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Surface water modelling and water balance in the northwest region of Bangladesh

A project of the South Asia Sustainable Development Investment Portfolio (SDIP)

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Important disclaimer

Ethics

The activities reported herein have been conducted in accordance with CSIRO Social Science Human Research Ethics approval 030/17.

SDIP goals

This report designed and implemented by CSIRO contributes to the South Asia Sustainable Development Investment Portfolio and is supported by the Australian aid program. Further details on CSIRO SDIP projects are available from http://research.csiro.au/sdip.

SDIP's goal is increased water, food and energy security in South Asia to support climate resilient livelihoods and economic growth, benefiting the poor and vulnerable, particularly women and girls

Gender statement

Considerations of gender and social inclusion are embedded in all CSIRO SDIP projects. In this report we have assumed that improved understanding of the water balance in northwest Bangladesh is of benefit to all, regardless of gender and other social factors. Excluding gender analysis, however, can lead to 'gender blind' tools, findings and decisions that reinforce existing gender inequities. This gap should be borne in mind when interpreting this report, and any application of its findings will need to integrate gender-specific and other social considerations to ensure benefits are distributed.

EXECUTIVE SUMMARY

In this report, we describe the calibration of a conceptual lumped hydrological model (NAM) and a one-dimensional hydrodynamic model (MIKE 11) to assess surface water and groundwater balance in the 16 districts of northwest region of Bangladesh. Model inputs include rainfall, potential evapotranspiration (PET), irrigation demand, together with model parameters. The model was calibrated and validated using observed groundwater level (GWL) and actual evapotranspiration (ETa) data for the period 1985 to 2015. Future scenarios on surface water availability and GWL were investigated using the calibrated model under a range of climate and land management options.

Scenarios

We developed 8 scenarios:

- 5 scenarios on future climate
- one scenario on irrigation water source
- 2 scenarios on inflow condition

to assess their role in, and impact on, the water balance of the region. The future climate scenarios cover the range from high to low climate change rainfall projections and high to low PET projections. The impacts of different scenarios were evaluated in terms of changes in ETa, GWL and river flow compared to current condition.

Key findings

This study supports that GWL across the northwest region has declined over the period of 1985 to 2015. The declining groundwater trend is small in most districts except for Nawabganj and Rajshahi districts. Dinajpur, Naogaon and Pabna show a decreasing trend in the range of 30 to 35 mm/year – low compared to Nawabganj (203mm/year) and Rajshahi (76 mm/year), both of which are in the drier parts of the region, but higher than 11 other districts. Assuming a specific yield of 0.1 (i.e., 0.1 m water release for 1 m decline of the GWL) and an average decline of 30 mm/year, the study estimated that the decline in GWL could be up to 9 m in 30 years in the Dinajpur, Naogaon and Pabna districts.

Under the future climate, both rainfall and PET are expected to rise in the entire northwest region. This has positive consequences for the river flow and GWL. The positive impacts of high rainfall on GWL are much higher than the negative impacts of high PET under future climate. The declining rate of GWLs was projected to reduce under 3 of the climate change scenarios and increase under 2 of them. Overall, climate change is likely to slow down the rate of groundwater decline in the northwest region. Most importantly, the alarming trend in Nawabganj and Rajshahi could be reversed if rainfall occurs as projected for future climate scenarios. In wetter districts where current declining trends are small, the model scenario exploration suggests that GWLs will be less affected by management or climate change.

The increase in river water use lessens the declining groundwater trend across the northwest region. Across the 16 districts, the greatest improvements in GWLs are found for the Nawabganj and Rajshahi districts (77 and 11 mm/year respectively) where GWLs are currently declining at a higher rate (203 and 76 mm/year respectively). Therefore, using more surface water for irrigation could be a potential management option. This is feasible if inflow through the rivers increases, or if surface water storages are built and used to supply a proportion of irrigation water.

Findings of this study are consistent with companion studies, (i) District Water Balance and (ii) Groundwater Modelling, as well as earlier CSIRO work in Bangladesh.

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Abbreviations and terms

Abbreviation	Expansion
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
CCM	Crop-Coefficient Model
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DFAT	Department of Foreign Affairs and Trades
DHI	Danish Hydraulic Institute
DTW	Deep Tubewells
GCM	Global Climate Model
GWL	Groundwater level
HD	Hydrodynamic
HM	Hydrological Model
HTW	Hand Tubewells
IPCC	Intergovernmental Panel on Climate Change
IWM	Institute of Water Modelling
MSL	Mean Sea Level
NWRM	Northwest Regional Model
PET	Potential Evapotranspiration
RSM	Remote Sensing based Model
SDIP	Sustainable Development Investment Portfolio
SF	Scaling Factor
STW	Shallow Tubewells

Term	Description
ton	Equivalent to tonne, ie metric ton; 1,000 kg
NAM	Commercial software (DHI) for modelling rainfall-runoff
MIKE 11	Commercial software for modelling rivers and channels

1 INTRODUCTION

1.1 BACKGROUND

The northwest region is one of the major food hubs in Bangladesh and it has the largest irrigated agricultural production in the country (Mainuddin et al., 2014; Mainuddin et al., 2019; Mainuddin et al., 2020; Peña-Arancibia et al., 2020; Peña-Arancibia et al., 2021a). About 97% of the current irrigation supply comes from groundwater (Mainuddin et al., 2014; Mainuddin et al., 2019) and it is thought to be a major cause of declining groundwater level across the region (Ahmad et al., 2014; Dey et al., 2017; Hodgson et al., 2014; Kirby et al., 2014; Kirby et al., 2015; Mojid et al., 2019; Mustafa et al., 2017). The problem of declining groundwater is more pronounced in the Barind area and it has created a concern for the management authorities for the sustainable use of water resources in the region. However, it is not clear whether the declining groundwater levels in the region result from a decline in rainfall, or from excessive use of groundwater, or from a combination (Peña-Arancibia et al., 2020). Therefore, further studies were recommended to examine these issues and to provide greater certainty of the volumes of groundwater that could be sustainably used for irrigation.

The CSIRO project '*Sustaining groundwater irrigation for food security in the northwest region of Bangladesh*' under the Sustainable Development Investment Portfolio (SDIP) of the Australian Department of Foreign Affairs and Trade (DFAT) aimed to define the sustainable level of water (particularly groundwater) use for irrigation and their impacts on the socio-economy and livelihood of the farmers including women in the northwest region of Bangladesh. A key element of the project was to develop changes to water balances under a range of climate and management scenarios for the districts of northwest Bangladesh.

The study reported herein is one of a suite of studies conducted under the umbrella of SDIP Phase 2 to quantify the current trend in groundwater level and to explore potential options to improve the declining groundwater level. Companion studies describe district level water balance (Mainuddin et al., 2021), groundwater trend analysis (Hodgson et al., 2021; Mojid et al., 2019), rainfall-recharge dynamics (Mojid et al., 2021a) and groundwater modelling (Janardhanan et al., 2021), historical trends in land-use change and crop water requirements (Mojid et al., 2021b; Peña-Arancibia et al., 2020; Peña-Arancibia et al., 2021a; Peña-Arancibia et al., 2021b), the impacts and interactions between these on the socio-economic aspects around livelihoods and poverty, especially relating to gender-specific issues (Al-Amin et al., 2019; Rahman et al., 2020; Rahman et al., 2021). The surface water modelling project was undertaken to estimate the various water balance components and to assess the potential changes under future climate and various land management options.

1.2 OBJECTIVES

The main objectives of this study were to understand the water balance in the northwest region of Bangladesh and to investigate the impacts of climate and land use change on surface water and groundwater. The study aimed to achieve the following objectives:

- analyse the historical data of groundwater level, actual evapotranspiration (ETa) and the river flow to understand the surface water and groundwater interaction and its trends
- examine the impacts of climate change on rainfall and ET and subsequent changes in river flow and groundwater level
- investigate the water balance under future climate and land management scenarios.

2 STUDY AREA

2.1 CATCHMENTS

This study focused on the northwest region of Bangladesh which is bounded by the Jamuna (the name of Brahmaputra River in Bangladesh) River to the east, the Padma (Ganges) to the south, and India to the north and west (Figure 2.1). It consists of 16 administrative districts covering an approximate area of 32,600 km^2, spanning from 88°0'E to 89°50'E longitude and 23°45' N to 26°45'N latitude. Most of the northwest region is in the Jamuna River basin with a small proportion in the Ganges River basin.

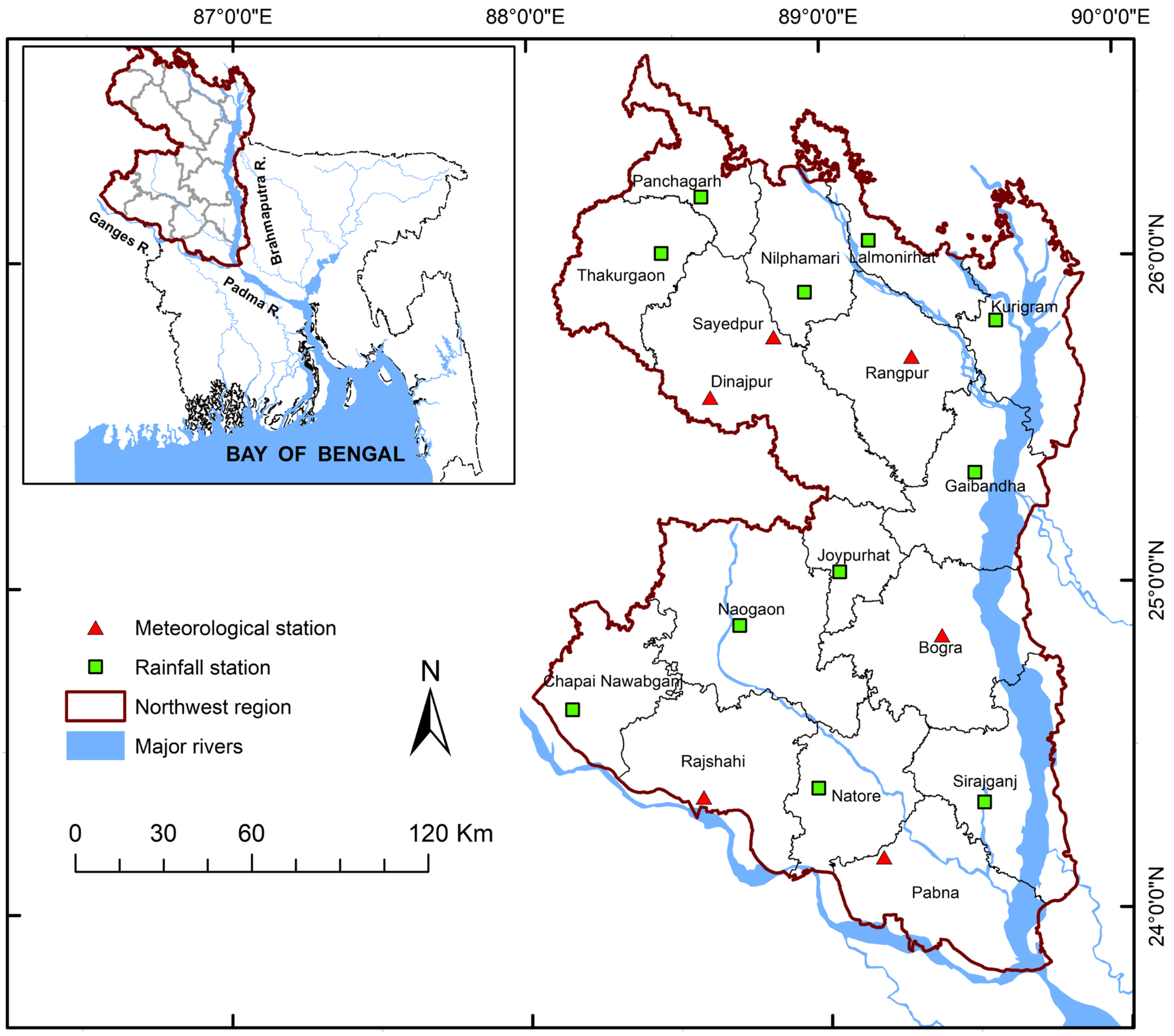

Figure 2.1 Study area map showing the 16 administrative districts, locations of meteorological stations and major rivers in the northwest region of Bangladesh

In the context of hydrological and hydrodynamic modelling studies, the territory of Bangladesh is covered using 6 regional models. The Northwest Region Model (NWRM) is the one of these which covers the 16 districts of the northwest region. The NWRM includes 51 regional rivers with a total length exceeding 2,800 km. An extensive area of depressions (locally known as Beels) exists in the south and central part of the region. This area is collectively called *Chalan Beel*. In the monsoon, the area acts as a huge flood retention reservoir. The main sources of inflow into the region are runoff from local rainfall, which sometimes can be very intense; and spilling from the large cross boundary rivers, particularly the Jamuna and Teesta. Overall topography of the northwest region is sloping from northwest to south-eastern direction with an altitude range of 90 m to less than 10 m above mean sea level (MSL). Based on topography, the northwest region is categorised into 3 sub-regions – the Upper sub-region consists of steep ground slope and highly permeable soil; the Middle sub-region is relatively flat with less permeable soil; and depressions and flood cells occupy most of the third southern Lower sub-region.

2.2 CLIMATE

There are 6 meteorological stations and 11 rainfall stations in the northwest region (Figure 2.1). The meteorological stations are monitored by the Bangladesh Meteorological Department (BMD) and rainfall stations monitored by the Bangladesh Water Development Board (BWDB). Daily rainfall and temperature data for 16 meteorological stations in the northwest region were obtained from the BMD and BWDB. These stations are spatially distributed across the region and there is at least one rainfall station in all 16 districts monitored either by the BMD or BWDB. Most of these stations have been operational since 1970. However, considering quality of measurement and continuity of records, only data from 1985 were used in characterisation of the observed temperature and rainfall. Observed data indicate that the temperature is increasing consistently throughout the region while rainfall shows an irregular trend on both increase and decrease (Karim et al., 2020; Peña-Arancibia et al., 2020). Overall, there is a decreasing trend in annual mean rainfall for the entire region (Mojid et al., 2019).

Annual mean rainfall for the 16 districts varies spatially ranging from 1,428 mm in Rajshahi to 2,543 mm in Kurigram with a mean of 1,895 mm (Figure 2.2). Monthly rainfall varies from just 4 mm in December (Joypurhat) to 585 mm in July (Panchagar) (Figure 2.3). About 93.6% rainfall occurs in the wet season (May to October) with 74.3% during the months of June to September. Dry season (November to April) rainfall is very small (~7%) with the minimum in December–January (less than 1%).

The annual potential evapotranspiration varies much less than the rainfall, both from year to year and from district to district. The average annual PET from 1985 to 2015 varied from 1,219 mm (minimum 1,106, maximum 1,318) in Thakurgaon district to 1,362 mm (minimum 1,183, maximum 1,613) in Pabna (Figure 2.2). Monthly mean PET across the region varies between 59 mm per month in January in Dinajpur to 161 mm in April in Pabna (Figure 2.3).

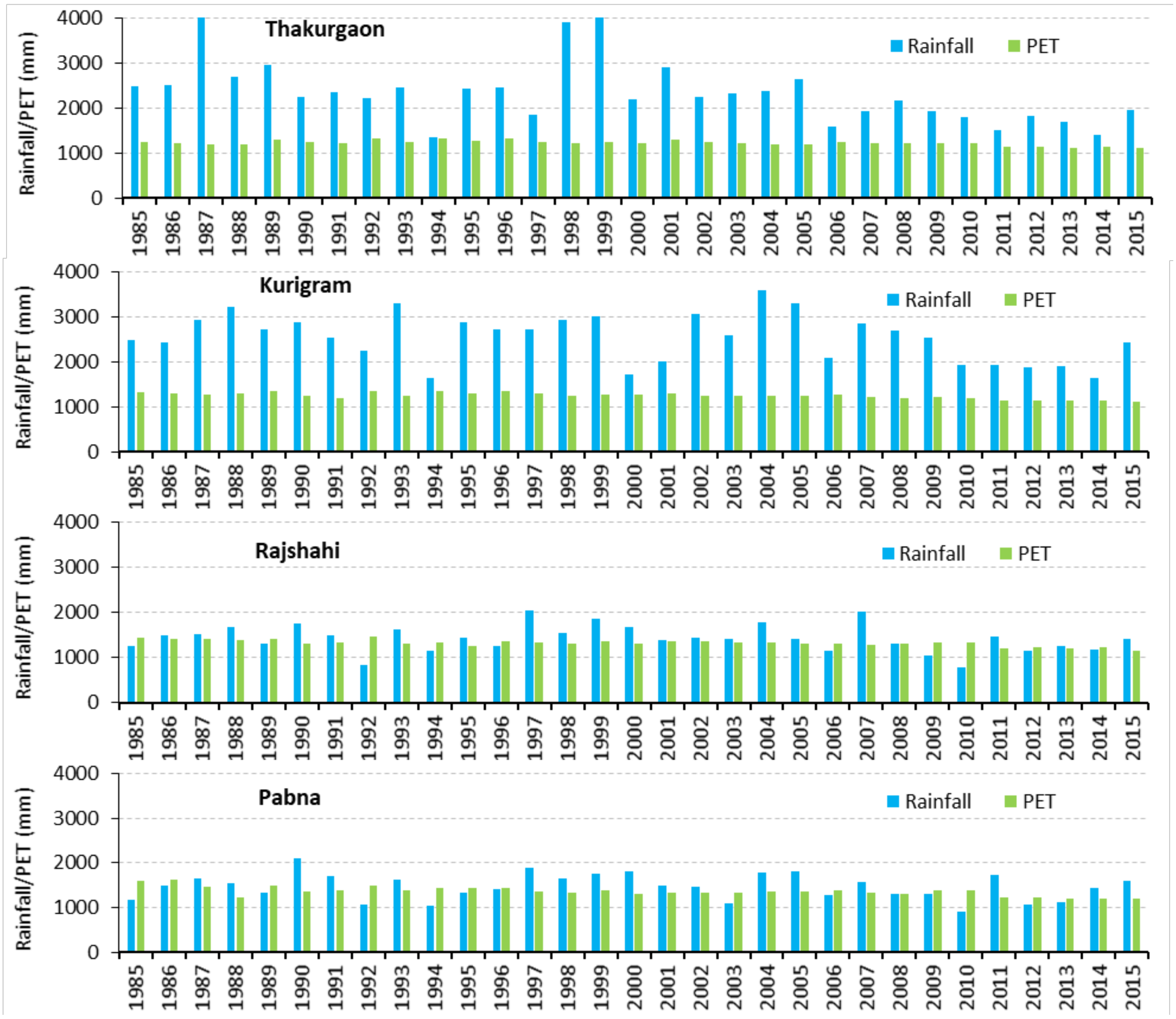

Figure 2.2 Mean annual rainfall and PET in the northwest region of Bangladesh based on data from 1985 to 2015) (refer to Figure 2.1 for locations)

