record various hydro-meteorological daily time series data (e.g. rainfall, temperature, humidity, solar radiation, water levels in rivers and haors) different instruments are required for this study. For meteorological data, a WeatherHawk ([www.weatherhawk.com](http://www.weatherhawk.com)) portable weather station with in-built datalogger was installed at the Shimul Buck village (Figure 3). The weather stations was mounted at the top of a 20 ft long mild steel pole so as to minimize any natural obstructions as one of the required conditions by the instrument and the risk of missing/stealing. A class A evaporation pan (galvanized steel; size: 1.2 m diameter and 12.6 cm height) as prescribed by the US Bureau of Reclamation (USBR) was manufactured in a local workshop (Figure 4). This pan was placed on a wooden platform near the experimental site and was fenced with a nylon net so as to protect it from any external disturbances. Daily evaporation rate is measured from this evaporation pan; the effect of rainfall, if any, is compensated by adding measured daily rainfall from the corresponding evaporation.



Figure 3. Installation of portable weather station by PI and Co-PI along with Field assistant of the project.



Figure 4. Locally made Class A evaporation pan installed at the experimental haor site.

In order to monitor water levels in the haor and river, eight staff gauges (or water level gauges) were made in a local workshop and these gauges are specially customised for haor areas. Each of the gauges is made of 4 inch PVC pipe with engraving laminated graduated scale on the pipe (Figure 5). Later this scaled PVC pipe was tightly screwed at the both ends to a long straight bamboo pole inserted into the pipe as shown in Figure 5. It can be mentioned that initially we adopted this manual approach since we could not procure desired water level dataloggers on time due to delaying disbursement of necessary fund. Nonetheless, later these staff gauges were replaced with water level dataloggers. All of the mentioned instruments are maintained and patrolled by a Field Assistant.



Figure 5. Installation of staff gauge at Agolpahaor.

## 10.2 Topographic survey and digital elevation model (DEM) data generation

This study requires elevation data of the experimental haor in order to delineate the topography of the haor. Digital elevation data, commonly known as digital elevation model (DEM) data, are generally derived from satellite sensed data and widely used since these data are easily available (Lindsay et al., 2004; Murphy et al., 2007). Although there are many sources of DEM data, they differ in their accuracy. Therefore, before employing such data it is customary to test their accuracy. Because field surveyed elevation data is not often available, satellite sensed DEM data is being widely used as proxy for various purposes. For this study, we collected DEM data from two data sources: HydroSHED (90 m horizontal resolution) data from USGS and ALOS World 3D (30 m horizontal resolution) data from the Japan Aerospace Exploration Agency (JAXA). To test the accuracy of these data, an attempt was taken to survey the entire haor for its topographic feature. Initially an on-ground topographic survey with a Sokkia B20 level (Figure 6) was conducted but this approach was found to be not appropriate for the area. We started the survey work along the periphery of the haor in the middle of January 2017 however encountered problems in surveying inside the haor area because handling survey instruments through the already Boro rice planted fields was damaging the young seedlings. Moreover, this approach was found to be very slow and cumbersome. For this reason, after taking readings at 57 points along the periphery (see Figure 6) the survey work was deferred until the next flooding period (June – October) when the haor remains completely under water.

In October 2017, we resumed the survey work but this time ground surface elevations at different locations of the inundated haor were measured with a boat; therefore, this surveying technique is named as boating or on-water-surface approach. For the boating topographic (BT) survey, the following instruments were used- a boat, a 5 m long staff gauge, and a Garmin Oregon 750 GPS. With this approach, first the boat is anchored at a desired location and then the depth of water is measured vertically lowering a staff gauge to the bed of the haor (Figure 7). The geographic coordinates of each location are recorded with the GPS. In this way we were able to measure water depths at more than 100 hundred locations across the haor within a single day. At the end of a working session (here a day) the elevation of water surface was measured with respect to known reference elevation marked on a building built near the bank of the haor which is actually Shimul Buck village the only protruding island during the flooding period. Subtracting measured water depths from the water surface elevation results in ground surface elevations at previously surveyed

locations. In order to reduce measurement uncertainties, the following cautions were maintained: (i) the survey was conducted in such a day when water surface remains calm i.e. there was no wave, and (ii) this approach is mainly suitable for shallow inundated areas where water surface elevation remains constant at least during a working session. Figure 8 demonstrates the locations of surveyed points across the haor.



Figure 6. Topographic surveying of the experimental haor.



Figure 7. Boating topographic survey of the Agolpahaor.

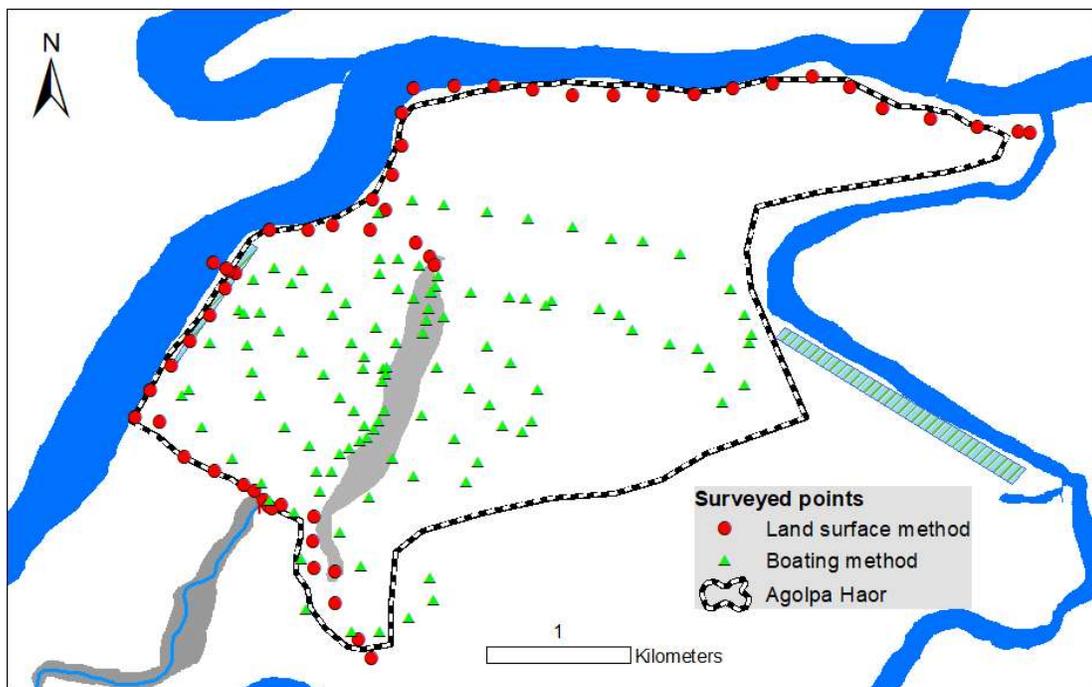


Figure 8. Location of topographic survey points of the Agolpahaor.

Using the spatial analyst tool in ArcGIS platform, a DEM data of 90 m horizontal resolution was generated from the surveyed 167 point elevations. An Inverse Distance Weighting (IDW) deterministic interpolation method was used to produce the DEM data.

### **10.3 Processing of future climate data**

This study requires future climate projection data; therefore, necessary climate change data of five Global Climate Models (GCMs) were downloaded from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) repository (<https://nex.nasa.gov/nex/projects/1356/>). NEX-GDDP is one of a few initiatives to downscale CMIP5 GCM data to finer spatial resolution (~27 km or ~0.25°) for the entire world and to make them freely available for use in scientific research. The 1991–2010 period was assumed as a baseline/reference period. The 2031–2050 period was selected since Bangladesh has aspirations to be a developed nation by 2041 (Jha 2017) and its development plans up to and beyond this date include haor agriculture for which there is a need to incorporate the potential impact of climate change. For future projections, the RCP4.5 (Representative Concentration Pathway, associated with the stabilisation of radiative forcing at 4.5  $W\ m^{-2}$  at the end of 21<sup>st</sup> Century) scenario was selected. World-wide policy makers and climate modellers have recognized this as the most optimistic scenario if plans to combat the current greenhouse gas emission rates could be properly implemented (IPCC 2013). Daily rainfall and temperature (maximum and minimum) data generated by those GCMs for the baseline and future periods were downloaded. In a previous study (Rahman, 2016) it was found that NEX-GDDP climate data showed considerable system errors i.e. biases, therefore, this study removes biases from raw NEX-GDDP data, hereafter referred to as GCM data, using a robust Quantile Mapping (QM) bias correction method as suggested by Rahman (2016). Five GCMs shown in Table 1 are selected for this study.