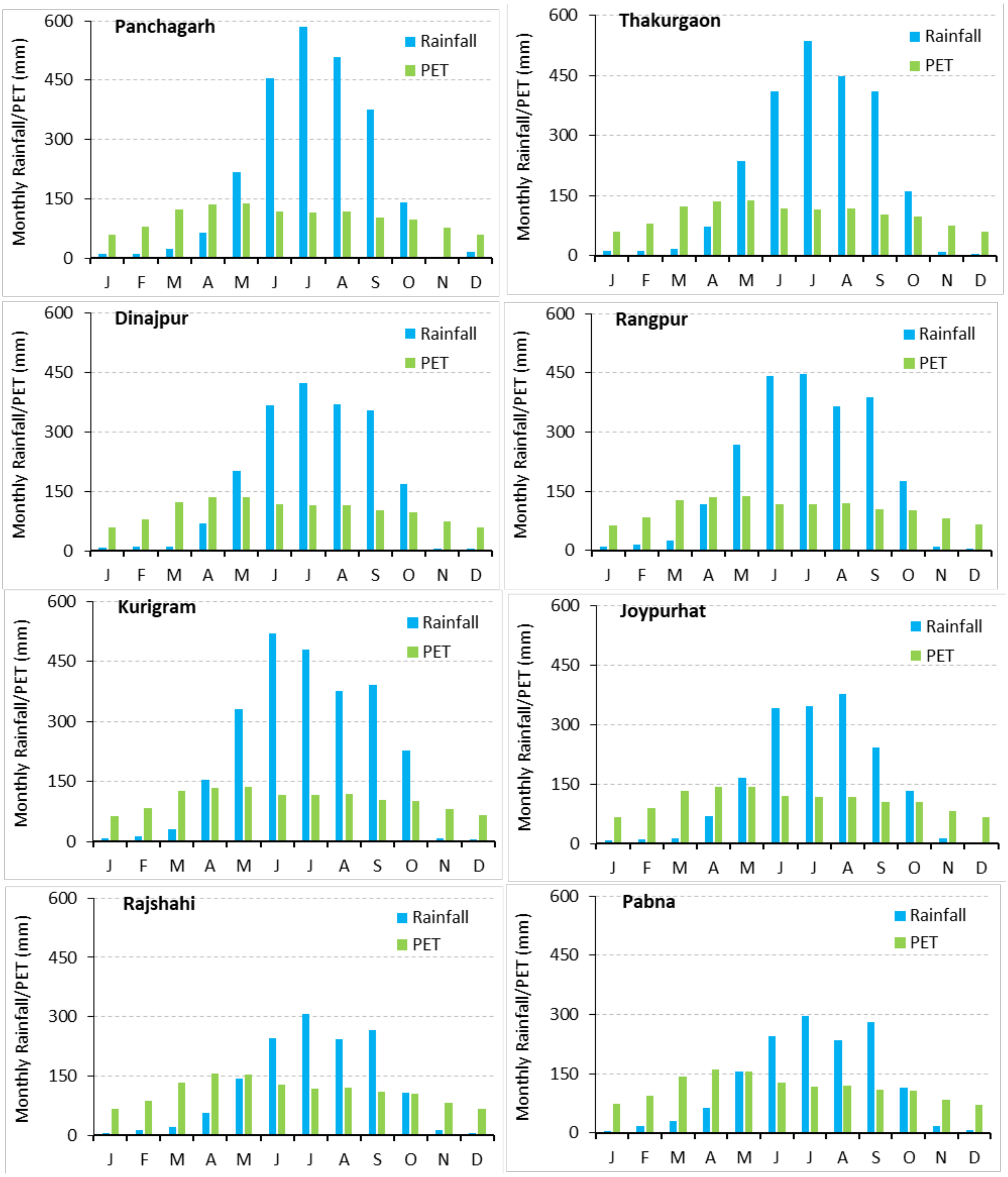

Figure 2.3 Monthly mean rainfall and PET at selected stations (based on data from 1985 to 2015) in the northwest region of Bangladesh (refer to Figure 2.1 for locations

2.3 GROUNDWATER USE FOR AGRICULTURE

The northwest region has the largest areas of cropping in Bangladesh, and supplies about 35% (6.6 million tons) of the nation's irrigated dry season rice (Boro rice) and more than 60% (2.4 million tons) of wheat and maize (BBS, 2018; Mainuddin et al., 2019). During the last few decades, there has been a large increase in the area planted to Boro rice (dry season crop) and a decrease of Aus rice while the area of Aman rice (main wet season) has remained steady (Mainuddin et al., 2020). The areas of many other dry season crops have also increased due to crop intensification, including potatoes, maize, wheat and pulses (Mainuddin et al., 2019).

Groundwater is the main source of water for irrigated agriculture in the northwest region of Bangladesh. About 97% of irrigation water comes from groundwater, which is extracted mainly by shallow tubewells (STW) and deep tubewells (DTW), in addition to some small-capacity pumping technologies, such as hand pumps, popularly known as hand tubewells (HTWs), rower pumps, and treadle pumps (Mainuddin et al., 2019; Mainuddin et al., 2020). There are now 1.77 million irrigation pumps in the country, of which 1.56 million are STWs (Mojid et al., 2019). Most parts of the northwest region of the country are flood-free zones and the main source of groundwater recharge is rainfall, which (rainfall) is also the lowest in this region. Moreover, the expanding presence of plough pans due to the increasing practice of rice cultivation (Neumann et al., 2009), and the thick sticky clay surface (6.1 to 21.3 m) of the Barind Tract act as aquitards and hinder groundwater recharge by increasing surface runoff. As a result, groundwater use in the Barind area has exceeded recharge and groundwater levels have been successively falling over the years, with increasing withdrawal for irrigation (CSIRO et al., 2014; Mojid et al., 2019).

3 METHODS

The study was conducted using a combination of a rainfall-runoff model (NAM) and a hydrodynamic model (MIKE 11). The NAM model was used to estimate the subcatchment scale runoff from rainfall and the MIKE 11 model used to estimate the river flow by combining inflow from cross-boundary rivers and locally generated runoff. In this study, NAM model was executed separately, and the outputs were added to the MIKE 11 model as a local water source (point source as well as distributed source).

3.1 HYDROLOGICAL MODELLING USING NAM

3.1.1 INTRODUCTION

NAM rainfall-runoff model is a physically based lumped hydrological model (DHI, 2008). The model forms part of the MIKE 11 River modelling system for simulation of rainfall-runoff processes in subcatchments (DHI, 2017). The model operates by continuously accounting for the moisture content in 3 different and mutually interrelated storages (e.g., surface storage, lower or root zone storage, groundwater storage) and produces runoff in the form of overland flow, interflow and baseflow. As the model is lumped, it treats subcatchments as single units – therefore parameters and variables represent average values for the entire subcatchment. The model allows treatment of man-made interventions in the hydrological cycle such as irrigation and groundwater pumping. In addition to catchment runoff, the model produces several other water balance components such as actual evapotranspiration, soil moisture content, groundwater recharge and groundwater levels.

A NAM model can either be applied independently or used to represent one or more contributing catchments that generate lateral inflows to a river network. In this way, it is possible to treat a single catchment or a large river basin containing numerous catchments and a complex network of rivers and channels within the same modelling framework (Doulgeris et al., 2011). The NWRM is an example of such modelling framework where NAM output is dynamically linked with the MIKE 11 river model.

3.1.2 MODEL INPUT AND PARAMETERS

The data requirements for the NAM rainfall-runoff model are meteorological data, stream flow data, physical and hydraulic properties of the catchments and definition of initial conditions. The basic meteorological data requirements are precipitation time-series, potential evapotranspiration time-series, and temperature and radiation time-series if snow accumulation and melt are to be modelled. For the irrigation module, additional information is needed on infiltration rate, crop coefficients and sources of irrigation water (e.g., local groundwater, local river or external river). The main inputs to the NAM are:

- catchment area
- rainfall
- potential evapotranspiration (PET)
- irrigation demand
- crop coefficient
- pumping rate
- water source (e.g., groundwater, local river, external river)

- observed flow data.

The main outputs from the model include:

- runoff
- net rainfall
- overland flow
- interflow
- baseflow
- actual evapotranspiration (ETa)
- soil moisture content (upper and lower zones)
- groundwater level and recharge
- surface storage.

The model computes runoff using 13 parameters that govern surface runoff, sub-surface runoff and baseflow (Table 3.1). Initial model parameters were estimated based on soil properties and land uses. Final parameters were obtained by a calibration process. Runoff peaks and low flows, timing of peaks and low flows, and total volume of runoff were the key variables considered during calibration. In addition, actual evapotranspiration (ETa) and groundwater level (GWL) were used as key variables to calibrate the model.

Table 3.1 NAM input parameters and their recommended range along with calibrated values

Storage zone	Parameter	Description	Recommended range	calibrated	Effect
Surface zone	Umax	Maximum water content in surface storage	10-200 mm	100-1000 mm	Peak runoff, total runoff reduces as Umax increases
	Lmax	Maximum water content in root zone storage	50-300 mm	65 mm	Peak runoff, total runoff reduces
	CQOF	Overland flow runoff coefficient	0.1–1.0	0.5	Peak runoff decreases but total runoff increases
	CK1,2	Time constant for routing overland flow	3–48 hours	6–75 hours	Peak runoff decreases, shape expand horizontally
	CKIF	Time constant for routing interflow	500–1000 hours	48–250 hours	Amount of interflow, decreases with larger time constant
Rootzone	TOF	Root zone threshold value for overland flow	0–0.99	0–0.2	Overland flow decreases with higher value
	TIF	Root zone threshold value for interflow	0–0.99	0.5–0.8	Interflow decreases with higher value
Groundwater	TG	Root zone threshold value for groundwater recharge	0–0.99	0–0.8	Increasing TG is less recharge to the groundwater storage
	CKBF	Time constant for routing baseflow	500–1000 hours	200–1200 hours	Increase the value reduces the baseflow
	GWLBF0	Threshold groundwater depth for baseflow	1–5 m	1–5 m	Represents the distance in metres between the average catchment surface level and the minimum water level in the river
	Sy	Specific yield of groundwater reservoir	0.01–0.10 for clay and 0.10-0.30 for sand	0.08–0.17	Increase the value, increases groundwater level
	K0	Infiltration rate at field capacity	0–1 mm/hour	0.25–0.45 mm/hour	Increase the value, increases groundwater level

3.1.3 SUBCATCHMENT DELINEATION

The northwest region was divided into 37 subcatchments including 3 cross-border (with India) subcatchments. These subcatchments were grouped into 3 topographically distinguishable sub-regions, having similar catchment characteristics for infiltration and interflow. Figure 3.1 shows the NAM subcatchments and the hydro-meteorological station network of BWDB.

Upper sub-region has 18 subcatchments: NW1U, NW1M, NW1L, NW2U, NW2L, NW3, NW5, NW7, NW12U, NW13, NW14, NW15, NW16U, NW16L, NW17, NW21, NW22, NW23. This region consists of fast responding catchments due to steep ground slope and highly permeable soil. Time constants for overland flow routing (CK1, CK2) and time constant for interflow (CKIF) values are low whereas specific yield and infiltration rates are high.

Middle sub-region has 8 subcatchments: NW4, NW10, NW11, NW12L, NW24, NW26, NW27, NW32U. Compared to the upper sub-region, the topography of this sub-region is flat and the soil is less permeable. Time constants CK1, CK2 and CKIF values are high though specific yield and infiltration rates are low.

Lower sub-region has 11 subcatchments: NW19, NW30, NW31, NW32M, NW32L, NW33, NW34, NW35, NW38, NW39, NW40. This sub-region lies in the southern part of the model area and is characterised by depressions and flood cells. NAM runoff routed to the system is controlled by these topographic features. Time constants CK1, CK2 and CKIF values are low, giving a fast routing of runoff from NAM into the flood cells.

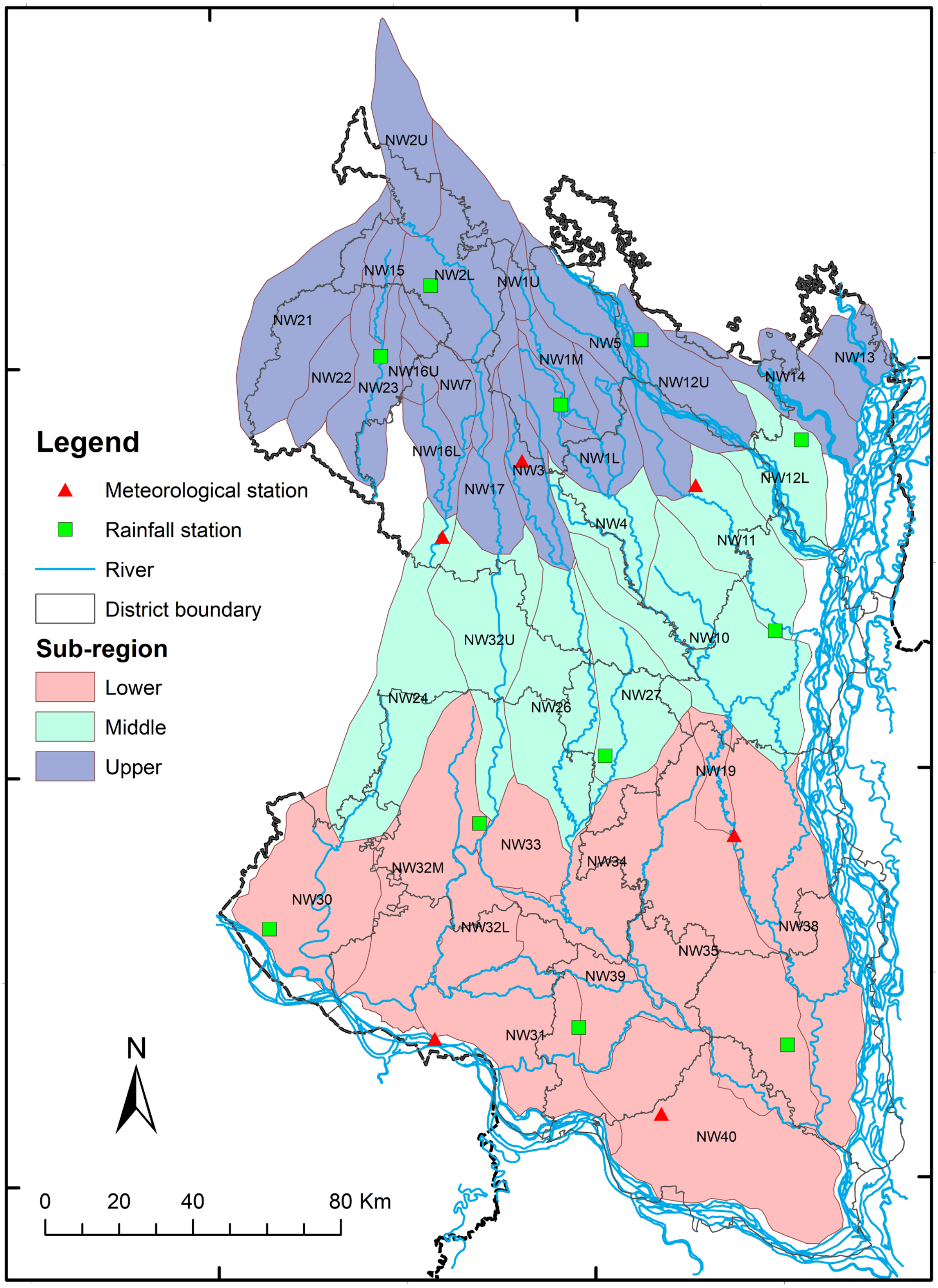

Figure 3.1 Subcatchment configuration in the NAM rainfall-runoff hydrological model setup

3.1.4 SENSITIVITY OF MODEL TO INPUT PARAMETERS

NAM is a lumped model. Simulated results largely depend on selecting an appropriate parameter value. To understand the physical significance of individual parameters we investigated the sensitivity of key NAM input parameters. Among others, root zone threshold value for overland flow (TOF), root zone threshold value for groundwater recharge (TG), infiltration rate at field capacity (K0) and specific yield of groundwater reservoir (Sy) are considered as significant parameters for volume of catchment runoff and groundwater level. However, K0 and Sy are found to be more sensitive compared to CKBF and TG (Figure 3.2) (see Table 3.1 for descriptions of these parameters).

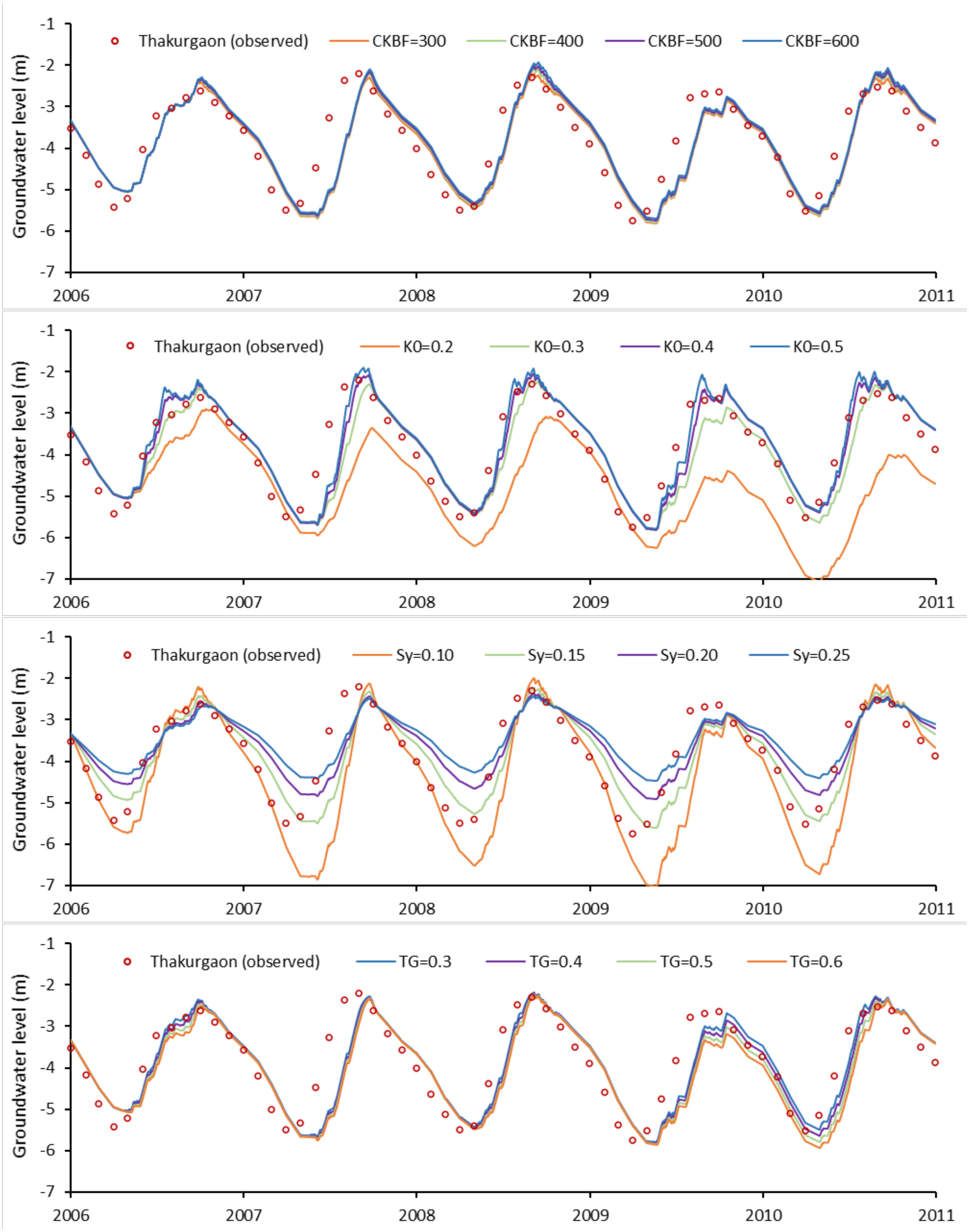

Figure 3.2 Sensitivity of NAM parameters – time constant for routing baseflow (CKBF), infiltration rate at field capacity (K0), specific yield of groundwater reservoir (Sy) and root zone threshold for groundwater recharge (TG)

3.1.5 NAM PARAMETER CALIBRATION

During calibration, NAM parameters were adjusted until satisfactory agreements between simulated and observed streamflow, actual evapotranspiration (ETa) and groundwater level (GWL) were attained. Both graphical and numerical performance measures were applied to evaluate model performance. The graphical evaluation included comparison of simulated and observed hydrographs, and comparison of simulated and observed accumulated runoff. The numerical performance measures included overall water balance error (i.e., difference between average simulated and observed runoff), and a measure of overall shape of the hydrograph based on coefficient of determination and Nash-Sutcliffe coefficient (NSE).

The following objectives were considered during model calibration:

- a good agreement between the simulated and observed catchment runoff
- magnitude of peak flow and timing of peak arrival at various locations
- number of zero flow days in a year
- actual evapotranspiration
- groundwater level.

Initial setting of parameters was based on landscape and soil characteristics of the region and previous study reports. A sensitivity study on model parameters was conducted to understand the significance and influence of individual parameter on, GWL). During the calibration process, major emphasis was given to the adjustment of the following parameters:

maximum groundwater level causing baseflow (GWLBF0)

- overland flow time constant (CK1,2)
- baseflow time constant (CKBF)
- maximum water content in root zone storage (Lmax).

In addition to the above NAM parameters, other groundwater parameters and loss parameters have been used for each sub catchment calibration. They are

- specific yield (Sy)
- crop coefficient and operational losses.

The model was calibrated for the period 1985 to 2015 using a two-step process. At first, parameters were calibrated using a single parameter value for the 37 subcatchments of the entire region. Initial results were reviewed for each subcatchment and then parameters were readjusted locally. As the study focused on low flow condition, model results were primarily evaluated in terms of actual ETa and GWD. NAM results for ETa were evaluated against 2 sets of data obtained from a crop-coefficient model (Mainuddin et al., 2021; Mojid et al., 2021b) and a remote sensing model (Peña-Arancibia et al., 2020; Peña-Arancibia et al., 2021b).

Figure 3.3 shows a typical comparison of NAM hydrological model (HM)-simulated ETa for the northern part of the study area (Upper sub-region) compared to results obtained from a crop-coefficient model (CCM) and a remote sensing model (RSM) at an annual time scale. Overall, NAM results are consistent with both CCM and RSM results. For the 18 subcatchments of the Upper sub-region, HM-simulated ETa varies between 1,039 to 1,169 mm (with an average of 1,115 mm), compared to 1,074 to 1,158 (average of 1,110 mm) by CCM and 1,087 to 1,161 (average of 1,119 mm) by RSM. Similar results are also obtained at annual time scale for the 19 subcatchments in the Middle and Lower sub-regions (Figure 3.4) with HM-simulated ETa varying from 1,060 to 1,185 mm (with an average of 1,105 mm), compared to 1,142 to 1,186 mm (average of 1,158 mm) by CCM and 1,032 to 1,170 mm (average of 1108 mm) by RSM. Results show that the range of ETa for the HM is relatively high (125 mm), compared to CCM (44 mm) and very close compared to RSM (138 mm). However, in both cases the overall bias is less than 2%. It is mentioned here that HM results were estimated at subcatchment scale while CCM and RSM results were estimated at district level. Therefore, some differences could be attributed to the difference in spatial resolution.

Subcatchment scale HM results were accumulated to district scale and compared with the CCM and RSM results (Table 3.2). Across the 16 districts, ETa varies from 1,024 to 1,160 mm (average of 1,100 mm) for the HM model, 1,046 to 1,143 mm (average of 1,101 mm) for the CCM and 1,047 to 1,140 (average of 1,112 mm) by RSM. Results show that the range of ETa for the HM is slightly higher (136 mm) compared to CCM (96 mm) and RSM (92 mm). However, HM-predicted averaged ETa across the region is very similar to the other 2 data sets.

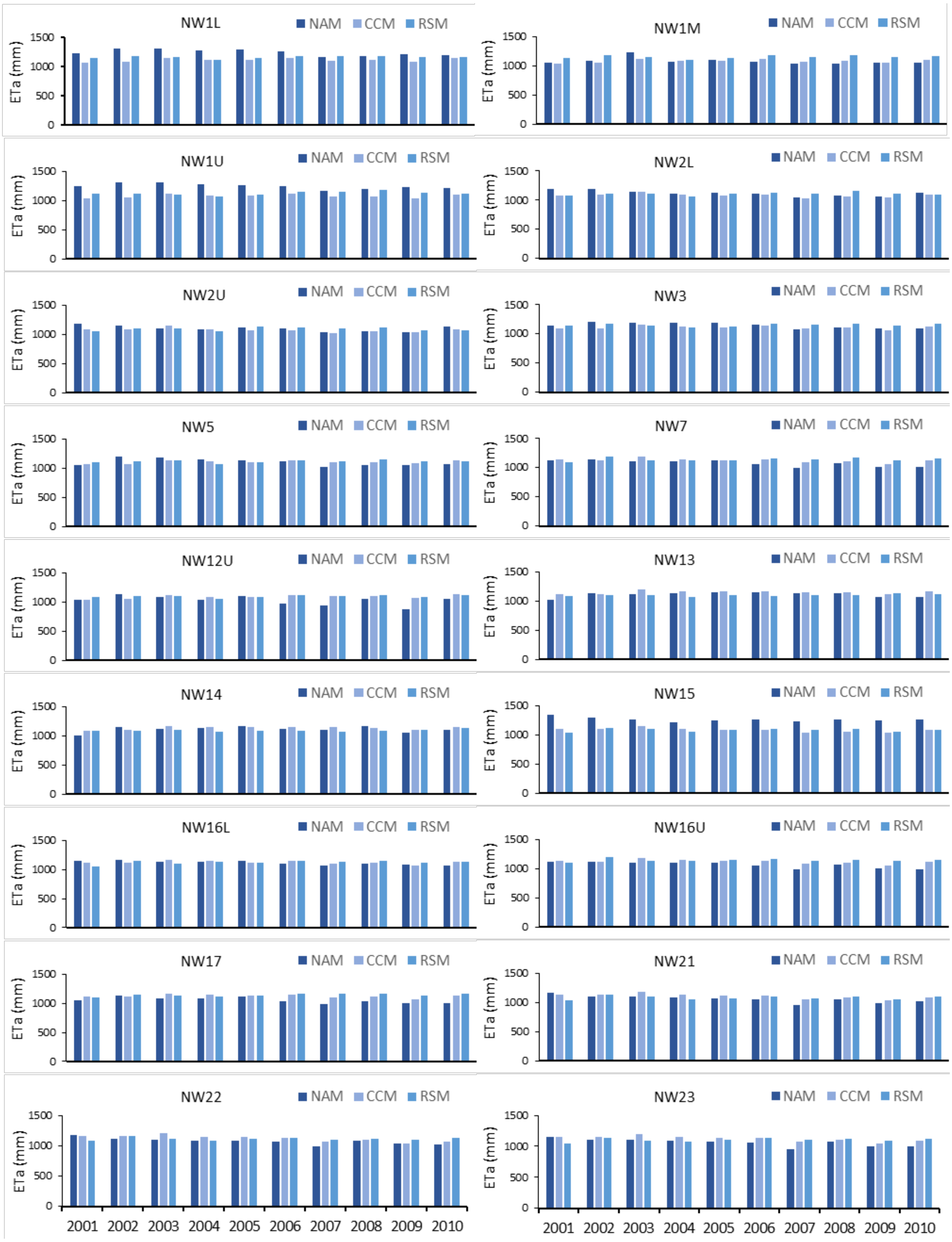

Figure 3.3 Comparison of mean annual actual evapotranspiration (ETa) from a hydrological model (HM), a crop-coefficient model (CCM) and a remote sensing model (RSM) in the Upper sub-region

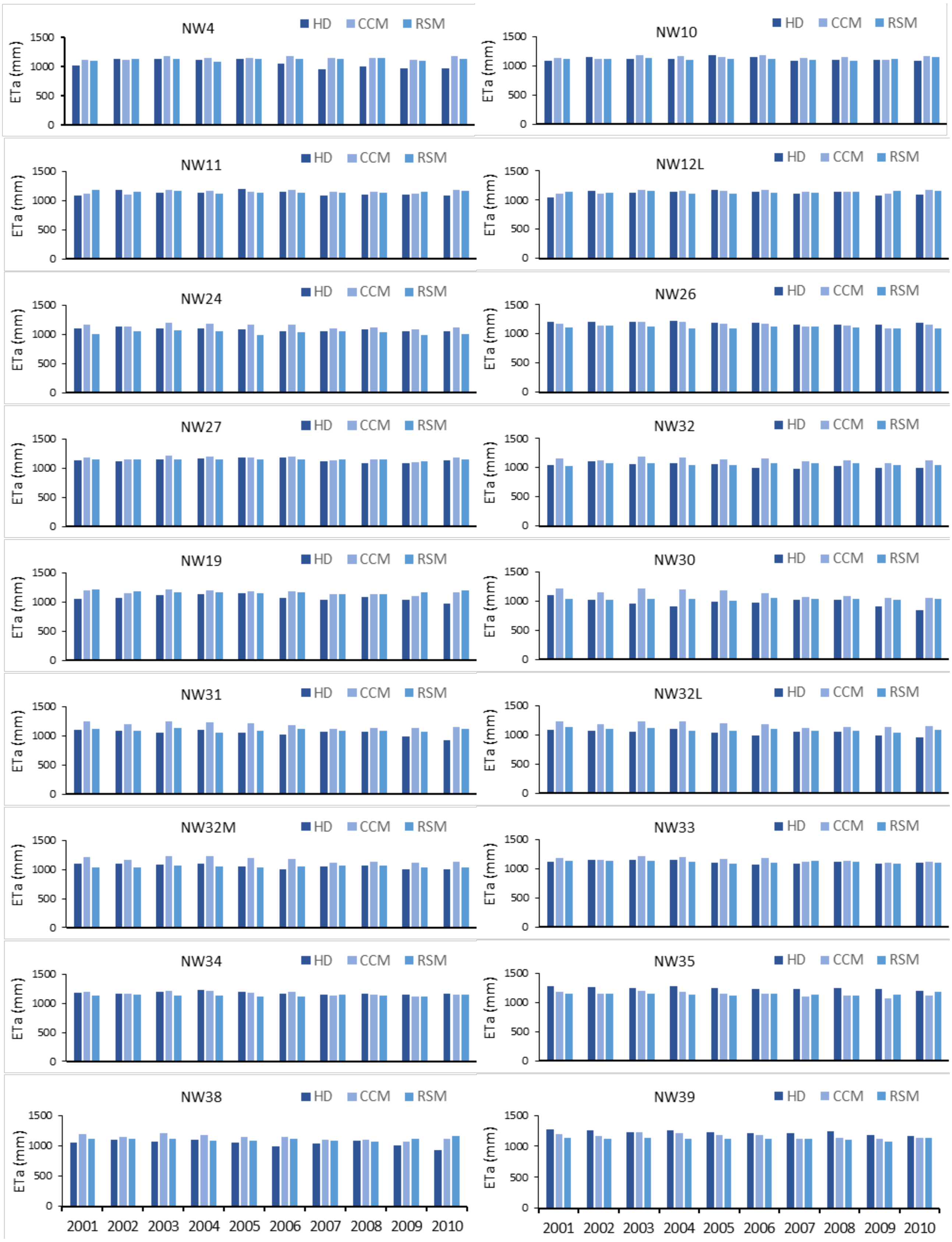

Figure 3.4 Comparison of mean annual actual evapotranspiration (ETa) from a hydrological model (HM), a crop-coefficient model (CCM) and a remote sensing mode (RSM) in the Middle sub-region (top 4 rows) and Lower sub-region (bottom 5 rows)

Table 3.2 Summary of actual evapotranspiration (ETa) in the 16 districts of northwest region simulated by the hydrological model (HM) compared to crop-coefficient model (CCM) and remote sensing model (RSM)

District	Actual Evapotranspiration (ETa)			% difference (PBIAS) compared to	
	HM	CCM	RSM	CCM	RSM
Bogra	1160	1107	1125	4.8	3.1
Dinajpur	1067	1099	1118	−2.9	−4.5
Gaibandha	1122	1126	1132	−0.4	− 0.9
Joypurhat	1152	1128	1135	2.1	1.5
Kurigram	1089	1121	1110	−2.8	−1.9
Lalmonirhat	1043	1076	1091	−3.0	−4.4
Naogaon	1088	1120	1093	−2.8	−0.4
Natore	1150	1116	1127	3.0	2.0
Nawabganj	1024	1068	1047	−4.1	−2.2
Nilphamari	1129	1087	1140	3.9	−0.9
Pabna	1098	1088	1115	0.9	−1.5
Panchagarh	1109	1046	1099	6.0	1.0
Rajshahi	1060	1143	1103	−7.2	−3.8
Rangpur	1102	1117	1135	−1.3	−2.9
Sirajganj	1155	1100	1120	5.0	3.2
Thakurgaon	1050	1080	1111	−2.8	−5.5

Minus '−' sign indicates HM model underpredicted ETa

Figure 3.5 shows a typical comparison of model simulated ETa at monthly time scale compared to results from CCM and RSM. The top 2 rows represent the subcatchments in the Upper sub-region, middle 2 rows in the Middle sub-region and the bottom 2 rows in the Lower sub-region. These subcatchments are located in Panchagarh, Thakurgaon, Rangpur, Joypurhat, Rajshahi and Natore districts respectively. In most cases, the lowest ETa produced by the HM is very close to the CCM and RSM results. However, there are discrepancies for the highest ETa. The HM model predicted higher ETa for the northern districts (e.g., Panchagarh and Thakurgaon) and lower ETa in the southern districts (e.g., Natore). For the 37 subcatchments across the region, correlation coefficients were found between 0.83 and 0.94 (average of 0.91) when compared with CCM results and 0.78 and 0.93 (average of 0.88) when compared with RSM results. The Nash-Sutcliffe coefficient (NSE) varies from 0.53 to 0.86 (average of 0.75) when compared with CCM and varies from 0.51 to 0.84 (average of 0.70) when compared with RSM results.