Table 1. Selected CMIP5 GCMs used in this study

GCMs	Developers	Spatial resolution <sup>a</sup> (Lat × Long)
CanESM2	Canadian Centre for Climate Modelling and Analysis	2.79×2.81
CCSM4	National Center for Atmospheric Research, USA	0.94×1.25
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence, Australia	1.87×1.88
GFDL-CM3	Geophysical Fluid Dynamics Laboratory	2.00×2.50
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.40×1.41

<sup>a</sup>The original spatial resolution of the GCM used to generate climate data

#### 10.4 SWAT<sub>rw</sub> model development for the Agolpahaor (SWAT<sub>rw</sub>\_Agolpa)

One of the foremost objectives of this study is to develop a distributed model capable of simulating haor hydrology. A number of available hydrological/catchment models were reviewed so as to evaluate the extent to which existing models are capable of simulating the hydrology of riparian haors where a strong hydraulic interaction is evident between haor wetlands, adjacent rivers and shallow aquifer. It was learned that most of the reviewed models are mainly suitable for Geographically Isolated Wetlands (GIW) where hydraulic interactions with rivers are hardly present unlike riparian haor wetlands. Recently Rahman et al. (2016) developed an improved version of Soil and Water Assessment Tool (SWAT) model, SWAT<sub>rw</sub> (SWAT for riparian wetland) that is especially configured for haor wetlands. Therefore, we decided to use this model for the present study. The SWAT, hence SWAT<sub>rw</sub>, model discretizes a catchment into several constituting sub-catchments according to river networks and topography of the catchment. Each sub-catchment is further divided into smaller spatial Hydrological Response Units (HRU) based on land use, elevation and soil type. A simple linear reservoir groundwater module is used to simulate shallow and deep aquifers underneath a catchment. A detailed description of SWAT model can be found at Neitsch et al. (2011).

The study area lies within the Sylhet Basin Agro-Ecological zone (AEZ) of Bangladesh. High yielding Boro rice (BRRIdhan-28 and BRRIdhan-29) is the only cultivated crop in the area and the soil type

varies from silty clay to silt loam. During delineation the entire Agolpahaor was assumed to be a single catchment with homogeneous land use (Boro rice) and soil type. However, a distinct spatial variation in soil surface slope is observed with steeper surface slopes towards the Agolpabeel (Figure 9). There are three slope classes 20, 30, and 120%. These slopes were generated from the previously developed DEM data of the haor. Owing to this diversity in surface slope, the haor catchment was split into three HRUs while building the SWATrw model. One of the distinguishing features of SWAT is its ability to simulate various crops including rice. Various required information regarding rice cultivation (e.g. planting date, irrigation, fertilizer etc.) were given to the model as inputs. Under this one year project, we were able to record hydro-meteorological daily time series data from 16 October 2017 to 15 June 2018. This time period well spans from flood receding time in the previous year to the next flooding in the following year.

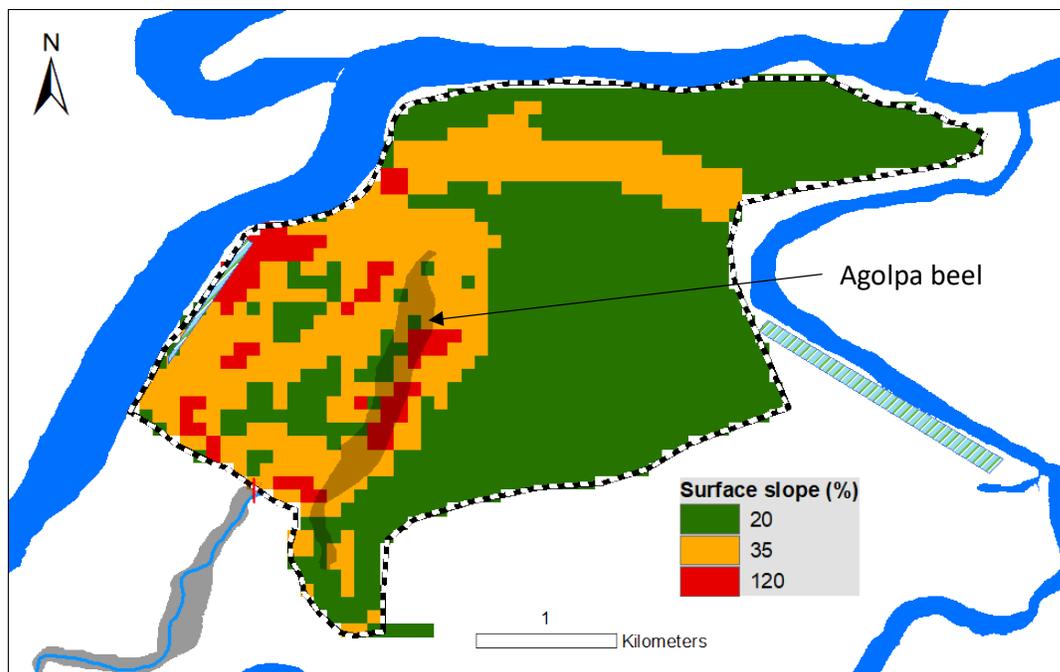


Figure 9. Spatial distribution of surface slopes of the Agolpahaor .

In order to model a depressional wetlands like the AgolpahaorSWATrw first represents the geometry of a haor by the following volume-area-depth relationships as originally adopted from Hayashi and van der Kamp (2000):

$$A_{wet} = b \cdot \left( \frac{D_{wet}}{D_{wet,0}} \right)^{2/p} \quad 1$$

$$S_{wet} = \left( \frac{b}{1 + \frac{2}{p}} \right) \cdot \frac{D_{wet}^{(1+\frac{2}{p})}}{D_{wet,0}^{\frac{2}{p}}} \quad 2$$

where  $S_{wet}$  and  $A_{wet}$  respectively denote wetland water volume and surface area at depth  $D_{wet}$ ,  $b$  and  $p$  are the scale and shape parameters of the wetland, respectively, and  $D_{wet,0}$  indicates unit wetland depth. The parameters for a particular wetland can be calibrated against the observed area-depth relationship curve outside of SWATrw (e.g. using a spreadsheet programme). In order to calibrate these two parameters, we first calculate horizontal surface areas and volumes at different depths of the haor using the Spatial Analyst Tool of ArcGIS. Figure 10 demonstrates the extents of different elevation classes after reclassification of DEM data. Later this data was used to generate the volume-area-depth relationship curve of the haor as shown in Table 2.

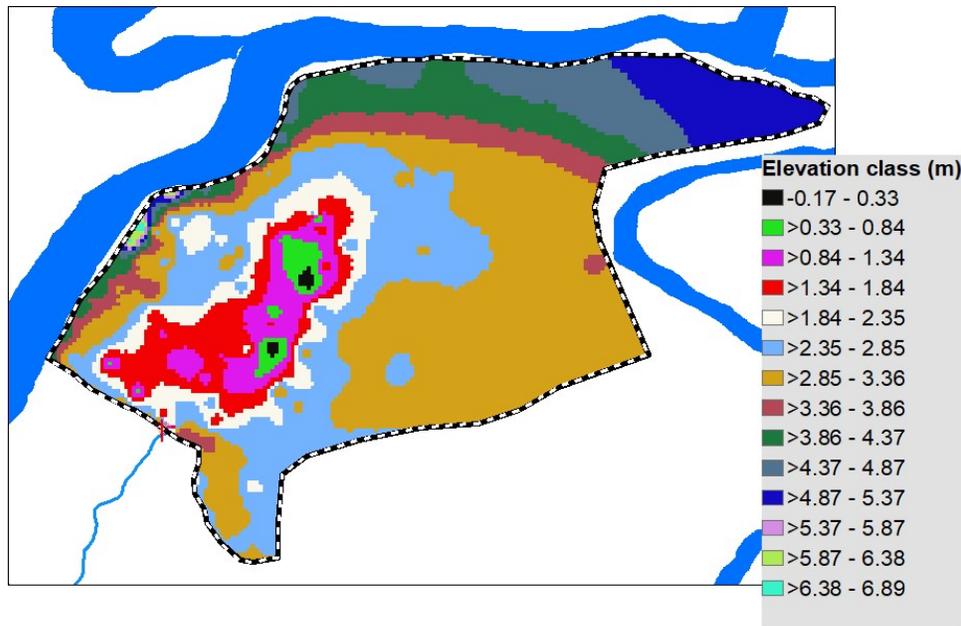


Figure 10. Elevation classes of the Agolpahaor generated from the surveyed DEM.

Table 2. Volume-area-depth relationship of the Agolpahaor

Elevation (m)	Surface area (ha)	Volume (ha-m)
0.33	2.2	0.42
0.84	15.9	4.38
1.34	58.1	20.84
1.84	125.6	68.63
2.35	194.3	148.12
2.85	400.5	286.70
3.36	755.8	600.68
3.86	816.9	1000.75
4.37	899.0	1433.73
4.87	970.8	1910.65
5.37	1033.1	2423.30
5.88	1034.5	2948.61
6.38	1036.1	3475.00
6.89	1036.6	4001.80

Calibration of the SWATrw model was performed in two phases: first, the scale and shape parameters of the haor's geometric model (equations 1 and 2) were calibrated against the previously calculated volume-area-depth relationship curve using an excel sheet programme. Later, these calibrated parameters (Table 3) are transferred to the SWATrw input file. Second, the model was forced with necessary hydro-meteorological data and calibrated its various parameters (see Table 3) against observed daily time series of water depth in the haor (16 October 2017 – 30 May 2018). An automatic calibration was used to minimize the objective function in Equation 3 as adopted by Coron et al. (2012):

$$\epsilon = RMSE[\sqrt{D}](1 + Bias) \quad 3$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{k=1}^n (D_{sim,k} - D_{obs,k})^2} \quad 4$$

$$Bias = \frac{\sum_{k=1}^n D_{sim} - \sum_{k=1}^n D_{obs}}{\sum_{k=1}^n D_{obs}} \quad 5$$

where,  $\epsilon$  is the error indicator,  $RMSE$  is the Root Mean Square Error,  $D_{sim}$  and  $D_{obs}$  are the respectively simulated and observed water depths, and  $n$  is the number of simulated and observed data pairs. One thousand samples of the 12 parameters set were drawn randomly from the assigned parameter ranges and then the model was run for each of those parameter samples. In addition to the above model evaluating criteria, the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), a widely practised method to judge hydrological models, was used:

$$NSE = 1 - \frac{\sum_{k=1}^n (D_{sim,k} - D_{obs,k})^2}{\sum_{k=1}^n (D_{obs,k} - \overline{D_{obs}})^2} \quad 6$$

where  $\overline{D_{obs}}$  is the mean of measured water depths and other symbols have already been explained.