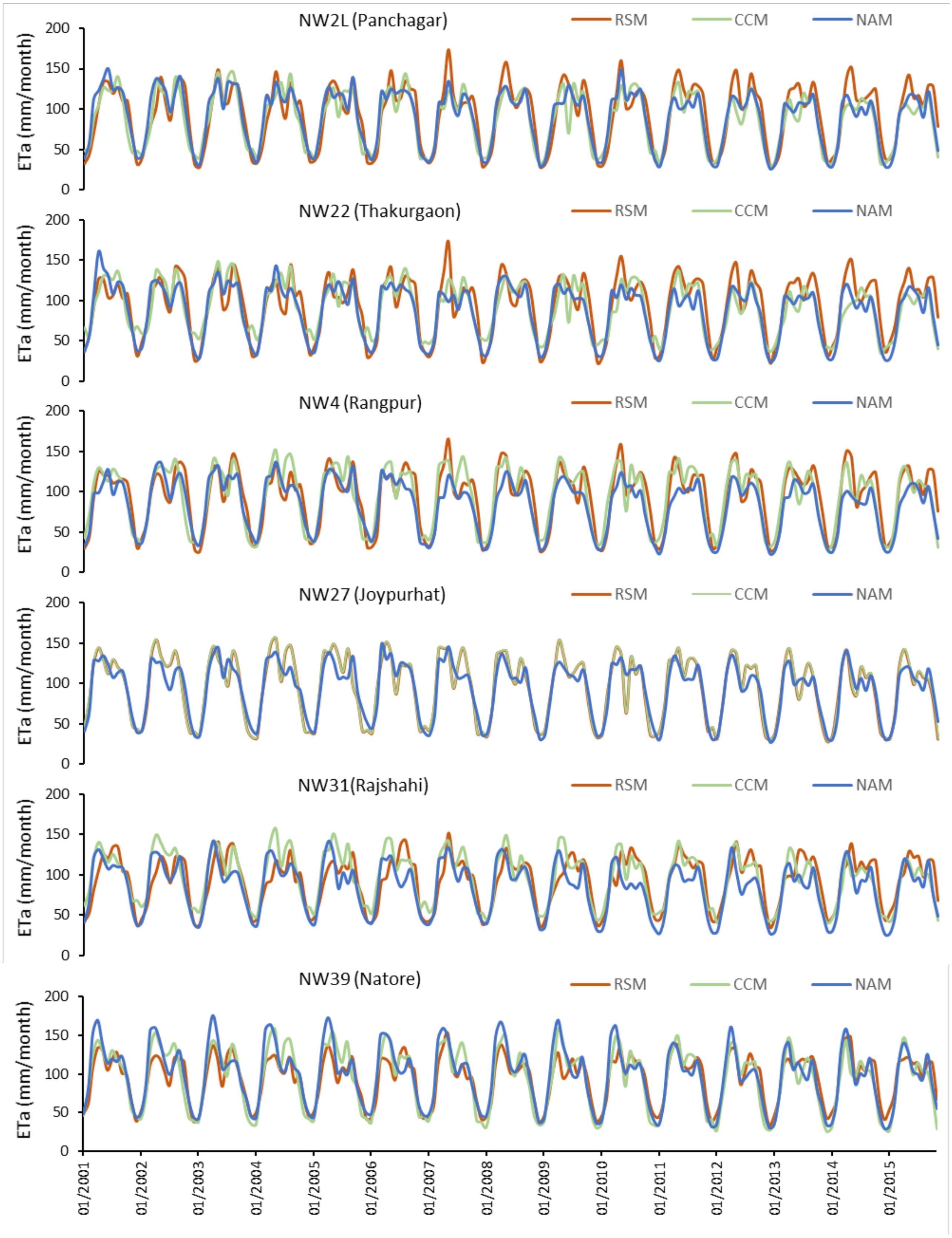

Figure 3.5 Comparison of actual evapotranspiration (ETa) from a hydrological model (HM), a crop-coefficient model (CCM) and a remote sensing model (RSM) in the Panchagarh, Thakurgaon, Rangpur, Joypurhat, Rajshahi and Natore districts (top to bottom respectively)

Groundwater level was used as a key variable to constrain NAM model parameters. While all simulations were carried out at a daily time step, an average monthly groundwater level was used to compare with observed data. The observed groundwater levels are monthly time series of the average groundwater level in each district, gathered during the earlier CSIRO project (CSIRO et al., 2014), with the period further extended for this project. Model parameters were calibrated using two-step process as described in the previous section (e.g., using single set of groundwater parameters for all subcatchments for an overall fit and then reiterate the parameters for individual subcatchment to reflect physical characteristics of local areas). Figure 3.6 shows a comparison of simulated and observed groundwater levels in the 16 districts of northwest region. In general, model results are consistent with observed data in terms of absolute magnitude and pattern of monthly fluctuation except for a few locations (e.g., Rajshahi and Nawabganj). The NSE varies from 0.41 to 0.81 with an average NSE of 0.71. The model produced best fit for Pabna district (NSE of 0.81) and worst fit for Nawabganj district (NSE of 0.41).

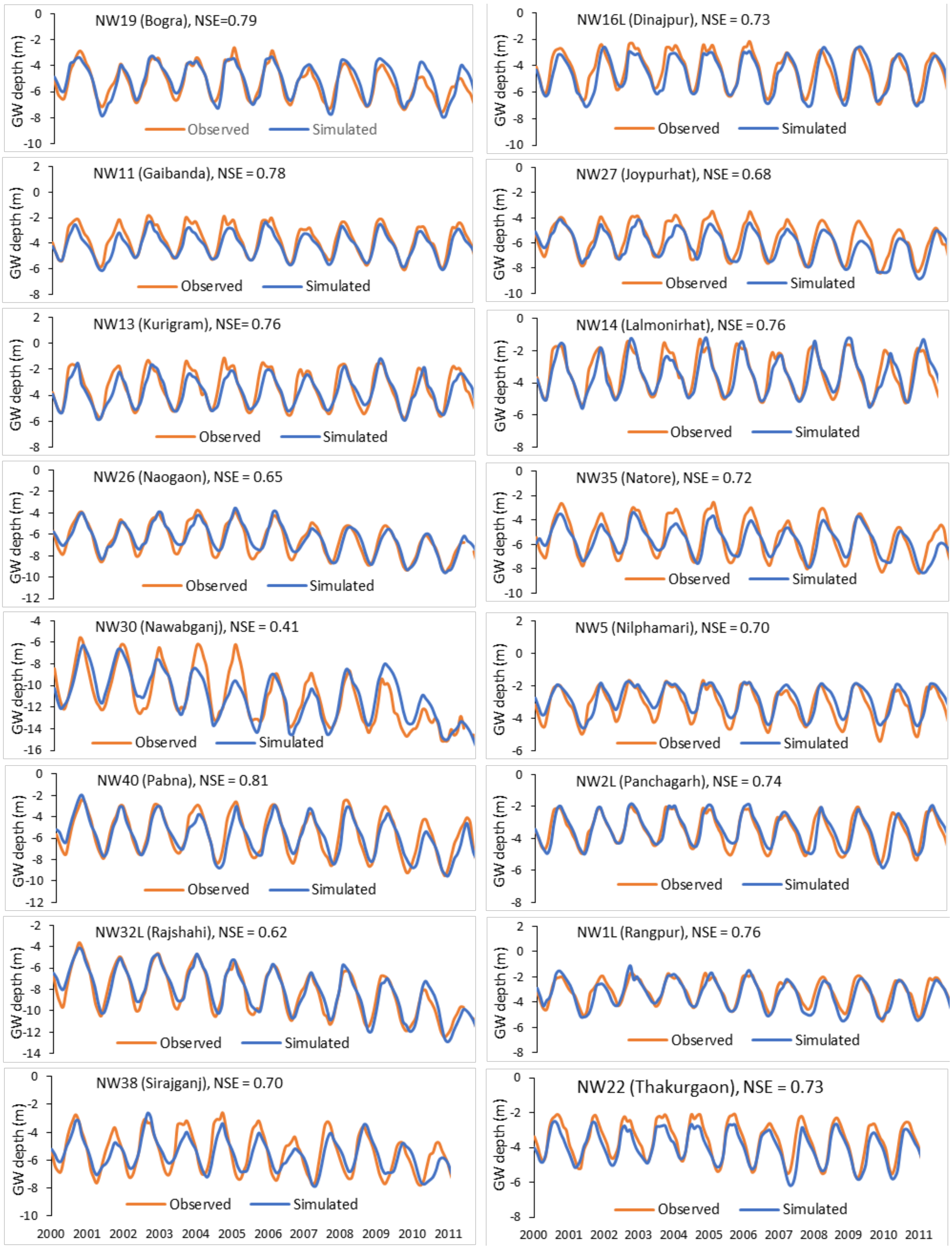

Figure 3.6 Comparison of observed and model simulated groundwater level (GWL) across 16 northwest districts (one subcatchment in each district)

3.2 HYDRODYNAMIC MODELLING USING MIKE 11

3.2.1 INTRODUCTION

The MIKE 11 one-dimensional hydrodynamic (HD) model (Havno et al., 1995) was used to simulate time-varying water level and discharge across the river network. The model is based on an implicit, finite difference scheme for the computation of unsteady flows in rivers and floodplains. The model is widely used in Bangladesh to estimate river height and discharge. for the water resource assessment and flood modelling. In this study we have used the northwest regional model (NWRM) which was configured by the Institute of Water Modelling (IWM) using MIKE 11 HD NAM.

3.2.2 MODEL CONFIGURATION

Major rivers represented in the NWRM model are Teesta, Dudkumar, Dharla, Mohananda, Atrai, Jamuneswari, Karatoya and Bangali. Some minor rivers lie north of Panchagarh and west of Thakurgaon (Figure 3.7). Rivers in the northern part are mostly cross-border rivers and flashy in nature. With the exception of Mohananda, all rivers drain to the Jamuna (Brahmaputra) River, so their drainage and downstream condition is governed by stage of the Jamuna River. Moreover, there are several minor rivers in this area. Most of the rivers of this region flow from very steep to flat ground. A quick response of flash flood occurs in the upper portion of the region and inundates both banks of the rivers. However, flood cells and depression areas in the lower portion act as flood retention reservoirs.

The Upper Karatoya-Atrai-Baral and the Jamuneswari-Karatoya-Bangali are the 2 main river systems draining the greater part of the northwest region. The total area drained by these 2 systems is around 18,000 km (i.e., 55% of the total area). The drainage pattern in the middle part of the northwest region is complex in nature. The Atrai-Baral basin is characterised by flat topography in its southern part and slightly steeper ground in the north and northwest. The areas between these rivers comprise the inter-fluvial depression of the *Chalan Beel*, which conveys significant floodplain flows during the monsoon. In fact, the *Chalan Beel* acts as a huge flood retention area during monsoon and post-monsoon season.

The NWRM is validated for a recent hydrological event in 2016 based on data from BWDB as well as the IWM. Of the 83 natural rivers or connecting *khals* (canals), 52 have been updated in the NWRM with surveyed cross-sections during 2006-2016. Of the 79 water level/discharge gauging stations of BWDB in the region, measured water level data are not available for 8 of them. At only 29 locations, observed discharge data is available out of 44 discharge measurement points of BWDB. Several spill channels coming from the Jamuna River that are included in the model are not prevailing in the field due to construction of the Brahmaputra Right Embankment (BRE) on that portion. Some of the newly constructed or old structures are not incorporated in the model setup. Moreover, gate operation data are not collected regularly thus could not be incorporated in the model. Irrigation and drainage structures constructed by different government agencies are not incorporated in the model to capture dry season or low flow simulation.

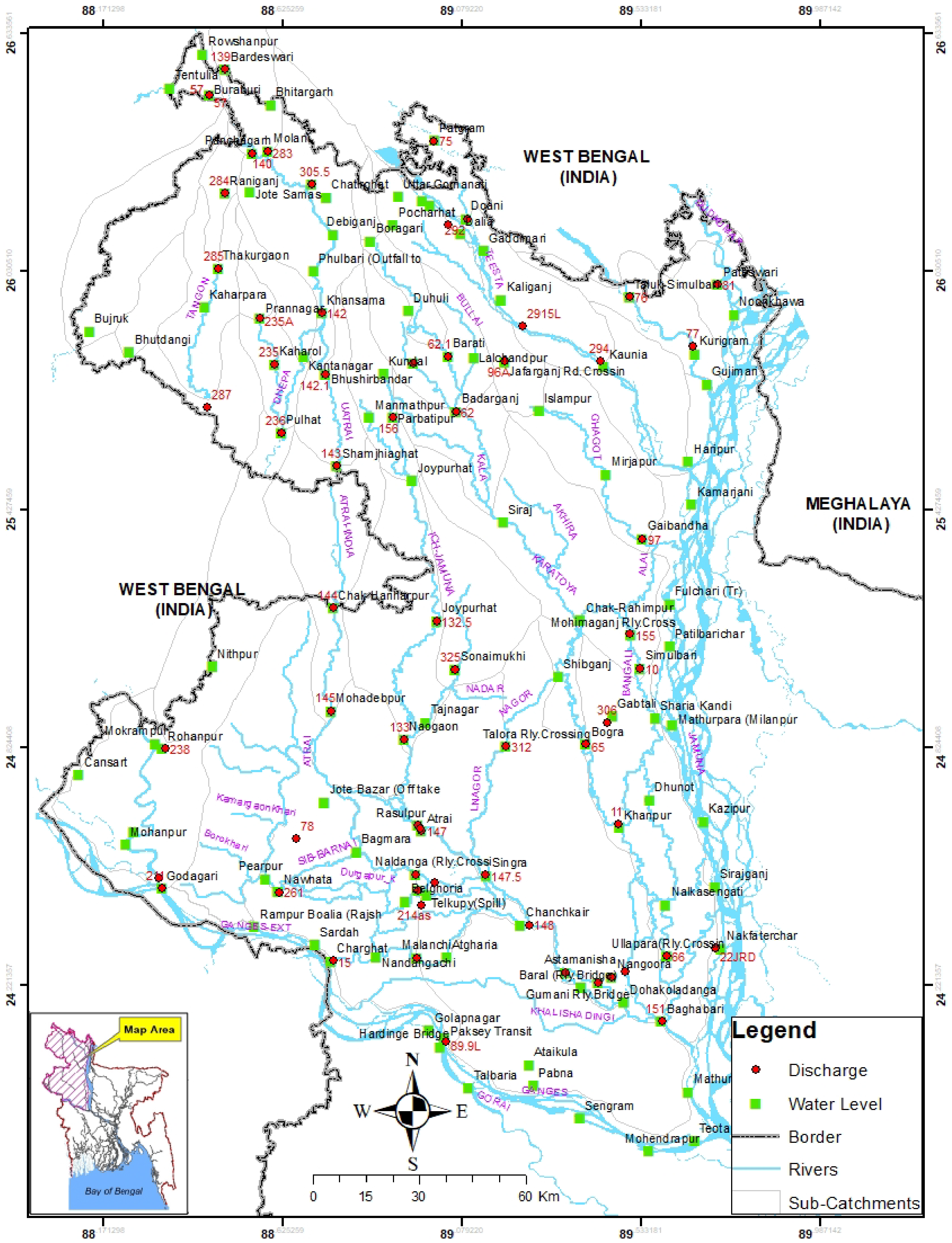

Figure 3.7 Hydrodynamic model setup showing river network and gauging stations for the northwest region.

3.2.3 Model boundaries

The model consists of 45 boundaries including 40 discharge and 5 water level boundaries. The upstream boundaries are defined with discharge time series for major rivers in this region. Discharge time series are generated using rating curves. Rating curves are updated and rectified where necessary with recent available observed discharge data. Otherwise, old rating parameters have been used applying necessary checking with recent measured discharge data. At upstream locations, where inflow is very insignificant, a constant discharge boundary (ranging from 0.1 to 1.0 m^3/s) has been applied to avoid drying up of rivers during dry period in model simulation. A total of 28 constant boundaries have been used in the model. The downstream boundaries have been specified with water level time series.

3.2.4 MIKE 11 HD MODEL CALIBRATION

The MIKE 11 HD model was calibrated using observed discharge and water level data at various locations where observed data were available. Two sets of observed data (from BWDB and IWM gauges) were used to constrain the MIKE 11 HD model. Calibration of the model is done by changing parameter values (e.g., Manning's roughness coefficient, *n*) or hydrometric data (e.g., cross-section, floodplain topography). During calibration, simulated hydrographs were visually inspected and statistical parameter such as mean, root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE) were evaluated. In the calibrated model, Manning's *n* varies between to 0.03 to 0.04 for rivers and between 0.04 and 0.05 for floodplain. In general, model-simulated discharge and water level match well with observed data (Figure 3.8 and Figure 3.9). It is important to note that there were very limited discharge data for a rigorous validation of the model results.