Table 3. Calibration parameters and their final values in the SWATrw model of the UMRB

Parameters	Description (unit)	Ranges	Calibrated values
WET_P	Wetland shape factor	-	0.78
WET_B	Wetland scale factor (ha)	-	25.56
SURLAG	Surface runoff lag coefficient (day)	0.01–3.00	2.35
CN2	Curve number	40–95	86.96
ESCO	Soil evaporation compensation factor	0–1	0.50
EPCO	Plant uptake compensation factor	0–1	0.86
GW_DELAY	Groundwater delay (day)	1–61	42.00
ALPHA_BF	Baseflow factor (day)	0–1	0.12
RCHRG_DP	Fraction of soil percolated water to deep aquifer	0–0.90	0.84
WETEVCOEF	Wetland evaporation coefficient	0.3–0.9	0.40
WET_K	Hydraulic conductivity of wetland bottom (mm/hr)	0.3–80	0.86
CCH_DFR	Fraction of main channel maximum depth at normal level	0–1	0.63
CCH_LFR	Fraction of main channel length to be overflowed at normal level	0–1	0.21
WEIR_CD		0.001–0.0095	0.007

## 11. Results and discussion

This sub-section discusses various results and outcomes of the study project. First, a brief exploratory analysis of different hydro-meteorological data recorded in this study is given. Second, the performance of the developed model in simulating early flash floods in the Agolpahaor is presented. Third, using simulation results from the model it will be shown that a sustainable water management could be practised to avert the early flash flood risk in the study haor.

### 11.1 Exploratory analysis of recorded hydro-meteorological time series data

Figure 11 shows recorded daily rainfall at the Agolpahaor site. The sporadic and intense rainfall in April and May of 2018 which can be as large as 45 mm/day was a crucial factor of causing floods in the haor area during the Boro harvest time. Figure 12 demonstrates the temporal variation of daily temperature over the recording period (16 October 2017 – 16 June 2018) for the area. Daily temperature gradually decreases from 30 °C on 17 October 2017 to the lowest 12 °C on 8 January 2018 before starting to rise again. The temperature levels off at 25 °C between March 2018 and 20 May June 2018.

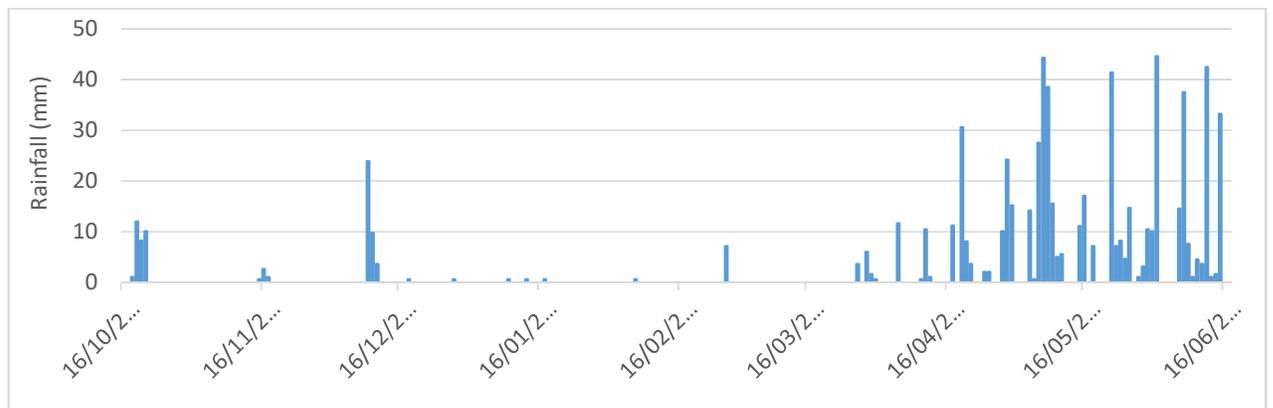


Figure 11. Time series of daily rainfall recorded with the portable weather station installed at the Agolpahaor site.

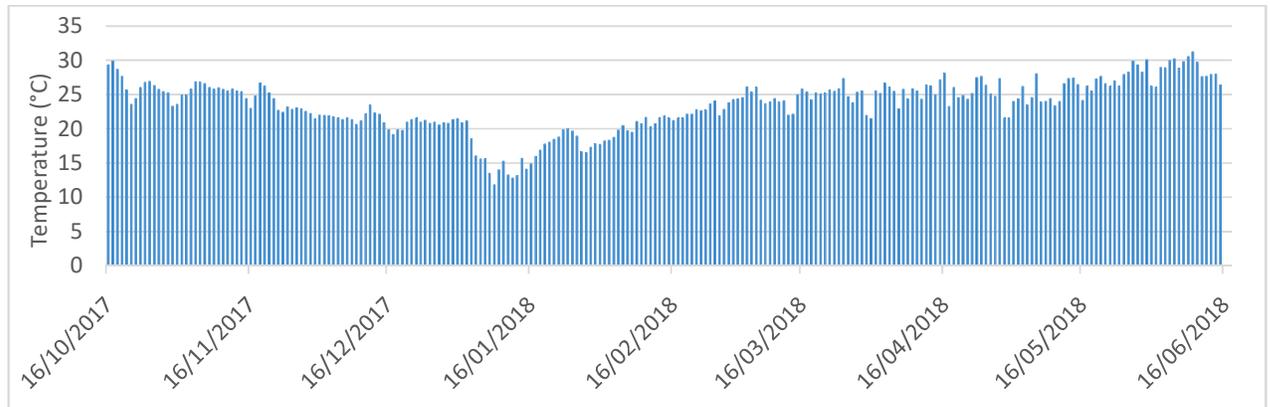


Figure 12. Time series of daily temperature recorded with the portable weather station installed at the Agolpahaor site.

The pattern of temporal variation in solar radiation seems nearly similar to that of temperature (Figure 13). This similarity is expected because the temperature of a place is directly related to the solar radiation therein. The highest wind speed (10.5 m/s) was recorded on 21<sup>st</sup> October 2017 and from late November to February wind speed in fact drops below 1 m/s except the one (5 m/s) of 12<sup>th</sup> December 2017. In October when the haor remains inundated a high relative humidity is observed (> 80%) followed by a gradual decreasing onwards (Figure 15).

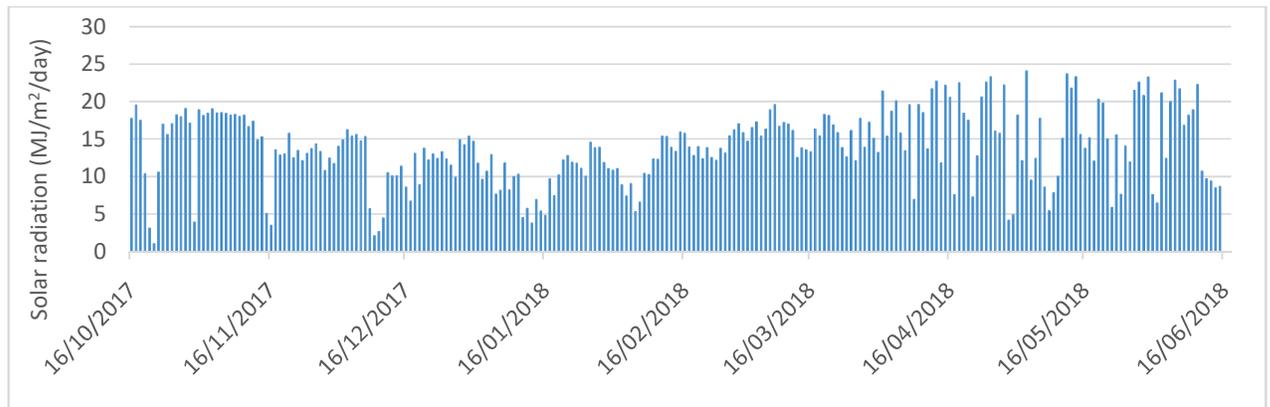


Figure 13. Time series of daily solar radiation recorded with the portable weather station installed at the Agolpahaor site.