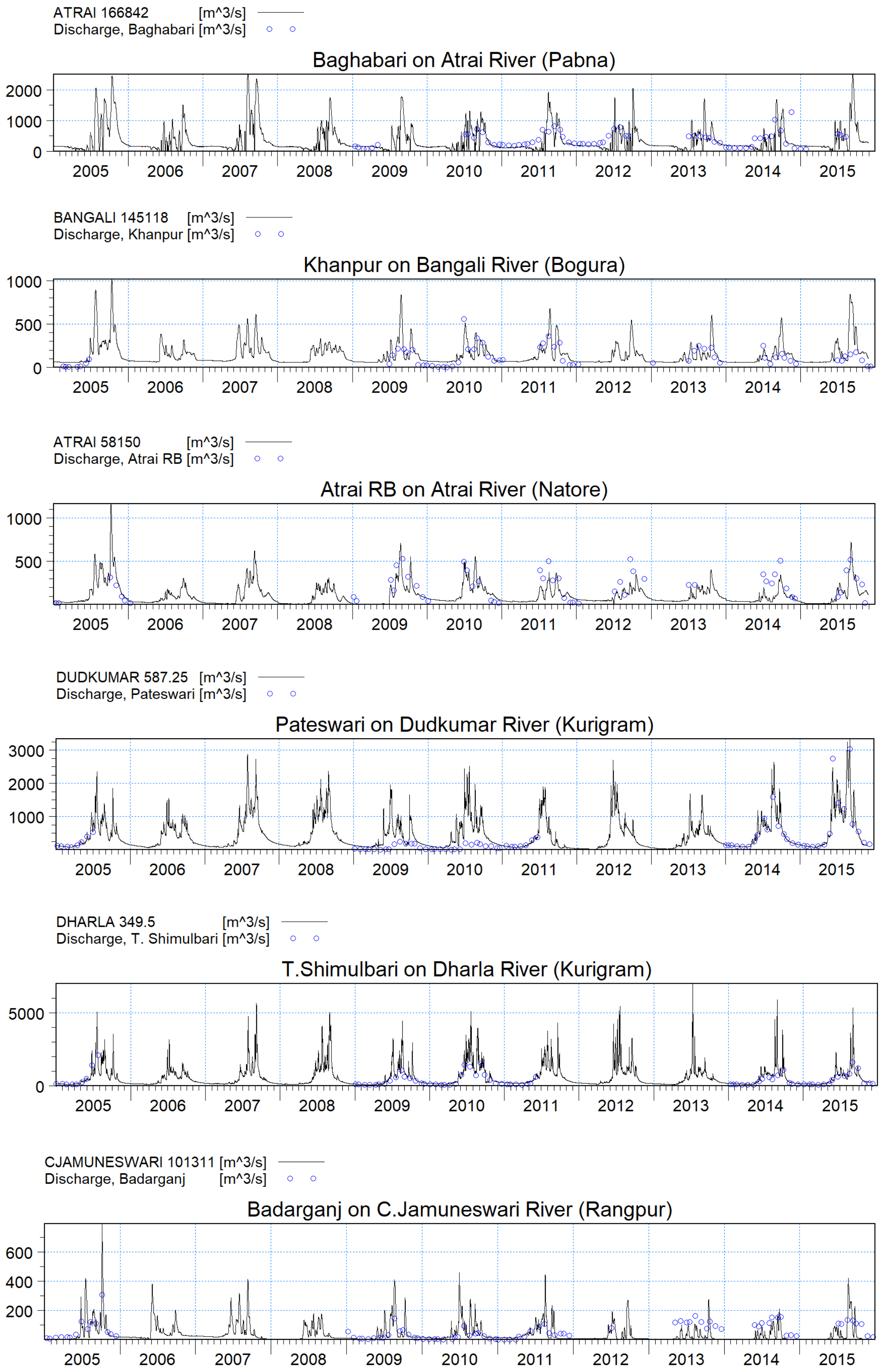

Figure 3.8 Comparison of observed and simulated discharge at selected gauging stations (refer to Figure 3.7 for locations). The number after the station name represents the chainage (i.e. distance from upstream end of the river) in meter

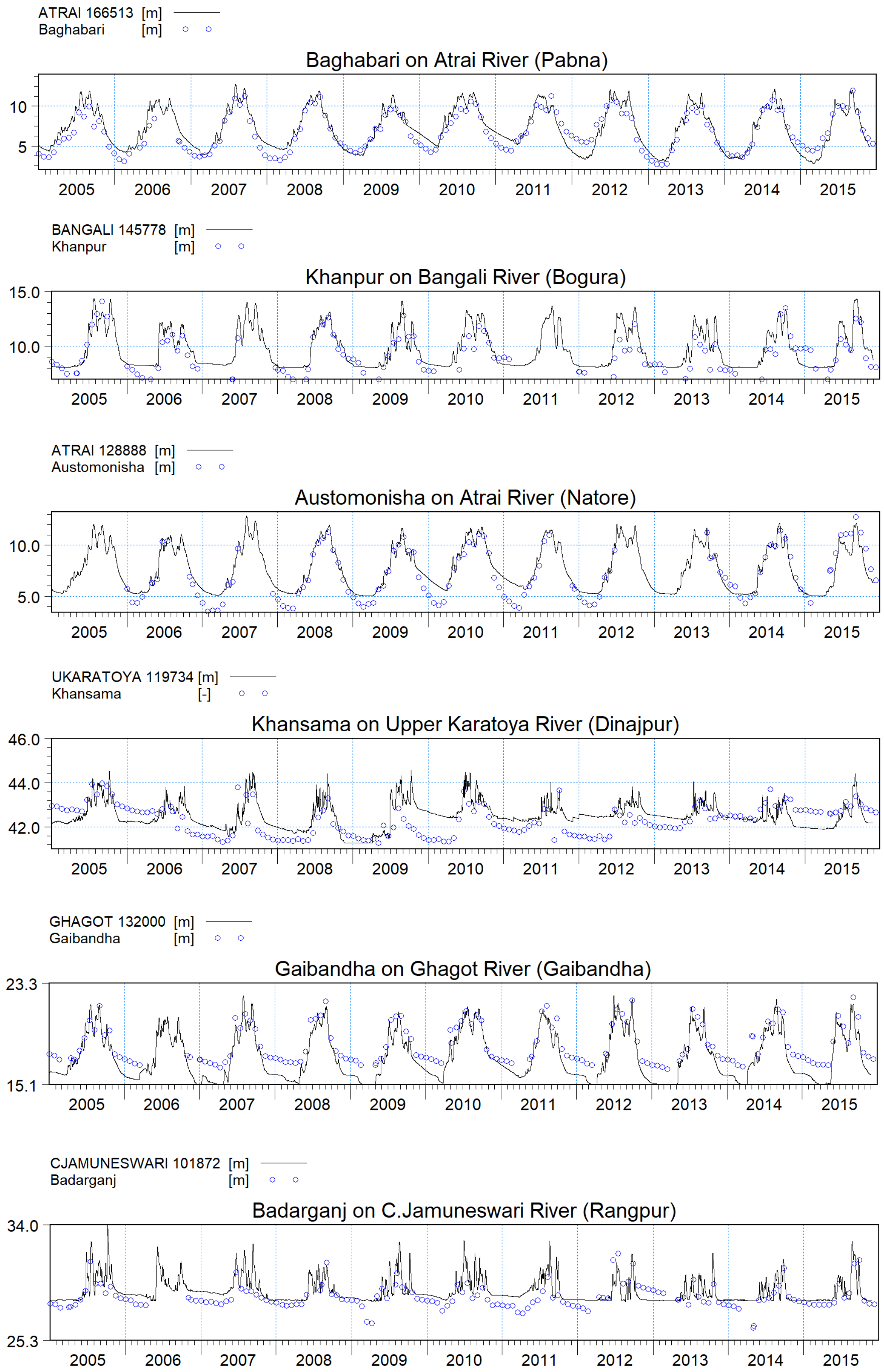

Figure 3.9 Comparison of observed and simulated water level at selected gauging stations (refer to Figure 3.7 for locations)

3.3 WATER BALANCE ANALYSIS

The water balance of the northwest region is calculated by combining the results from the NAM rainfall-runoff and MIKE 11 hydrodynamic models. Daily timeseries of water balance components were extracted from the model results for individual subcatchments and aggregated to district to estimate water balance. Results were accumulated to annual time scale to evaluate overall groundwater trend in the region.

It is important to note that the lateral groundwater inflow/outflow between districts is not included in the current NAM and MIKE 11 modelling. Therefore, the results are based on the assumption that lateral groundwater inflow is the same as outflow. Detailed water balance analyses including the lateral groundwater inflow/outflow can be found in the companion reports on district water balance (Mainuddin et al., 2021) and groundwater modelling (Janardhanan et al., 2021).

In this study the water balance is estimated as follows:

Catchment and river water balance:

$$P + Igw - ETa - D + Rin - Rout + \Delta SW = 0 \quad (1)$$

Groundwater balance:

$$D - Igw + \Delta GW = 0 \quad (2)$$

Combined catchment, river and groundwater balance:

$$P - ETa + Rin - Rout + \Delta S = 0 \quad (3)$$

where *P* is the rainfall, *Igw* the groundwater component of irrigation supply, *Isw* the surface water component of irrigation supply, *ETa* the actual evapotranspiration, *RO* catchment runoff (overland flow and interflow), *BF* baseflow, *D* deep drainage to the groundwater (also called recharge), *Rin* river inflow, *Rou*t river outflow, *ΔSW* changes in surface water storage, *ΔGW* changes in groundwater storage, *ΔS* changes in combined surface water and groundwater storage.

3.4 SCENARIO ANALYSIS

Impacts of future climate and land use changes on key water balance components were assessed through 8 scenarios: 5 on future climate, one on irrigation water source and 2 on inflow condition (Table 3.3). Impacts were evaluated in terms of changes in actual evapotranspiration (ETa), groundwater level and river flow.

Table 3.3 Summary of selected future climate and river flow scenarios for the northwest region of Bangladesh

SCENARIO TYPE	SCENARIO NAME	DESCRIPTION	PURPOSE
Current climate	S0	Current climate and current irrigation	To estimate current trend of groundwater status. This condition is considered as baseline scenario and the impacts of other scenarios are evaluated with respect to this scenario
Future climate	S1	Average PET, Low rainfall, (AvPETLoR)	Investigate the impacts of projected future rainfall and PET under global climate change scenarios
	S2	High rainfall, Average PET (AvPETHiR)	
	S3	Average rainfall, Average PET (AvPETAvR)	
	S4	Low PET, Average rainfall (LoPETAvR)	
	S5	High PET, Average rainfall (HiPETAvR)	
Irrigation source	S6	Increase river water use to 20% to meet irrigation demand (i.e., 80% GW, 20% SW)	This scenario evaluates the changes in GW level if more surface water is available for irrigation

Scenario type	Scenario Name	Description	Purpose
River flow	S7	Increase in river flow from upstream catchments by 20%	Investigate the impacts of river inflows from upstream catchments
	S8	Decrease in river flow from upstream catchments by 20%	

3.4.1 Current climate and development scenario

This scenario presents baseline condition (S0) and is the same as the calibrated condition described in the hydrological and hydrodynamic modelling sections. For this scenario the area of crops and other vegetation are held constant at their 2015 values rather than varying throughout the simulation period (1985 to 2015). The impacts of future climate (S1 to S5), irrigation water source (S6) and river flow condition (S7, S8) are evaluated based on comparisons to this scenario.

3.4.2 Climate change scenario

Changes in the natural climate are a major concern for food security in Bangladesh and it is anticipated that water balance and cropping opportunities will be affected by climate change (Acharjee et al., 2019; Kirby et al., 2016; Mainuddin et al., 2015). Given the difficulty of making firm projections about future climate, this study investigated 5 alternative scenarios of future climate that span a reasonable range of potential future climates, each based on the RCP4.5 emission scenarios (Karim et al., 2020; Zheng et al., 2018). For each scenario, future climate projections from 28 global climate models (GCMs) were investigated and the best model was selected for each scenario. A GCM was considered best that projected rainfall and PET closest to the average value of all GCMs. 5 scenarios were chosen to give contrasting changes in rainfall and potential evapotranspiration (PET) and include the uncertainties in GCM predictions. These include: (i) lower bound of rainfall with average change in potential evapotranspiration (AvPETLoR), (ii) highest potential increase in rainfall with average change in potential evapotranspiration (AvPETHiR), (iii) average change in rainfall with average change in potential evapotranspiration (AvPETAvR), (iv) average change in rainfall with most negative change in potential evapotranspiration (LoPETAvR) and (v) average change in rainfall with most positive change in potential evapotranspiration (HiPETAvR).

In this study, changes in future rainfall and PET were estimated for the period of 2045 to 2075 using the results from the 5 selected GCMs. The projections were made for the 16 districts in the northwest region using empirical scaling factors as described in Zheng et al. (2018). Historical daily data for the period of 1985 to 2015 were used to construct time series of future climate data for the period of 2045 to 2075 using annual scaling factors. Detail of climate change projections can be found in Karim et al. (2020). Table 3.4 presents the list of GCMs and their scaling factors for the 5 selected scenarios.

Table 3.4 Selected GCMs and annual scaling factors (SFs) for the 5 climate scenarios used in this study

Scenario	Description	Symbol	Best GCM	Rainfall SF	PET SF
S1	Average PET, Low rainfall	AvPETLoR	GFDL-ESM2G	0.983	1.029
S2	Average PET, High rainfall	AvPETHiR	MIROC-ESM	1.220	1.039
S3	Average PET, Average rainfall	AvPETAvR	BCC-CSM1-1	1.118	1.034
S4	Low PET, Average rainfall	LoPETAvR	GISS-E2-H-CC	1.096	0.991
S5	High PET, Average rainfall	HiPETAvR	IPSL-CM5A-LR	1.019	1.075

3.4.3 USE OF MORE SURFACE WATER FOR IRRIGATION

Current agricultural policy in Bangladesh envisages substituting some groundwater use with surface water, in order to curb the supposed unsustainable use of groundwater. In this scenario, we assumed that 20% of the water for irrigation comes from surface water (i.e., local rivers or other surface storages, such as ponds) rather than groundwater. This scenario is named as 'river_water'.

3.4.4 CHANGES IN RIVER FLOW FROM UPSTREAM

It is likely that inflow from upstream Indian catchments will change under future climate. Due to this uncertainty, we have assessed 2 scenarios – 20% more and 20% less river flow. The changes in inflow are implemented at 11 cross boundary rivers – Buriteesta, Dharla, Dudkumar, Punarbhaba, Teesta, Karatoya, Jamuneswari, Ghagot, Ganges extension, Mohananda and Jamuna (Figure 3.10).

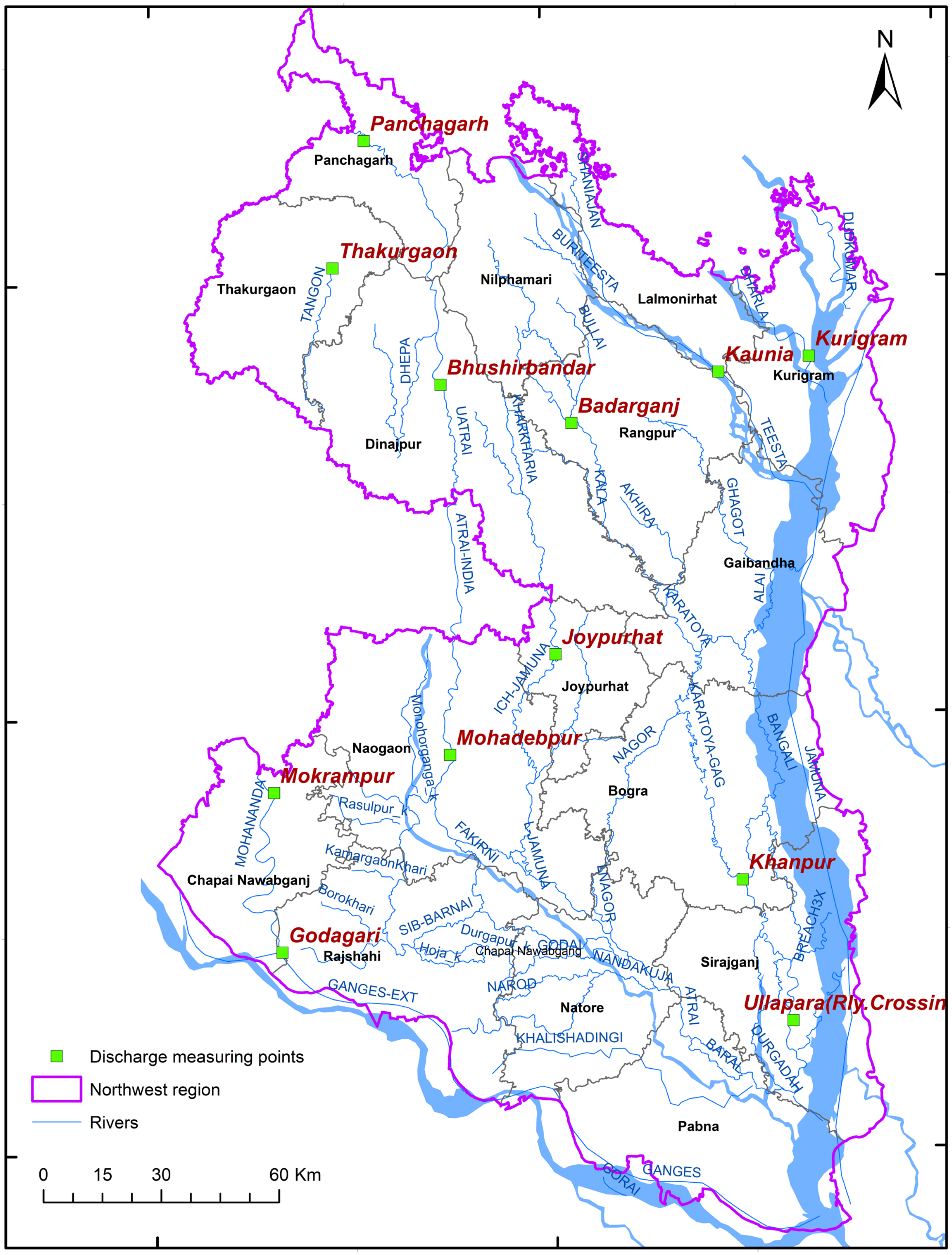

Figure 3.10 Location of discharge measuring points where changes in flow are evaluated for future climate and inflow conditions

4 RESULTS

4.1 RAINFALL

Rainfall in the northwest region varies both spatially and temporarily with a general trend of decreasing rainfall across the region. From 1985 to 2015, mean annual rainfall varied from 1,430 mm in Rajshahi (minimum in the northwest region) to 2,540 mm in Kurigram (maximum in the northwest region). Under the climate change scenarios, however, rainfall is expected to rise in the entire northwest (Figure 4.1).

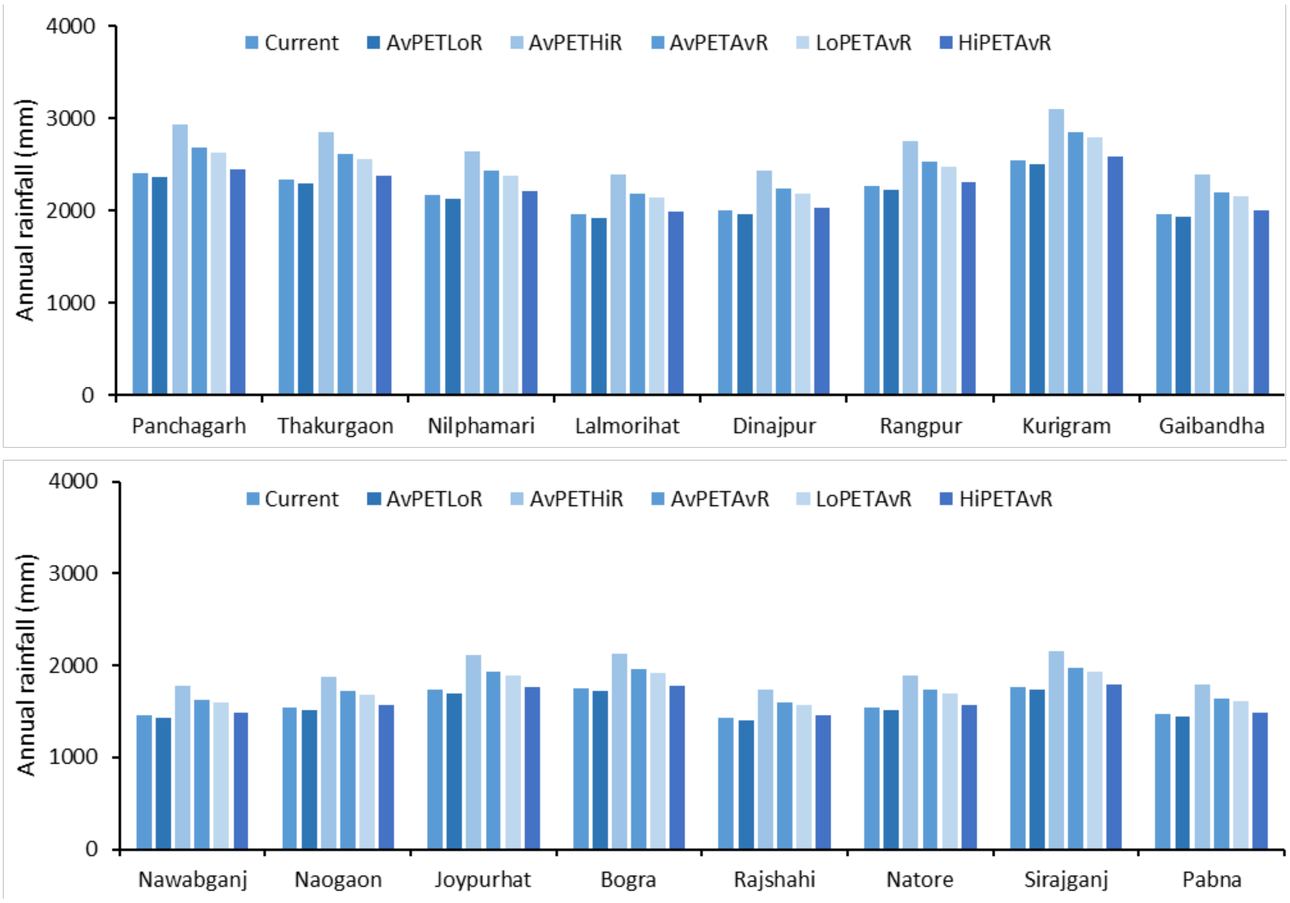

Figure 4.1 Mean annual rainfall for the 16-northwest districts under current and the 5 climate change scenarios

4.1.1 IMPACTS OF CLIMATE CHANGE ON RAINFALL

Figure 4.2 shows the changes in annual rainfall for the 5 climate scenarios compared to current average rainfall. Results show that for an average climate change scenario (AvPETAvR), rainfall could increase up to 11.8%. For the low rainfall scenario (AvPETLoR), a small reduction in rainfall (1 to 2%) is projected, while for the high rainfall scenario (AvPETHiR), the increase could be up to 22%. Increase in rainfall is also projected for the high PET scenario. At district level, the increase is about 170 mm (maximum of 313 mm) for the Rajshahi and 301 mm (maximum of 558 mm) for the Kurigram for an average future climate.

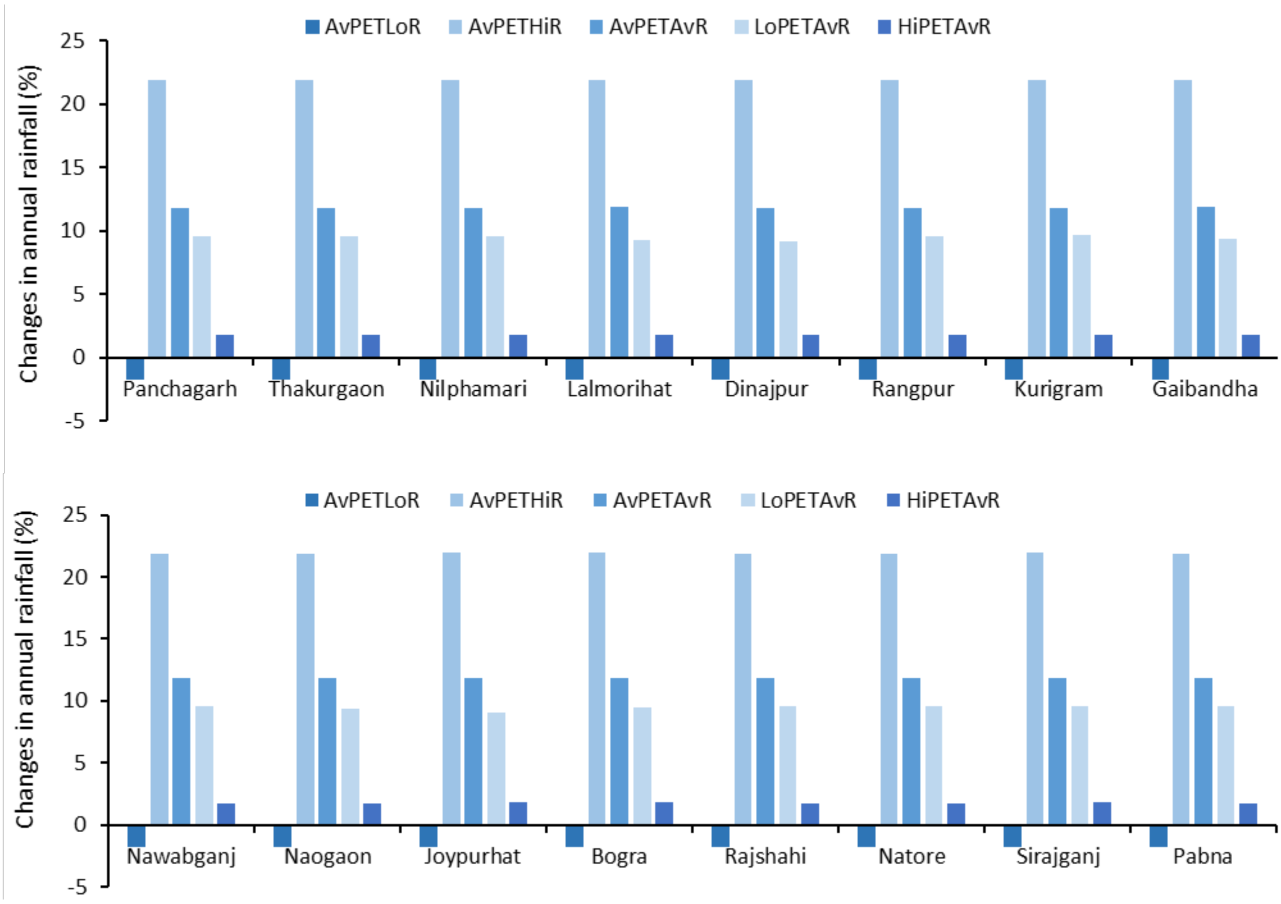

Figure 4.2 Change in annual mean rainfall for the 16-northwest districts under the 5 climate change scenarios

4.2 EVAPOTRANSPIRATION

The mean annual actual evapotranspiration (ETa) varies from 1,024 mm in Nawabganj (minimum 932 mm, maximum 1,139 mm) to 1,160 mm in Bogra (minimum 1,029 mm, maximum 1,236 mm) with an average of 1,100 mm across the northwest region (Figure 4.3). Compared to rainfall variation (as seen in the previous section), the variation in ETa is much less between the stations. Inter-annual variability is also small for the ETa. The inter-annual variation in the period 2000 to 2015 was found highest (238 mm) for the Thakurgaon district (minimum 935 mm, maximum 1,173 mm) and lowest (177 mm) for the Dinajpur district (minimum 967 mm, maximum 1,144 mm).

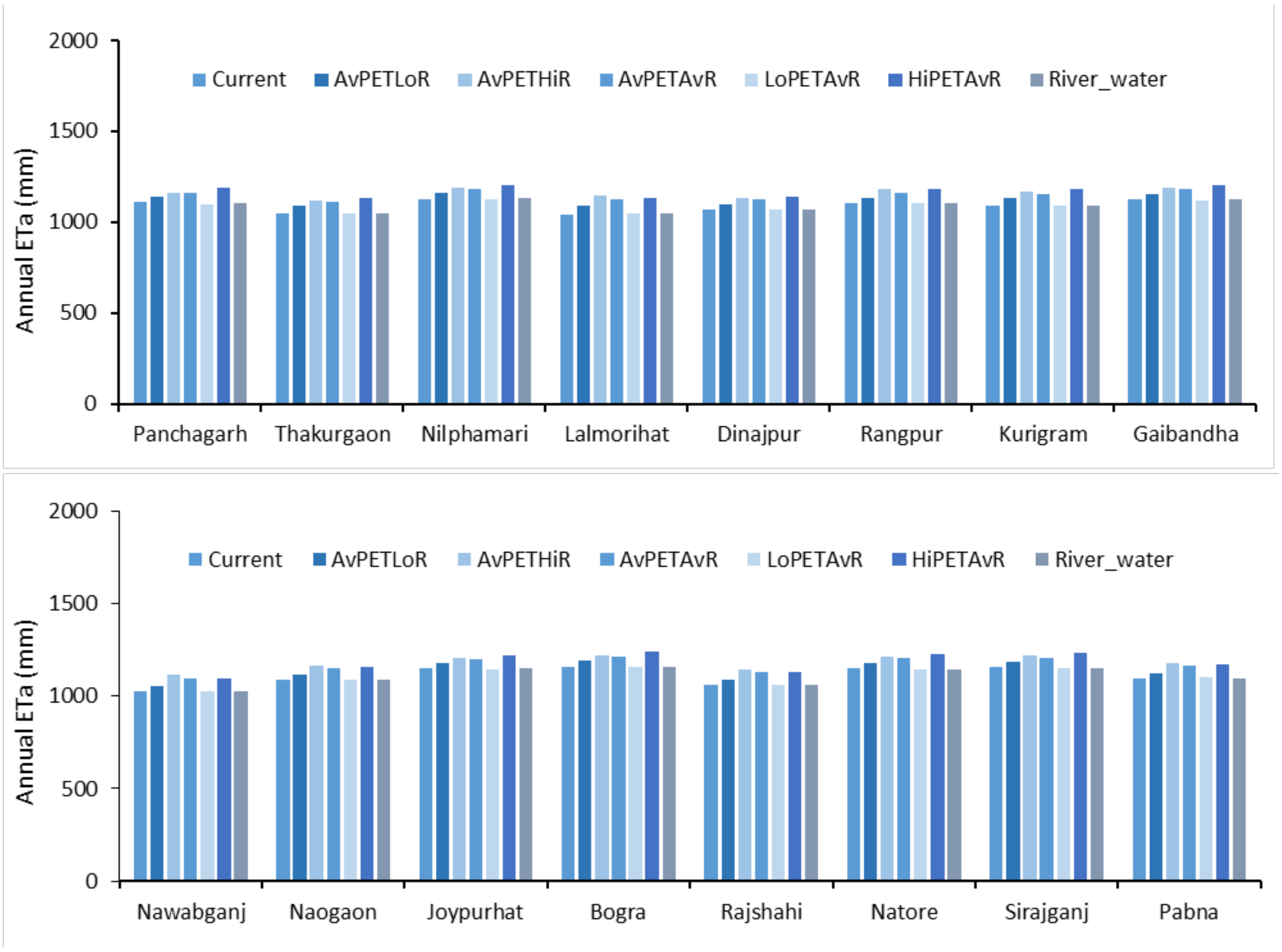

Figure 4.3 Actual evapotranspiration (ETa) in the 16-northwest districts under the climate and land management scenarios compared to current climate and land use condition

4.2.1 IMPACTS OF CLIMATE CHANGE

Figure 4.4 shows the changes in annual ETa under the future climate scenarios compared to average ETa in the period 1985 to 2015. Under the 5 climate scenarios, mean annual ETa for the entire northwest region is projected to vary from 1,098 mm for the low PET and average rainfall (LoPETAvR) scenario to 1,193 mm for high PET and average rainfall (HiPETAvR). Under an average future climate scenario (AvPETAvR), projected mean ETa is 1,161 mm which is 61 mm more than the current climate (about 5.6% increase). The increase in ETa under the low rainfall scenario (AvPETLoR) is relatively low (31 mm, 2.9%) compared to 72 mm (7.0%) under the high rainfall scenario (Figure 4.4). Under climate scenarios, maximum ETa of 1,237 mm is projected for Bogra and minimum ETa of 1,026 mm is projected for Nawabganj.

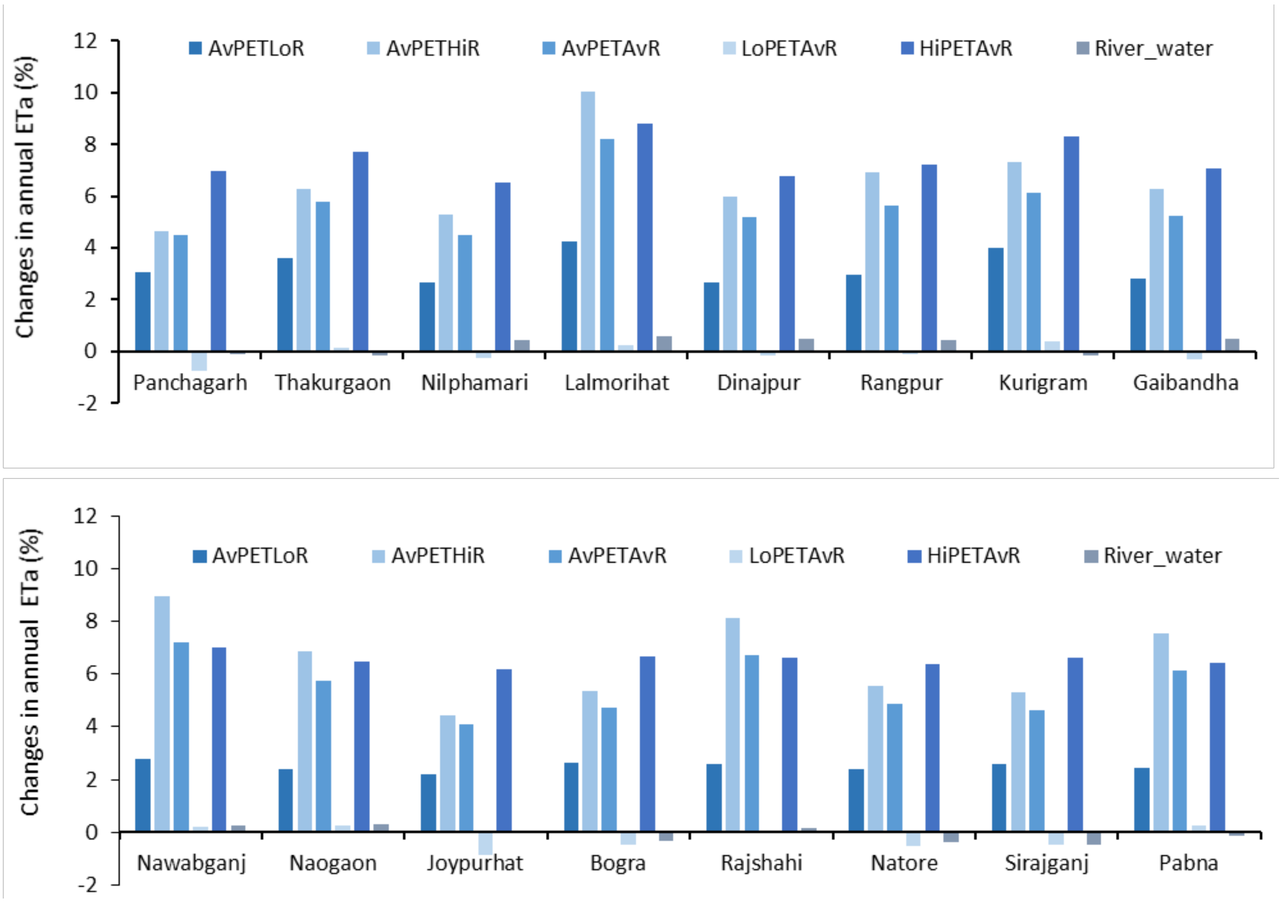

Figure 4.4 Changes in mean annual evapotranspiration (ETa) in the 16-northwest districts under the climate and irrigation source scenarios compared to current climate and land use condition

4.2.2 Impacts of increased surface water use for irrigation

Impact of irrigation water source on ETa is very nominal (Figure 4.4). The mean annual ETa across the region is 1,101 mm for the increased river water scenario (80% GW and 20% SW), which is only 1 mm more than the current condition (97% GW and 3% SW). Across the 16 districts, ETa varies from 1,026 to 1,156 mm compared to 1,024 to 1,160 mm for the current condition.