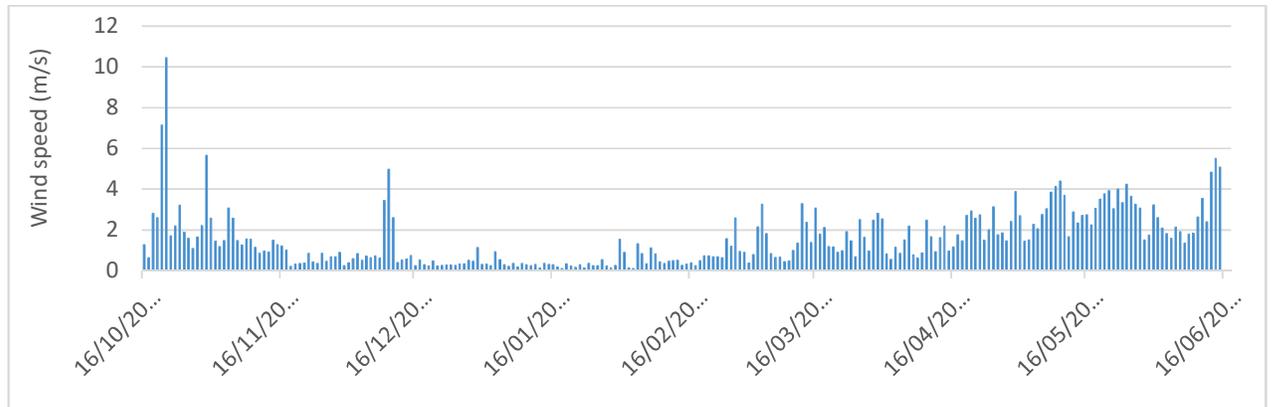


Figure 14. Time series of wind speed recorded with the portable weather station installed at the Agolpahaor site.

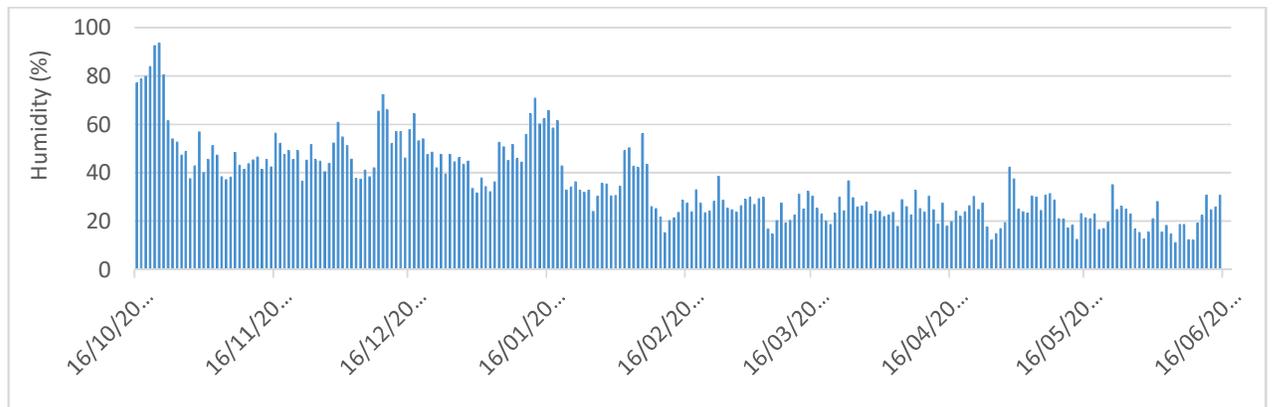


Figure 15. Time series of daily humidity recorded with the portable weather station installed at the Agolpahaor site.

### 11.2 Comparison of field surveyed and satellite derived topographic map of Agolpahaor

The surveyed topographic map of the haor is contrasted with the corresponding satellite derived HydroSHED and AW3D maps. From the field surveyed map, elevation of the haor varies between 0.01 m below mean sea level (msl) to 7 m above msl whereas HydroSHED and AW3D DEM data respectively give this range as of 0–10 m and -17–65 m with respect to msl. Undoubtedly, high resolution AW3D DEM data (30 m× 30 m grid size) greatly differs from the corresponding surveyed data in depicting the topography of the haor. This disparity is almost 10 times the surveyed DEM data. We presumed that AW3D has this systematic error for this region and therefore redefined the DEM by dividing each grid elevation by 10 using raster calculator in ArcGIS platform. Figure 16 illustrates the topographic map of the haor derived from survey data, HydrSHED and AW3D DEM

data. None of the satellite data (Figure 16b & c) cannot appropriately represents the hypsographic profile of the area as shown in the surveyed elevation map (Figure 16a). Presence of many dotting spurs in the HydroSHED data across the haor causes distorting the actual shape of the haor. The AW3D map results in an almost flat topography (-0.5–0.5 m) except some scattered islands. This comparison is further verified by comparing elevation profiles of the three DEM data along a transect stretching from west to east (Figure 17). The transect is drawn through some selected surveyed points so that the corresponding elevation profile can be thought as a measured profile. The aforementioned shortcomings in AW3D data is clearly visible whereas HydroSHED DEM consistently overestimates the surveyed profile with some spurs. With these findings, it is suggested that the two satellite DEM data cannot substitute the necessity of field surveyed DEM for the regional haors.

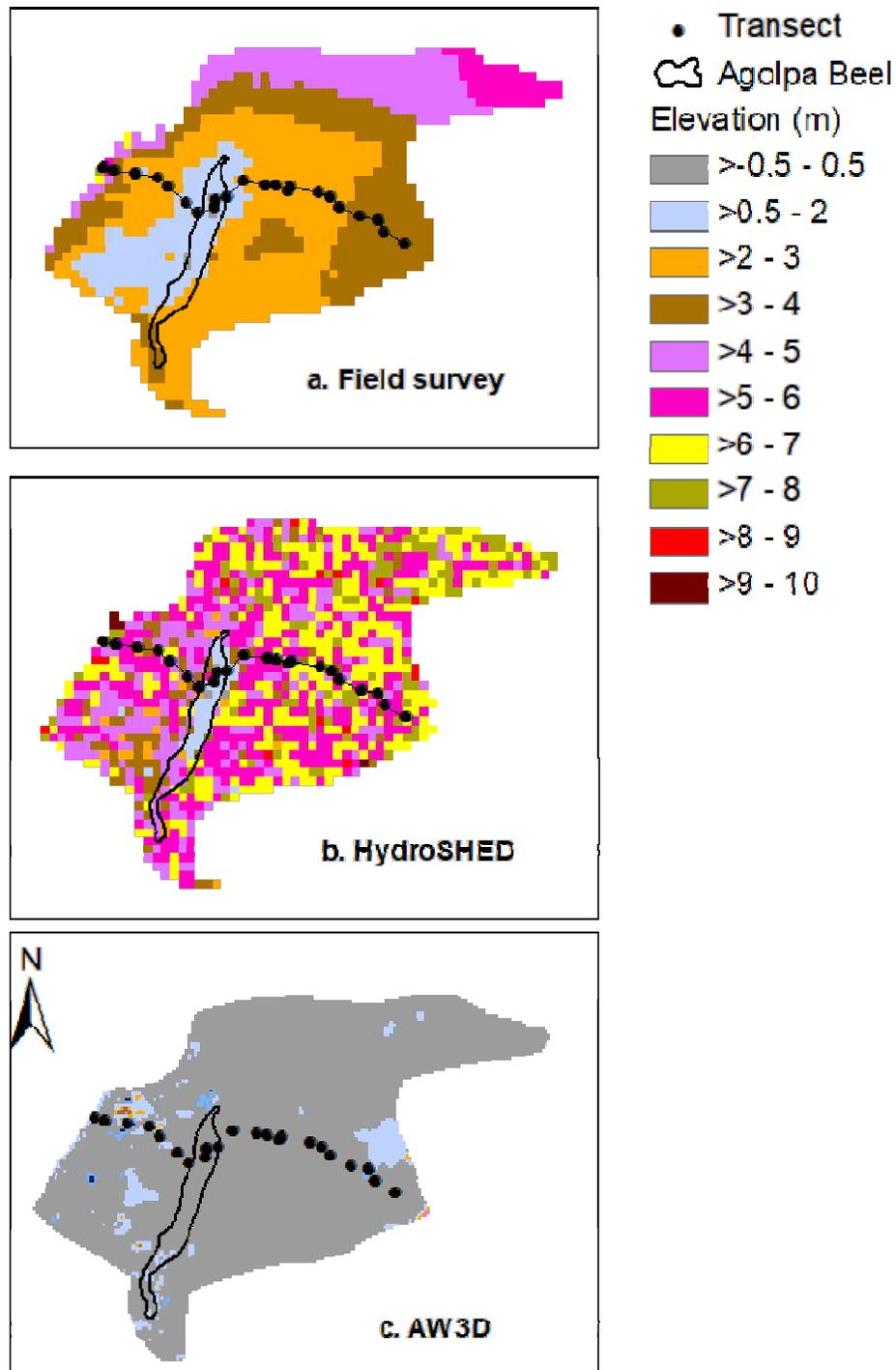


Figure 16. The topographic map of the Agolpahaor generated from HydroSHED, AW3D and surveyed DEM data.

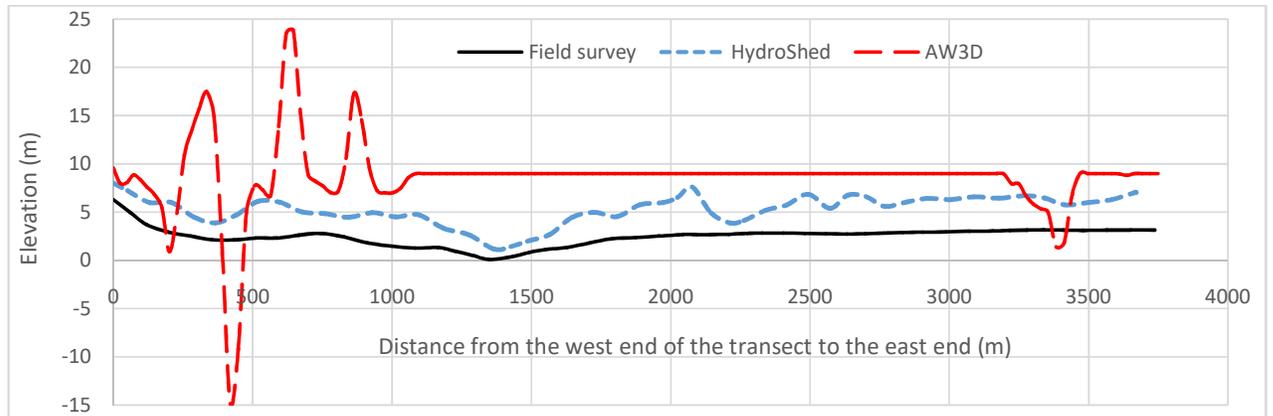


Figure 17. Elevation profile along the transect drawn across the haor (see Figure 16).

### 11.3 Model calibration results and predictive ability of the model to explain flash floods within the haor

The calibrated haor geometric model (Equations 1 and 2) is found to be quite competent to resemble the measured volume-area-depth relationship curve of the haor (Figure 18). At higher elevations the model slightly underestimates surface area and volume. Overall, higher values of estimated coefficient of determination in both cases statistically confirm the superiority of the model (Figure 19).

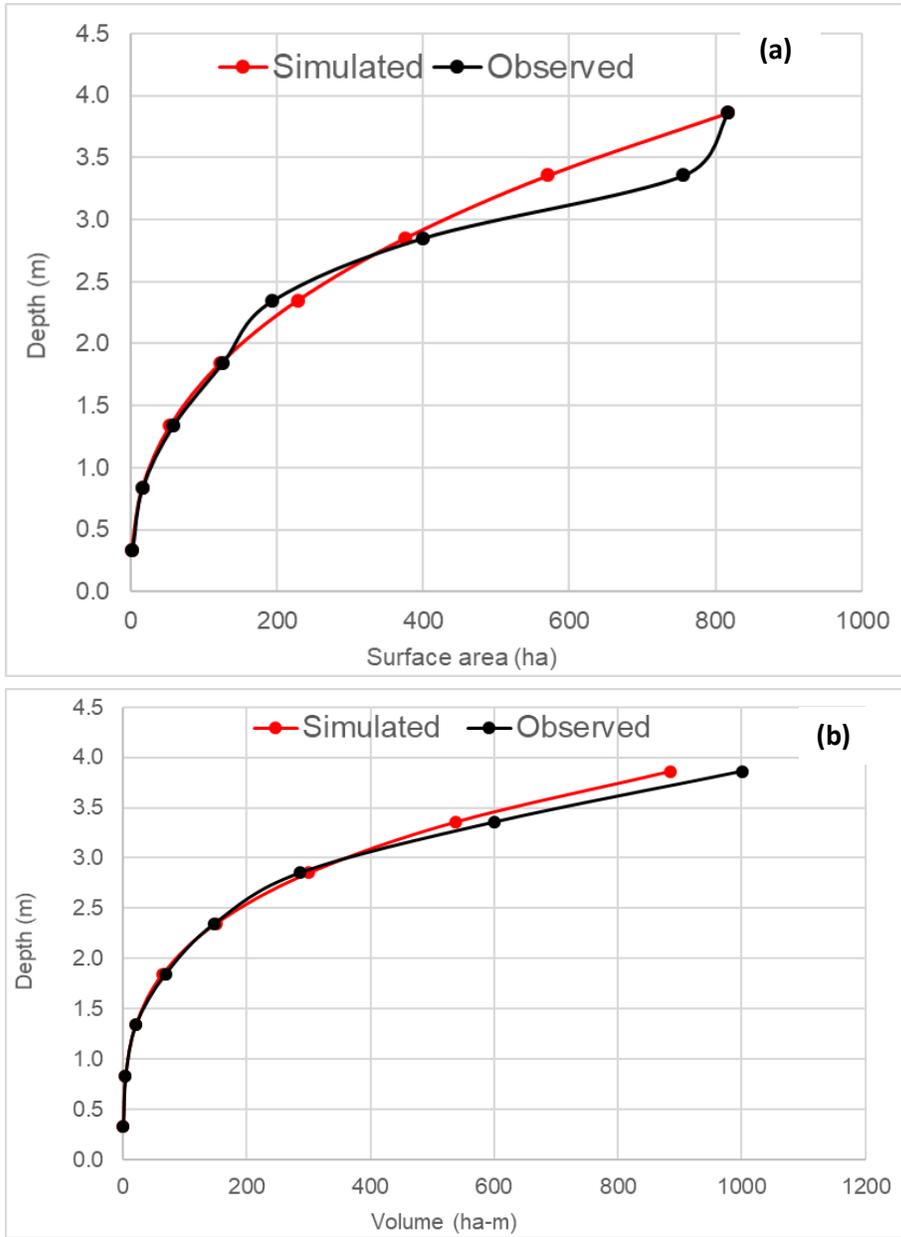


Figure 18. Comparison of simulated and measured (or observed) volume-area-depth relationship curves of the Agolpahaor. Depth is measured from the bed of the haor.

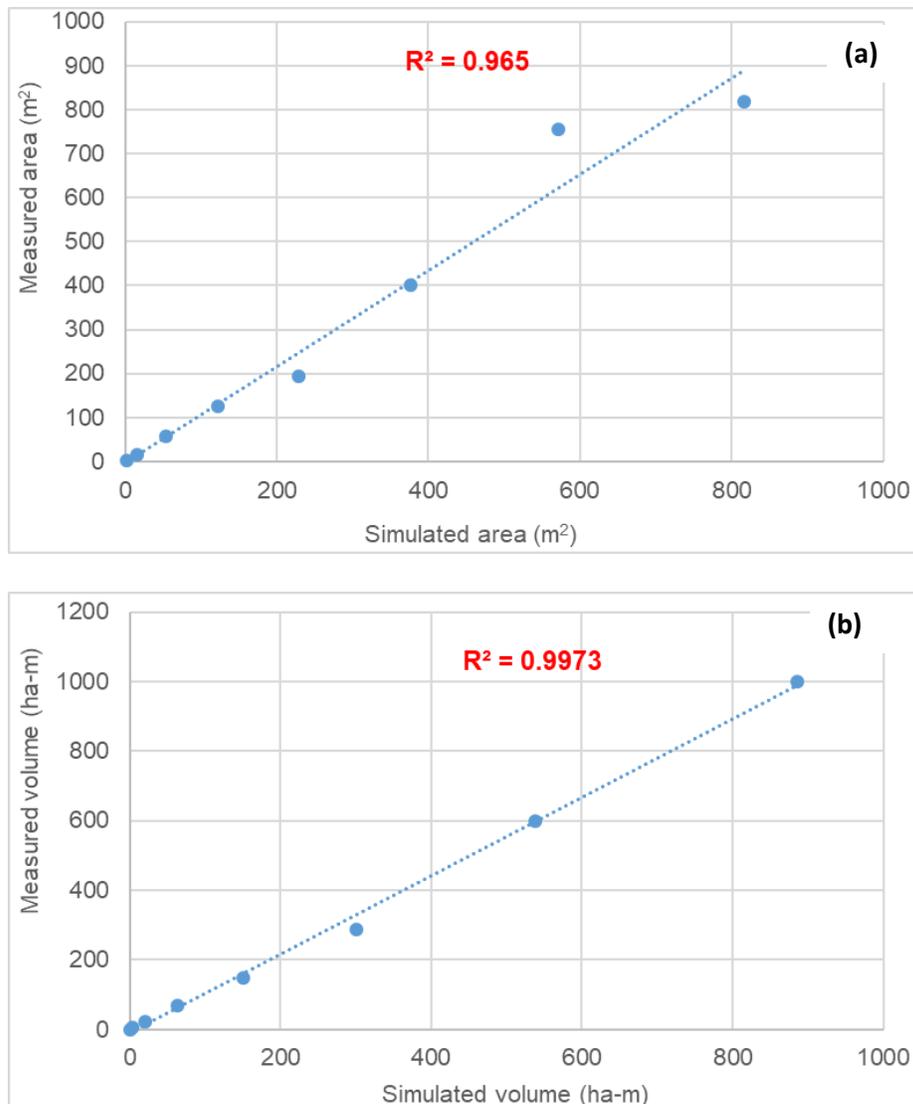


Figure 19. The degree of linear agreement between simulated and measured volume-area-depth relationships of the Agolpahaor.

The performance of the calibrated SWATrw model is evaluated statistically and graphically. For the optimized/calibrated parameter set (Table 3), the corresponding values of NSE, Bias and  $\epsilon$  are respectively 0.89, 0.02 and 0.13 which indicates the reliability of the model. Simulated water depths in the Agolpa haor are shown in Figure 20 alongside with the corresponding measured/observed water depths during the modelling period. As can be seen from the graphical presentation, the SWATrw model of the Agolpahaor reasonably mimics observed water depths, particularly those lie between mid November 2017 and 12 May 2018. The sudden drop of measured water depth at the beginning and rise at the end of the simulation period cannot be

resembled as well as is for the middle period. During recession time, the haor loses water due to natural surface drainage to the adjacent Dhanur River, seepage through the haor bed, and evaporation. The sharp fall in haor water depth happened arguably for its accelerated drainage causing by the faster receding Dhanu River. If we look at the temporal dynamics of Dhanu River's water levels (Figure 20) it is clear that the pattern of water levels in both the haor and river is same meaning a strong influence of the river on the haor's hydrology when surficial hydraulic connectivity prevails between them. The gradual underestimation of haor water depths after 12 May 2018 again can be linked not to accurately simulate sudden influx from rising Dhanu River.