4.3 Groundwater level

Figure 4.5 presents the summary of groundwater declining rate in the 16 districts of the northwest region for the current and projected future climates. Results shows that the declining rate varies from 8 mm/year (Bogra) to 203 mm/year (Nawabganj). The rate is very high for the Nawabganj (203 mm/year) and Rajshahi (76 mm/year) compared to most other districts. In the Dinajpur, Naogaon and Pabna districts, the declining rate is relatively small (~30 to 35 mm/year) compared to Nawabganj and Rajshahi, but high compared to 11 other districts where the declining rate is less than 20 mm/year (Figure 4.5).

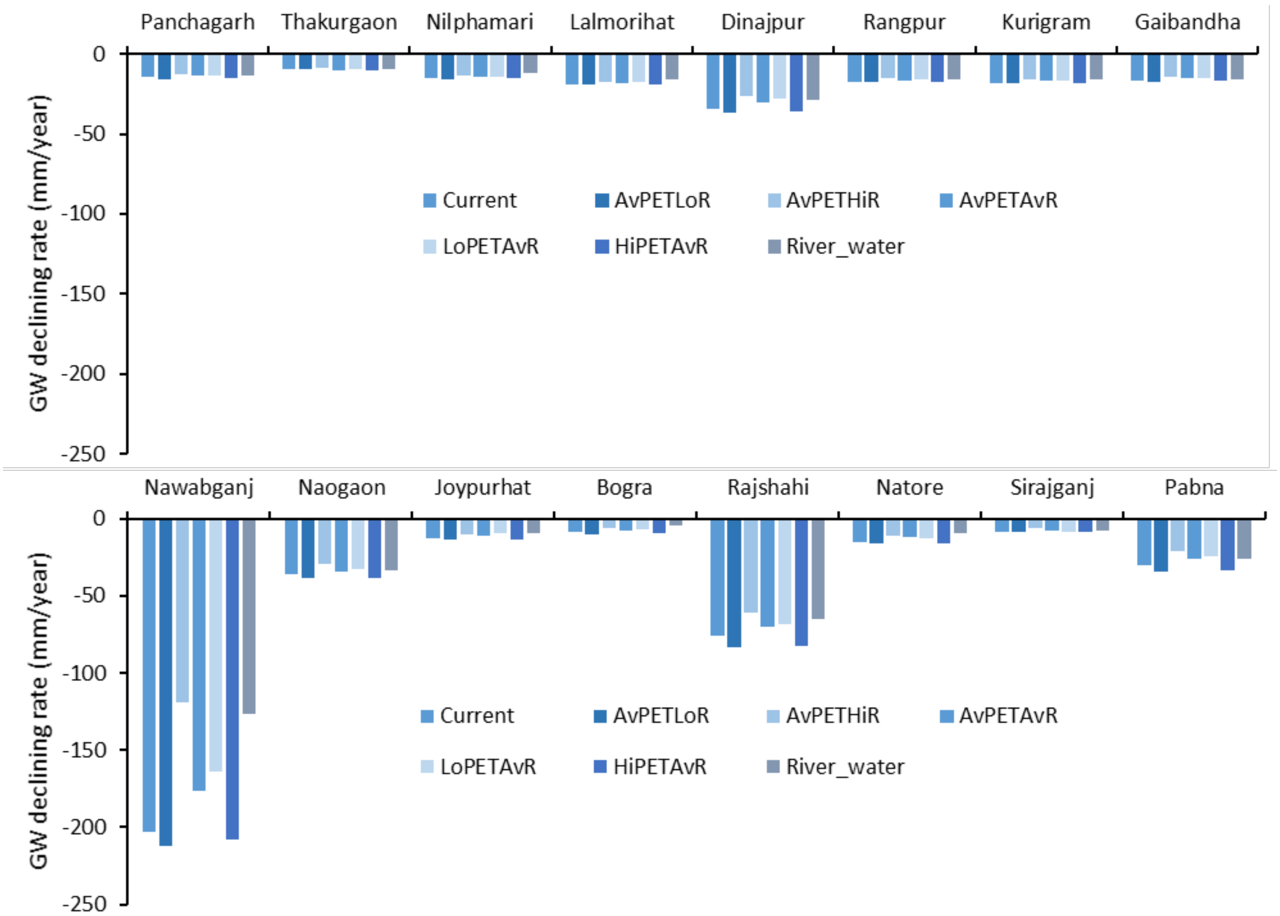

Figure 4.5 Declining rate of groundwater in the 16-northwest districts under the current and future climate and river flow scenarios

4.3.1 Impacts of climate change

Projected changes in groundwater level under the climate change scenarios are positive (i.e., less declining) for 3 scenarios (AvPETHiR, AvPETAvR, LoPETAvR) and negative for 2 scenarios (AvPETLoR, HiPETAvR) (Figure 4.6, Table 4.1). However, the positive impacts are higher (up to 42%) compared to negative impacts (<20%). For the average climate scenario (AvPETAvR), the reduction in declining rate varies from 0.3 mm/year (Rangpur) to 20.7 mm/year (Natore) for the 16 districts. As expected, both low rainfall and high PET scenarios added further decline in groundwater level compared to current condition. The decline for low rainfall scenario varies from 0 to 18.9 mm/year while for the high PET scenario maximum decline is 14.0 mm/year (Figure 4.6).

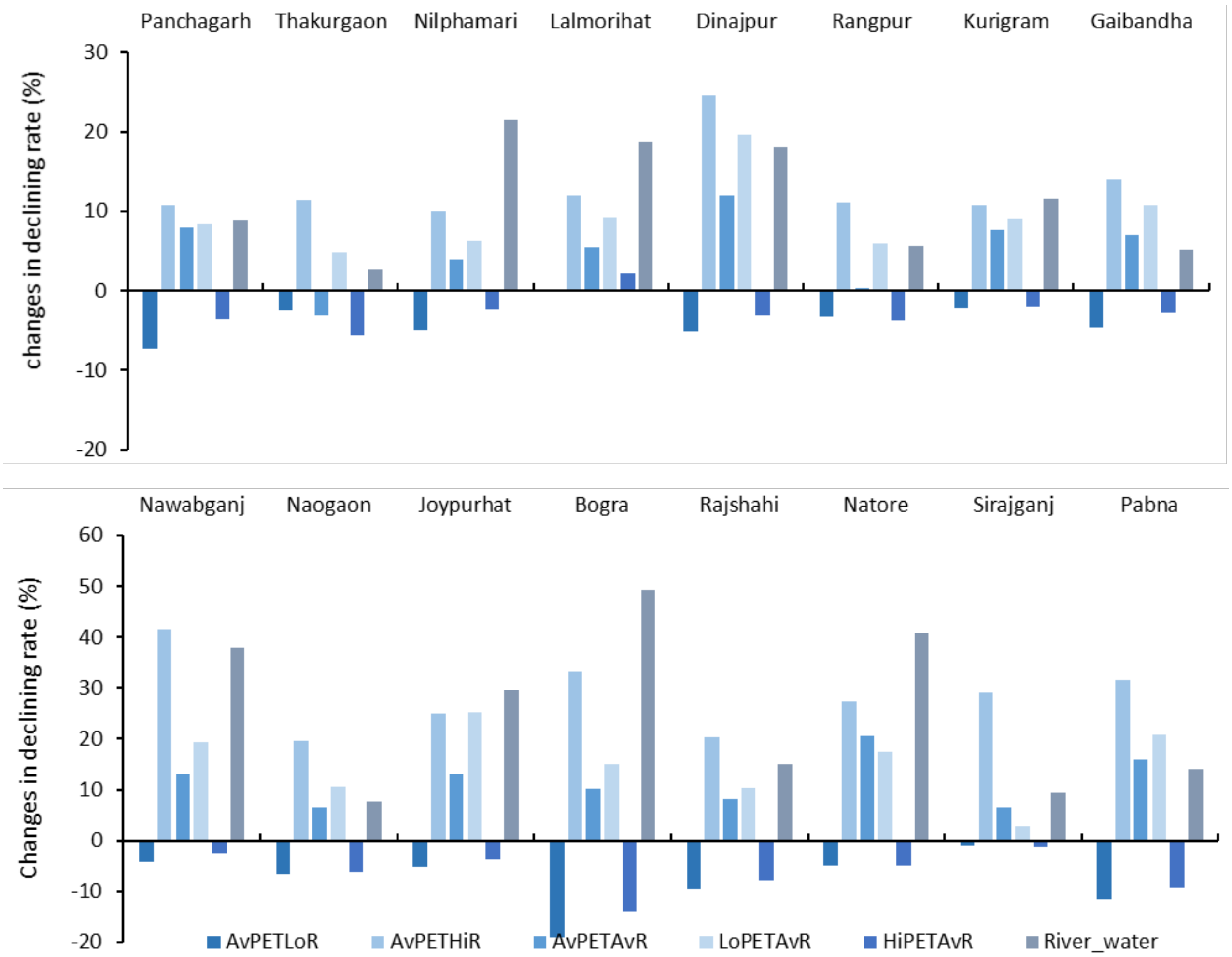

Figure 4.6 Changes in declining groundwater level with respect to current trend in the 16-northwest districts under the future climate and river flow scenarios

Table 4.1 Projected changes in groundwater trend under future climate and river flow scenarios compared to current condition

District	Current declining rate (mm/Year)	Projected changes under different scenarios (mm/year, negative sign indicates further decline and positive sign indicates less decline compared to current trend)					
		AvPETLoR	AvPETHiR	AvPETAvR	LoPETAvR	HiPETAvR	River_water
Bogra	8	−2	3	1	1	−1	4
Dinajpur	35	−2	9	4	7	−1	6
Gaibandha	16	−1	2	1	2	0	1
Joypurhat	13	−1	3	2	3	0	4
Kurigram	18	0	2	1	2	0	2
Lalmonirhat	19	0	2	1	2	0	4
Naogaon	36	−2	7	2	4	−2	3
Natore	15	−1	4	3	3	−1	6
Nawabganj	203	−9	85	27	39	−5	77
Nilphamari	15	−1	2	1	1	0	3
Pabna	30	−4	10	5	6	−3	4
Panchagarh	15	−1	2	1	1	−1	1

District	Current declining rate (mm/Year)	Projected changes under different scenarios (mm/year, negative sign indicates further decline and positive sign indicates less decline compared to current trend)					
		AvPETLoR	AvPETHiR	AvPETAvR	LoPETAvR	HiPETAvR	River_water
Rajshahi	76	−7	15	6	8	−6	11
Rangpur	17	−1	2	0	1	−1	1
Sirajganj	9	0	2	1	0	0	1
Thakurgaon	10	0	1	0	0	−1	1

4.3.2 Impacts of water source for irrigation

The increase in river water use for irrigation (scenario S6, Table 3.3) results in lessening of the declining groundwater trend across the northwest region. Table 4.1 presents the changes in absolute term and Figure 4.6 shows the changes in proportion to current condition. The change varies between 0 and 77 mm/year across the region with an average of 8 mm/year. Among the 16 districts, highest declining rates are noticed for the Nawabganj (77 mm/year, 37.8%) and Rajshahi (11 mm/year, 14.9%) districts. Some districts (e.g., Bogra and Natore) show high proportionate change because declining rate at current condition is very small (8 and 15 mm/year respectively).

4.4 River flow

The surface water resource across the northwest region depends on 2 main sources, (i) inflow from upstream catchments through cross boundary rivers and (ii) locally generated runoff from rainfall. This study presents results from 2 sets of scenario modelling. Firstly, we have evaluated effects of inflow from boundary rivers at various locations within the northwest region and secondly, impacts of climate change on locally generated river flow assuming same inflows from upstream rivers.

4.4.1 Impacts of inflow condition

Figure 4.7 shows a typical example of changes in river flow at various locations within the northwest region for the (i) 20% more and (ii) 20% less inflow through the cross-boundary rivers. The effects of inflow are pronounced differently for different local rivers and the changes vary from 0 to 20% based on location. As expected, changes are large for the rivers that receive direct inflow from the upstream catchments (e.g., Dharla, Dudkumar, Teesta, Jamuneswari, Mohananda, Ganges, Figure 3.10) and small for other rivers (e.g., Ichamati-Jamuna). Results show that the effects of inflow also vary between months. For example, highest change for the Mohadebpur station in Naogaon was found in January (17%) and lowest in October (6%). In contrary, for the Ullapara station in Sirajganj, highest change was found in August (18%) and lowest in February (1%). At an annual scale, the increase in river flow for increased inflow is very similar to the decrease in river flow for decreased inflow (Figure 4.8).

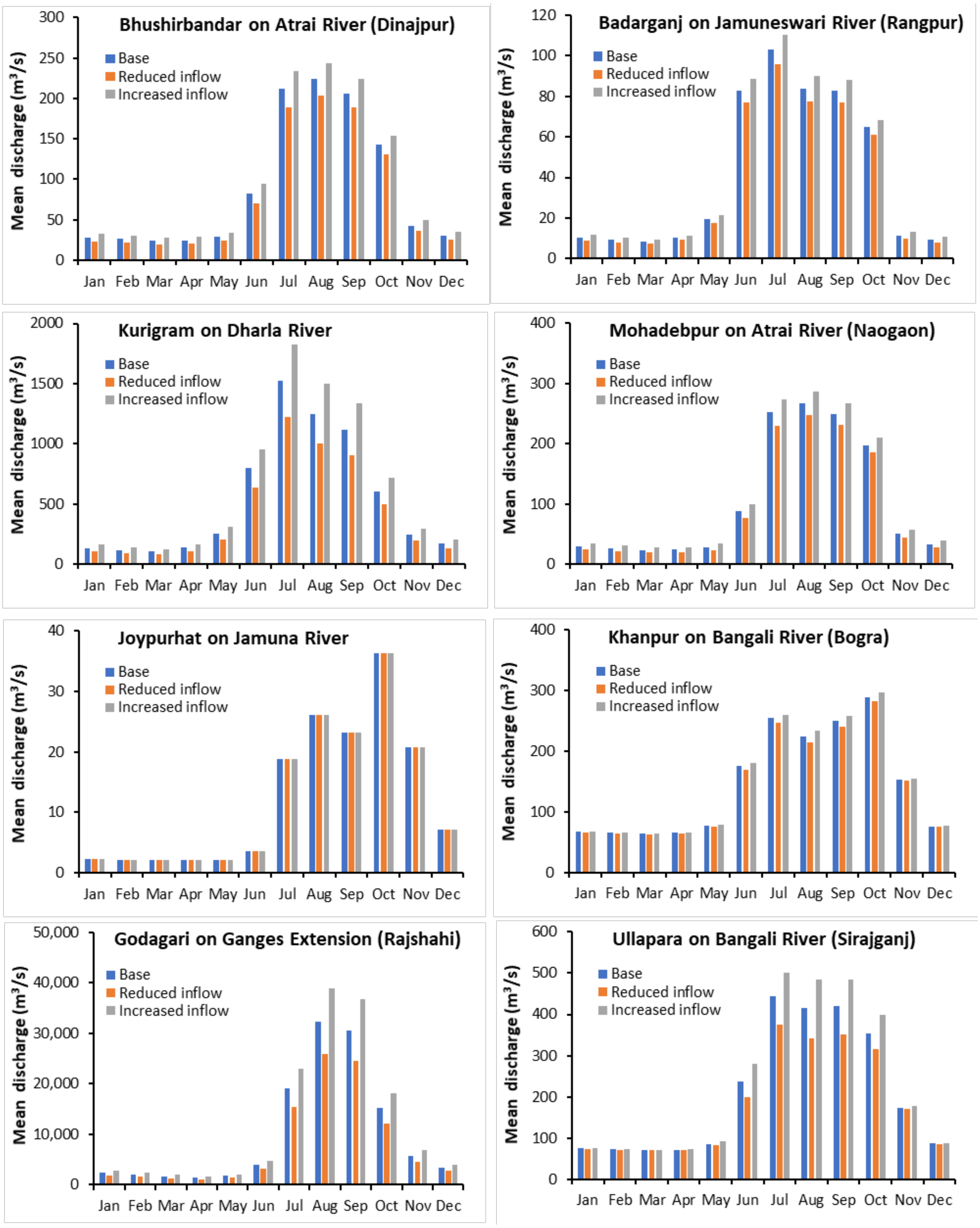

Figure 4.7 The impacts of inflow condition on river flow across the northwest region (note that y-axis values are not the same in all charts)

Table 4.2 Changes in monthly river flow at selected stream gauge sites for increased and decreased inflow scenarios

Location of flow gauge	Inflow condition	Changes in river flow with respect to current condition (%)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mohadebpur (Naogaon)	+20%	16.5	17.2	17.1	17.3	17.4	13.1	8.9	7.5	7.3	6.1	12.9	16.1
	−20%	−16.7	−17.4	−17.3	−17.5	−17.5	−13.0	−8.9	−7.5	−7.3	−6.1	−13.0	−16.1
Khanpur (Bogra)	+20%	1.9	1.7	1.5	1.3	2.0	3.1	2.8	4.3	3.4	2.2	1.0	1.7
	−20%	−1.8	−1.6	−1.4	−1.2	−2.2	−3.0	−2.1	−4.3	−3.5	−2.5	−1.1	−1.7
Ullapara (Sirajganj)	+20%	1.7	1.5	1.2	0.9	4.6	16.3	15.3	17.8	16.4	10.7	1.5	1.5
	−20%	−1.6	−1.4	−1.1	−1.6	−7.6	−18.1	−13.4	−16.8	−15.3	−12.8	−3.4	−1.7
Badarganj (Rangpur)	+20%	13.2	12.5	11.7	9.9	9.7	7.0	7.1	7.5	6.9	5.9	13.5	15.4
	−20%	−13.2	−12.4	−11.9	−9.9	−10.2	−7.0	−7.1	−7.5	−6.9	−5.9	−13.4	−15.4
Kurigram	+20%	20.0	20.0	20.0	20.0	20.0	19.6	19.7	19.6	19.3	18.1	19.8	20.0
	−20%	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5	−19.7	−19.7	−19.4	−18.1	−19.7	−20.0
Godagari (Rajshahi)	+20%	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	−20%	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0
Joypurhat	+20%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	−20%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bhushirbandar (Dinajpur)	+20%	17.4	17.3	17.1	17.2	17.4	14.4	10.6	8.9	8.7	8.4	15.2	17.6
	−20%	−17.4	−17.3	−17.2	−17.4	−17.5	−14.3	−10.6	−8.8	−8.6	−8.4	−15.2	−17.6

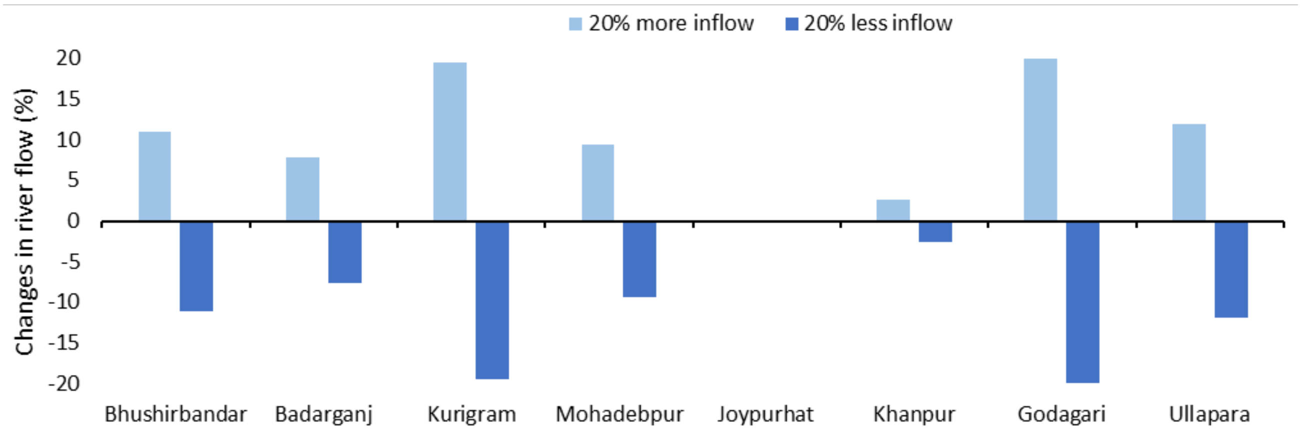

Figure 4.8 Changes in river flow at various locations under scenarios of increased/decreased inflow from upstream catchments

4.4.2 Impacts of climate change on river flow

River flow could be significantly influenced by climate change across the northwest region (Figure 4.9). As expected, changes vary based on the location and amount of inflow from the upstream. Climate impacts are more pronounced for the places where inflows from the upstream rivers are small (e.g., Badarganj on Jamuneswari River in Rangpur district and Joypurhat on Jamuna) and less pronounced where inflows from upstream rivers are high (e.g., Kurigram, Godagari and Mokrampur). The impacts also vary between months. While absolute changes are higher during wet seasons (June to October), relative change varies between months. Figure 4.10 shows the changes in river flow at selected locations under different climate scenarios.

Under the low rainfall scenario (AvPETLoR), river flow deceases in the range of 1 to 6 m^3/s; under the high rainfall scenario (AvPETHiR), river flow increases by 65%.

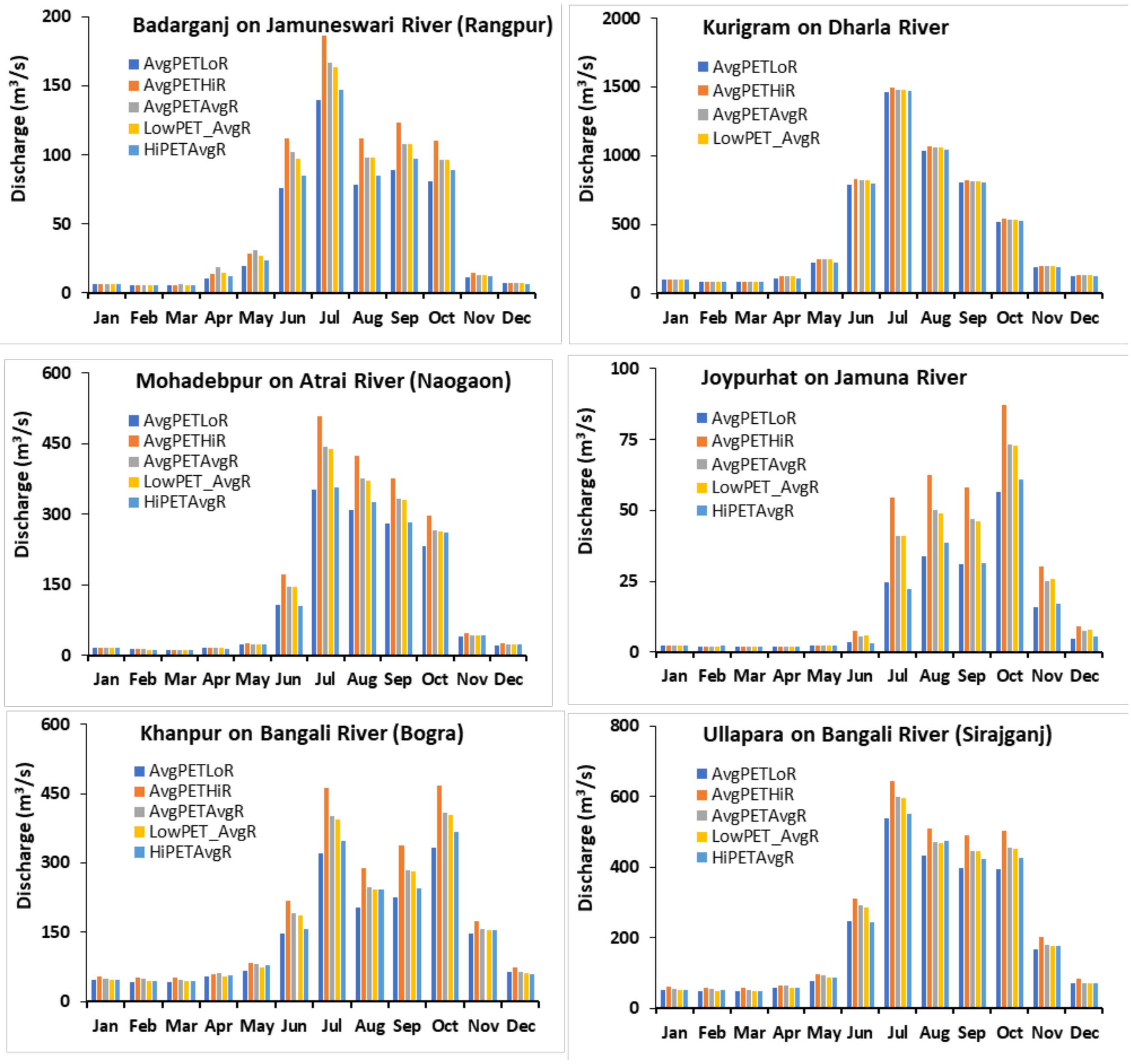

Figure 4.9 Impacts of climate change on river flow across the northwest region (note that y-axis values are not the same in all charts)

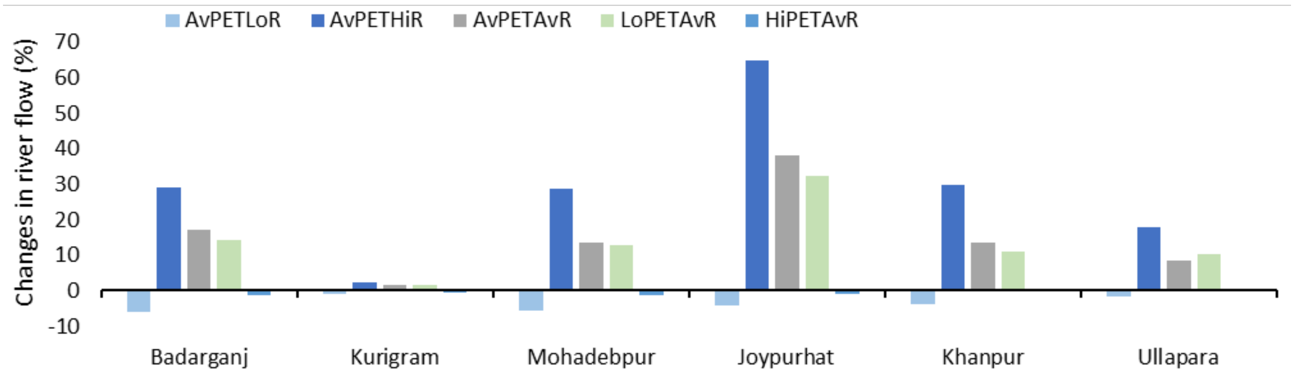

Figure 4.10 Percentage changes in river flow under the 5 climate change scenarios compared to current condition

5 DISCUSSION

This study investigated water balance in the northwest region of Bangladesh under a range of future climate and land management scenarios. Presentation and discussion of results have been limited to 3 key water balance parameters: (i) rainfall, (ii) actual evapotranspiration, and (iii) groundwater level. Findings of this study are consistent with project companion studies – district water balance (Mainuddin et al., 2021), trends in actual evapotranspiration (Mojid et al., 2021b) and groundwater modelling (Janardhanan et al., 2021) – and earlier CSIRO work in Bangladesh (Kirby et al., 2014; Mojid et al., 2019; Peña-Arancibia et al., 2020).

The study assessed that, under potential future climates, the impact on rainfall in the northwest region of Bangladesh is mostly positive (i.e., increase in rainfall) under 4 of the 5 scenarios (excepting the low rainfall scenario (AvPETLoR)). While an increase in mean annual rainfall is generally projected for the entire northwest region of Bangladesh, there is a possibility of a decrease in rainfall in some months (Karim et al., 2020). Although future projections are for generally increased rainfall, Peña-Arancibia et al. (2020) noted that in recent decades (1985–2015), rainfall has declined in all 16 districts. While the intensity of rainfall and the number of rainy days are also important for groundwater recharge from rainfall, these were not analysed in this study.

Across the region, ETa varies from year to year and between districts. This is due to interannual climate variability and cropping intensity between districts. Increase in ETa is predicted under 4 of the climate scenarios. Under an average future climate scenario (AvPETAvR), about 5.5% more ETa is predicted compared to current climate. This indicates that ETa is very likely to increase under future climate. One reason is the increase in PET due to increase in temperature. Increase in rainfall is another contributor to high ETa. This is possibly due to more water availability for evapotranspiration. In contrast, the impact of irrigation water source (i.e., more river water than current condition) on ETa was found to be minimal (<1%). This is because water available for evapotranspiration remains the same.

This study supports the declining groundwater trend across the northwest region as reported in previous studies (Kirby et al., 2014; Mojid et al., 2019; Peña-Arancibia et al., 2020) and companion reports (Janardhanan et al., 2021; Mainuddin et al., 2021). For the current climate and land use condition, the study found that the level of groundwater is declining in all 16 districts at different rates. In most districts, the rate of decrease of groundwater is small (<20 mm/year) except for the Nawabganj and Rajshahi districts. Declining rates in Dinajpur, Naogaon and Pabna districts are similar (~30–35 mm/year) and are much lower than Nawabganj (203 mm/year) and Rajshahi (76 mm/year) districts. The difference in declining rate is primarily due to less rainfall and higher proportion of groundwater use. Assuming a specific yield of 0.1 and an average decline of 30 mm/year, groundwater level could decline by 9 m in 30 years. Therefore, while overall decline is small for most of the districts, the places where the declining rate is more than 30 mm/year are concerning unless measures are taken to curb the current trend. Projected changes in groundwater level under climate change scenarios were found to be mostly positive (i.e., reducing the rate of decline). Rainfall was found to be the most sensitive factor governing groundwater level. As expected, under the high rainfall scenario (e.g., AvPETHiR), groundwater level improves and under the low rainfall (e.g., AvPETLoR) and high PET (HiPETAvR) scenarios, groundwater level worsens. This is because high rainfall increases groundwater recharge but high PET increases irrigation demand. Overall, climate change impacts can be seen as positive for the declining groundwater (e.g., less decline). Most importantly, the alarming trend in Nawabganj and Rajshahi districts could be sustainable under high rainfall scenario (AvPETHiR). The increase in groundwater level under the high rainfall scenario is higher than the decrease under the high PET scenario. This is possibly because the increase in groundwater recharge is much higher under the high rainfall scenario than the increase in irrigation demand under the high PET scenario. Overall, the effects of climate change are positive for the declining groundwater in the northwest region. Most importantly, the alarming trend in Nawabganj and Rajshahi districts could be sustainable if rainfall increases as projected.

The increase in river water use results in lessening the declining groundwater trend across the region. An increase in the proportion of surface water for irrigation means less groundwater extraction and consequently less impact on groundwater level. Across the 16 districts, the highest improvement in groundwater level is expected for Nawabganj and Rajshahi districts (77 and 11 mm/year respectively) where groundwater levels are currently declining at higher rates (203 and 76 mm/year respectively). Therefore, using more surface water for irrigation could be a potential management option. This can happen if inflow through the boundary rivers increases during the dry season (November to April), or if storages are built to capture water during wet seasons. As expected, increase in inflow produces more surface water across the region and decrease in inflow reduces the availability of water. The effects of inflow express differently for different rivers based on whether a river receives direct inflow from upstream catchments. It is important to note that effects of inflow also vary between months. As the river flow during the dry season is very small (<10%), any increase in dry season flow would be beneficial for improving the groundwater level.

It is important to note that the lateral groundwater inflow/outflow between districts is not included in the current model setup. Therefore, the results are based on the assumption that lateral groundwater inflow is the same as outflow. Moreover, there are challenges to implement district level climate inputs to subcatchment (often smaller than a district and consists of proportions of multiple districts) and return subcatchment results to district level. In this study, significant efforts were given to investigate groundwater levels for all subcatchments in a district and selected subcatchments that produced best matches to observed groundwater levels. In some cases, averaged results from multiple subcatchments produced the best matches with observed data. Therefore, where precise groundwater information is needed, a coupled surface water and groundwater model (Janardhanan et al., 2021) could be a better option.

6 CONCLUSIONS

6.1 KEY FINDINGS

- The observed groundwater has declined in all 16 districts of the northwest region over the period 1985 to 2015. In most districts, declining groundwater trend is small except for Nawabganj and Rajshahi districts. Dinajpur, Naogaon and Pabna districts show decreasing trend in the range of 30 to 35 mm/year which is low compared to Nawabganj (203 mm/year) and Rajshahi (76 mm/year) but higher than the other 11 districts. Assuming a specific yield of 0.1 and an average decline of 30 mm/year, we estimated a 9 m decline in groundwater level in 30 years. Rainfall was found to be the most sensitive factor for the groundwater level.
- Under the future climate, both rainfall and PET are expected to rise in the entire northwest region. This has positive consequences for the river flow and GWL. The positive impacts of high rainfall on GWL are much higher than the negative impacts of high PET under future climate. The declining rate of GWLs was projected to reduce under 3 of the climate change scenarios and increase under 2 of them. Overall, climate change is likely to slow down the rate of groundwater decline in the northwest region. Most importantly, the alarming trend in Nawabganj and Rajshahi could be reversed if rainfall occurs as projected for future climate scenarios. In wetter districts where current declining trends are small, the model scenario exploration suggests that GWLs will be less affected by management or climate change.
- The replacement of groundwater usage by river water extraction resulted in lessening the declining groundwater trend across the region. Across the 16 districts, the greatest improvements in groundwater level were in Nawabganj and Rajshahi districts (77 and 11 mm/year respectively) where groundwater levels are currently declining at higher rates (203 and 76 mm/year respectively). Therefore, using more surface water for irrigation could be a potential management option. This is feasible if inflow through the boundary rivers increases, or if water storages are built for irrigation supply. At places with small groundwater declines, the model scenario exploration suggests that groundwater levels are projected to be not much affected by management or climate change.

6.2 FUTURE WORK

Under the majority of future climate scenarios, rainfall is projected to increase across the entire northwest region. However, a rainfall increasing trend is not evident in the historical data. Therefore, further investigation is needed with the latest results from the GCMs (i.e., IPCC's sixth assessment report, AR6). As the groundwater level is highly sensitive to rainfall, further investigation is needed with the improved predictions of future rainfall.

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