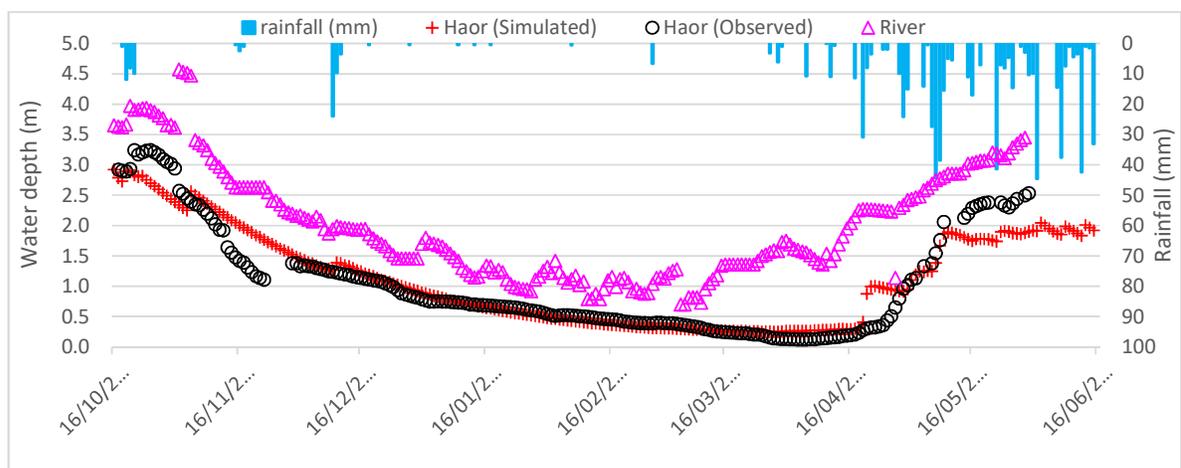


Figure 20. Comparison of simulated and measured (or observed) water depths.

#### 11.4 Water management strategy

In the Agolpahaor and its surrounding areas, usually Boro planting begins at some point between mid December and mid January. This year, however, farmers of the region could not plant their seedlings until 20 January 2018 due to labour shortage and intense cold. With the developed SWATrw model, this study first explores the hydrological dynamics of the haor and then draws some specific water management strategies that can reduce the risk of early flash floods. As observed in the site, although the adjacent Dhanu River started to spill after 12<sup>th</sup> May 2018, local rainfall within the haor catchment triggered inundating the nearly ripen Boro rice 21 days ahead of river spilling (19 April 2018) at the lower part of the haor. Measured inundated area as obtained by translating the corresponding measured water depth by the haor's geometric model was found to be 168 ha (16% of total haor area) on 13<sup>th</sup> May 2018 (Figure 22) when river water begins entering

the haor and this rose to 280 ha (27% of total area) on 30<sup>th</sup> May 2018 m (Figure 21). In contrast to measured inundations, simulated inundated areas are progressively smaller onwards the river spilling over its bank.

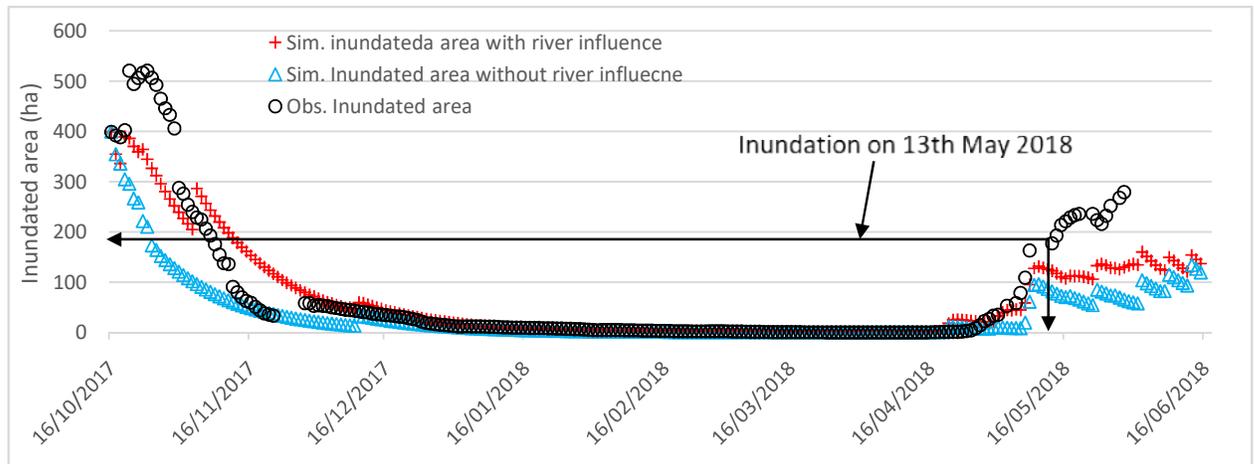


Figure 21. Comparison of simulated and measured (or observed) volume-area-depth relationship curves of the Agolpahaor. Depth is measured from the bed of the haor.



Figure 22. The Field Assistant with local day labourers salvaging inundated nearly ripen Boro rice due to local rainfall induced early floods in the Agolpahaor on 13<sup>th</sup> May 2018.

We calculated values of inflows entering the haor from the Dhanu River using a weir formula based on recorded water heads above the weir's crest. We suspect these estimates were not as accurate as actual values. Nonetheless, this research work reveals that damage of Boro rice in the Agolpahaor is due to local rainfall induced early floods rather than river overflowing which is a general perception of many experts in the country. Therefore, this study argues that only dyking of haor and/or adjacent river's bank may not adequately protect Boro rice from being damaged by early floods rather necessary attentions are to be paid to minimize local rainfall induced flooding in haor areas.

Although this year Boro rice in the haor region narrowly escapes river induced flash floods, this region remains at high risk of flooding as frequent early floods, mainly originating from flashy river, have been observed here in the past years. Installation and maintenance of sluice gates at the mouth of connecting channels and their timely operation can potentially reduce the vulnerability of Boro rice to early flash floods. Nor does a workable sluice gate prevent riverine flood water from entering the haor, it can be useful to drain off local rainfall induced flood water in a haor if water level in the adjacent river is lower than that of the haor. Harvesting of Boro rice grown in the lower part of the haor is generally delayed by 15-25 days due to their late planting since it takes longer time to dry the lower lands compared to upper lands. For this reason, rice in the lower part is more vulnerable to floods whatever its origin i.e. local rainfall or overflowing rivers. Amid this situation, improving existing land management could be an affordable practice in lessening the existing flooding risk of Boro rice. We found that elevating the height of existing rice field bunds can abstract a considerable amount of rainfall water thereby producing less runoff which otherwise can cause floods at least in the lower part of the haor. Usually these field bunds are not properly managed by farmers after receding flood water. In order to quantify this potential, we ran the developed model for increased land resistance runoff or decreased surface runoff coefficient. Raising bund height would surely decrease the runoff coefficient of existing agricultural lands. This is accomplished by decreasing curve number (CN) of the model. From Table 3, calibrated value of CN is 86.96. Therefore, we ran the model separately for CN values 70 and 50, respectively indicating moderately higher and extremely higher field bunds. It is clearly seen from Figure 23 that both inflows to the haor and inundated areas considerably decrease for raising field bunds. For example, existing 129 ha inundated area shrinks to 70 ha for moderately higher bund scenario on 13<sup>th</sup> May

2018 which means raising field bunds can reduce local rainfall induced inundated areas by 46%. For the extremely higher bund scenario, simulated inundated areas slightly lower than that of the moderately scenario.

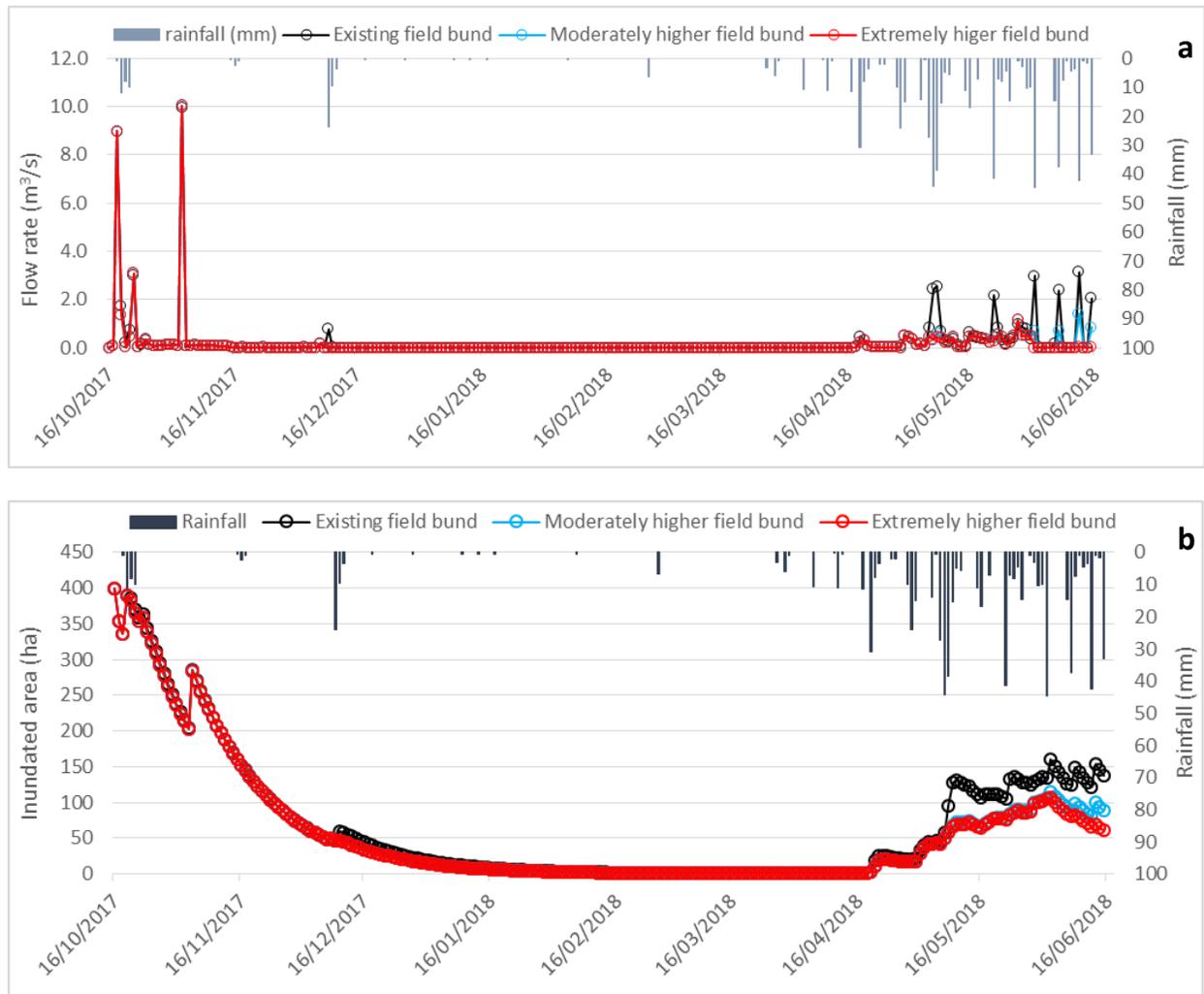


Figure 23. Simulated reductions in inflows (a) to the haor and inundated areas (b) of the haor after raising field bunds.

### 11.5 Climate change and haor early flash floods

Figure 24 demonstrates mean daily rainfall projected by each of the five GCMs for the future period 2031–2050. Rather than showing results for 12 calendar months, we are presenting climate change results for only simulation time window (October–June). Disagreements among the GCMs in projecting future daily rainfall are clearly evident from the figure. Therefore, ensemble mean of the

five GCMs' rainfall is used to force the model in order to generate future hydrological responses of the haor. Although total rainfall within the time period is projected to increase by 42 mm over the baseline 795 mm, no consistent pattern in ensemble mean rainfall is noticed (Figure 24). Unlike rainfall, a consistent increment in daily ensemble mean temperature (0.4–2.7 °C) is predicted for the future period (Figure 25). All the GCMs are in agreement on increasing future temperature although they differ in magnitude.

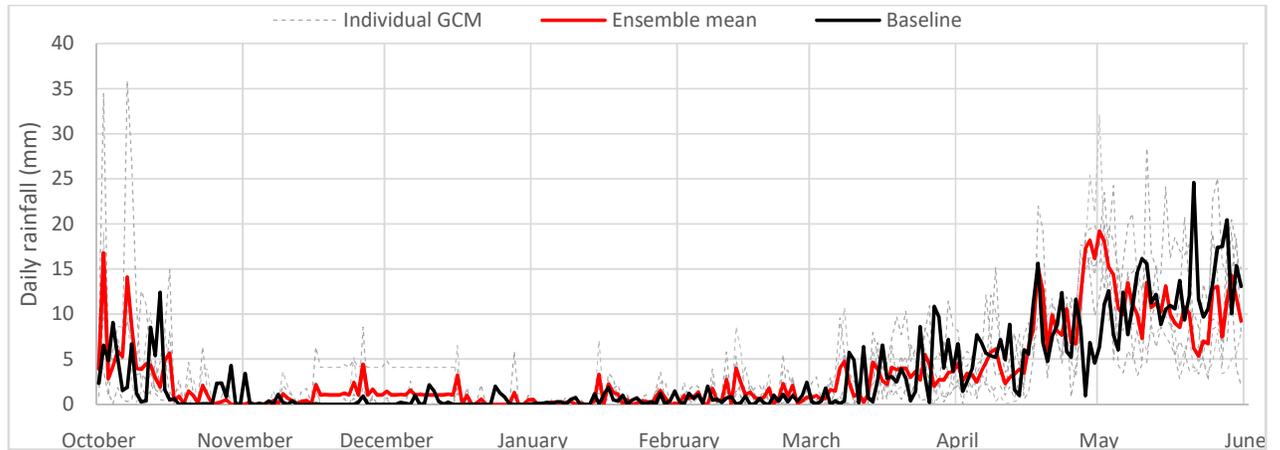


Figure 24. Comparative demonstration of baseline (1991–2010) and projected (2031–2050) mean daily rainfall. Ensemble mean rainfall was generated by averaging daily rainfall of 5 GCMs.

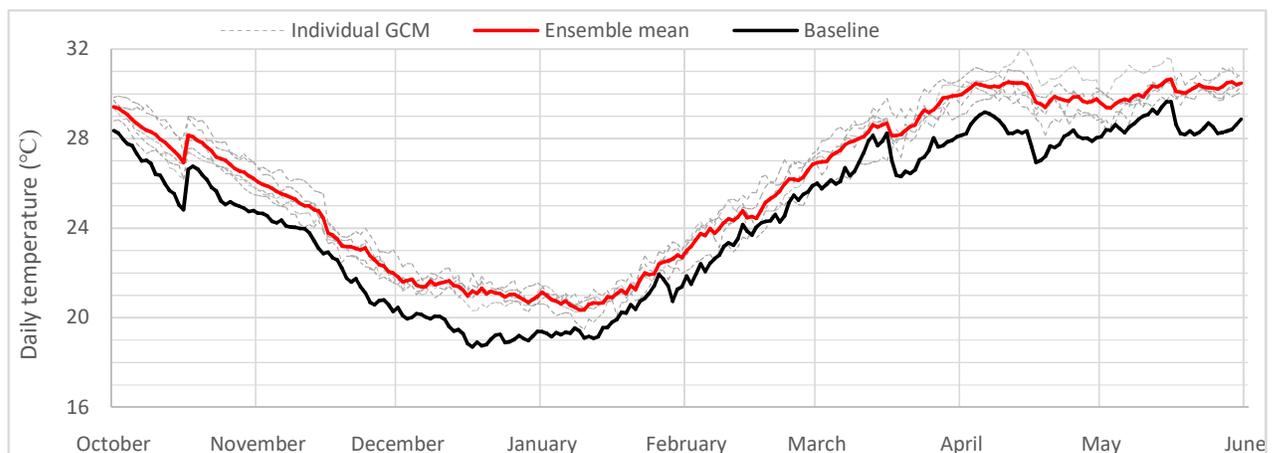


Figure 25. Comparative demonstration of baseline (1991–2010) and projected (2031–2050) mean daily temperature. Ensemble mean rainfall was generated by averaging daily temperature of 5 GCMs.

The model was forced with the above projected rainfall and temperature for the period 2031–2050 to simulate corresponding inundated areas of the Agolpahaor. Since influx from the Dhanu River can noticeably affect inundation extent of the haor, three scenarios of influx were considered while simulating future responses: (i) without any change in influx i.e. same baseline river flow will exist in the future period (ii) 15% increase in influx and (iii) 15% decrease in influx. For the first scenario, the haor is projected to be experiencing higher inundation during May–June in the future period by a maximum increment of 24 ha (22%) which can further rise to 31% if 15% increase in influx from the adjacent Dhanu River is amalgamated with projected increasing rainfall (Figure 26a & b). However, the extended inundation due to increased rainfall in the future period is diminished by lower influx (-15%) scenario (Figure 26c).

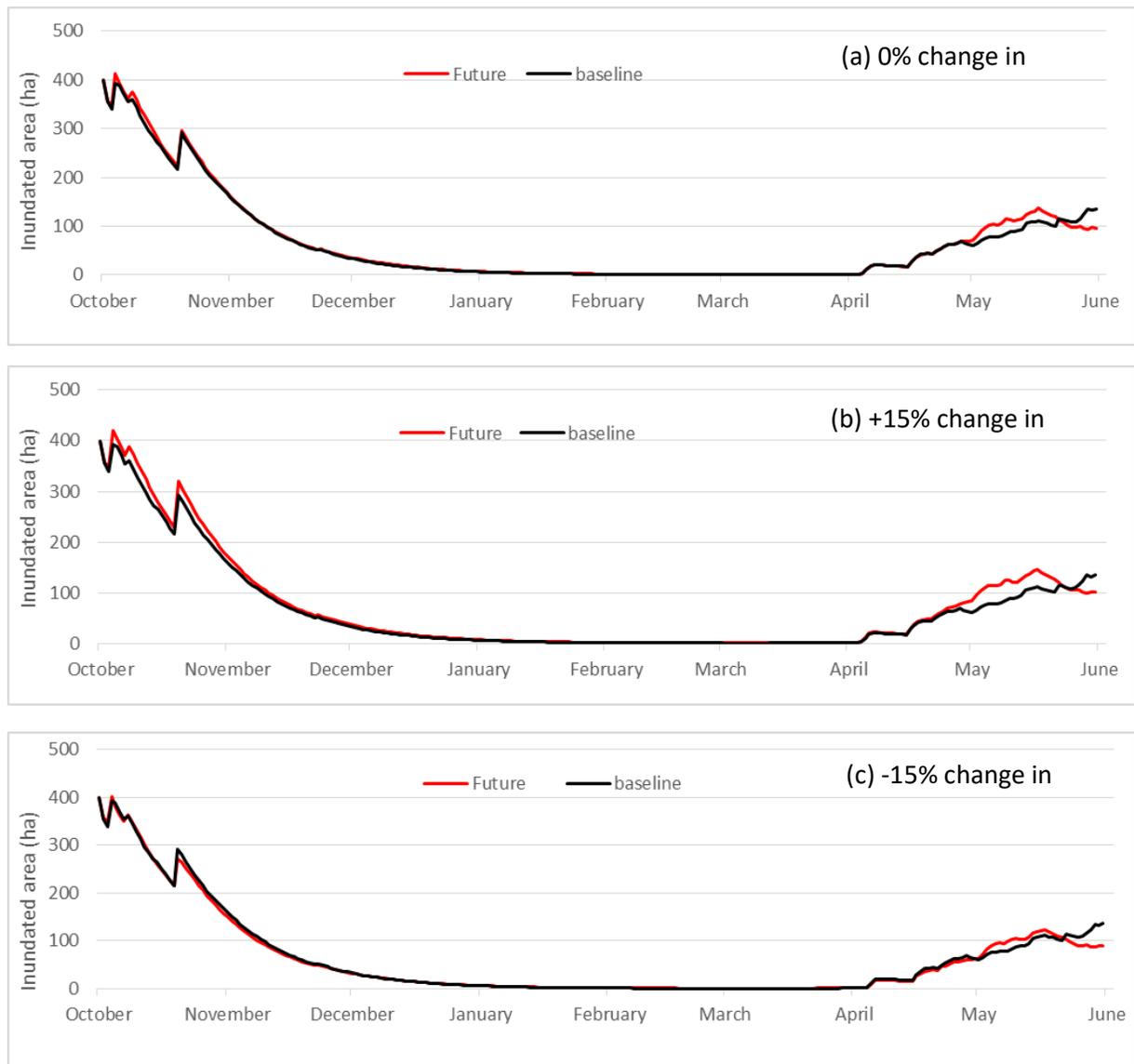


Figure 26. Comparative demonstration of baseline (1991–2010) and future projected (2031–2050) haor inundated area considering three different scenarios of influx from the Dhanu River.

## 12. Research highlight/findings:

- (i) Analysis of recorded hydro-meteorological data of the studied haor site reveals that heavy rainfall within haor catchment in April and May inundates lower Boro rice lands (16% of the haor area) while water level in the adjacent Dhanu river remains quite below the river bank. This indicates that the lower part of the haor is potentially susceptible to local rainfall induced early floods rather than river driven flash flood.

- (ii) A simple, quick and cost-effective boating topographic survey method was developed and applied in order to produce elevation map of the Agolpahaor. It was found that HydroSHED and AW3D satellite DEM data cannot be used as a substitute of field surveyed elevation map for haor areas.
- (iii) The developed SWATrw model of the Agolpahaoris able to successfully simulate hydrological dynamics of the haor.
- (iv) This study reveals that raising field bunds can drastically control local rainfall induced early floods in the haor. However, without proper functioning of sluice gates, dyking alone was found to be useless in preventing early floods in the haor.
- (v) The model predicts 22–31% increase in haor inundation for the future 2031–2050 period compared to the baseline period 1990-2010. Therefore, the projected future climate will exacerbate the existing flood challenges in haor areas which necessitates more attention to the haor water management.

## B. Implementation Position

### 1. Procurement:

Description of equipment and capital items	PP Target		Achievement		Remarks
	Phy (#)	Fin (Tk)	Phy (#)	Fin (Tk)	
(a) Office equipment					
*High speed workstation desktop computer	1	205,000	1	204,800	
*Laptop	1	60,000	1	59,600	
(b) Lab &field equipment					
*Automatic water level datalogger	6	468,000	6	466,200	
(c) Other capital items					
*Digital Elevation Model (DEM) data	21 km <sup>2</sup>	147,000	21 km <sup>2</sup>	146,580	

## 2. Establishment/renovation facilities:

\*\*\*\*\* Not applicable

Description of facilities	Newly established		Upgraded/refurbished		Remarks
	PP Target	Achievement	PP Target	Achievement	

## 3. Training/study tour/ seminar/workshop/conference organized:

\*\*\*\*\* Not applicable

Description	Number of participant			Duration (Days/weeks/ months)	Remarks
	Male	Female	Total		
(a) Training					
(b) Workshop					

## C. Financial and physical progress

**Fig in Tk**

Items of expenditure/activities	Total approved budget	Fund received	Actual expenditure	Balance/ unspent	Physical progress (%)	Reasons for deviation
A. Contractual staff salary	594330	554330	554330	0	100	
B. Field research/lab expenses and supplies	611000	618000	618000	0	100	
C. Operating expenses	130000	116743	116743	0	100	
D. Vehicle hire and fuel, oil & maintenance	50000	50000	50000	0	100	
E. Training/workshop/seminar etc.	-	-	-	-	-	
F. Publications and printing	100000	77464	40000	37464	100	
G. Miscellaneous	100000	79105	79105	0	100	
H. Capital expenses	412000	410980	410980	0	100	

## D. Achievement of Sub-project by objectives: (Tangible form)

Specific objectives of the sub-project	Major technical activities performed in respect of the set objectives	Output (i.e. product obtained, visible, measurable)	Outcome (short term effect of the research)
(i) Instrumenting some representative haors for monitoring real time hydro-meteorological data	# installation of water level data loggers, portable weather station, evaporation pan and staff gauges # topographic survey of the experimental haor	# recorded time series hydro-meteorological data # digital elevation model data or topographic map of the area	
(ii) Developing a distributed physics-based model for simulating haor hydrology	# delineation of the haor topography # calibration and validation of the SWATrw model	# digital elevation of the haor # the developed SWATrw model of the Agolpahaor	
(iii) Developing haor water management scenarios for different climate change induced hydrological alternations	# run the developed model to understand the hydrological dynamics of the haor # run the model to obtain best water management strategy for the haor # processing Global Climate Model (GCM) data for the area # simulate hydrological consequences of the haor due to climate change	# a best water management strategy has been identified # processed future climate data	

## E. Materials Development/Publication made under the Sub-project:

Publication	Number of publication		Remarks (e.g. paper title, name of journal, conference name, etc.)
	Under preparation	Completed and published	
Technology bulletin/ booklet/leaflet/flyer etc.	1		Abstract submitted in BAURES annual workshop proceedings
Journal publication	1		A manuscript is being prepared to be published with Elsevier's Wetland journal
Information development			
Other publications, if any			

## F. Technology/Knowledge generation/Policy Support (as applied):

### i. Generation of technology (Commodity & Non-commodity)

- \* A distributed SWATrw hydrological model of the experimental haor is developed and can be used for other similar haors
- \* Development of the boating topographic survey method for haor areas
- \* Introducing *elevated field bund* land management strategy for reducing local rainfall induced early floods

### ii. Generation of new knowledge that help in developing more technology in future

- \* Introducing the implications of distributed hydrological models in developing better water management strategies for haor areas so as to avert the risk of crop damage due to early floods.

### iii. Technology transferred that help increased agricultural productivity and farmers' income

Not applicable

### iv. Policy Support

Not applicable

## G. Information regarding Desk and Field Monitoring

### i) Desk Monitoring [description & output of consultation meeting, monitoring workshops/seminars etc.):

Not applicable

### ii) Field Monitoring (time & No. of visit, Team visit and output):

\* the experimental haor site was visited periodically in order to monitor the field works and the deployed instruments

**I. Lesson Learned/Challenges (if any)**

- i) this research showed that local rainfall, instead of river spills, induced early floods can be a great threat to haorBoro rice which is often not overlooked
- ii) elevating field bunds can potentially reduce the existing risk of early floods in haor areas
- iii) the satellite DEM data used in this study was found to be incompetent in resembling the haor’s actual topography. The developed boating topographic survey technique is a simple, quick and inexpensive surveying method that can be employed for acquiring accurate DEM data of shallow inundated areas like haors.

**J. Challenges**

- \* the rough road communication to the haor was one of the major hurdles for this study
- \* some installed staff gauges were stolen
- \* not disbursing a part of the approved project fund
- \* since this was a one-year project we had no sufficient time series data to validate the model

Signature of the Principal Investigator

Date .....

Seal

Counter signature of the Head of the organization/authorized representative

Date .....

Seal

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