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Modelling the impact of climate change and agricultural development scenarios on district water balances in northwest 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 011/17.

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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

Considerations of gender and social inclusion are embedded in all CSIRO SDIP projects. In this report we have assumed that improved understanding of the impacts of climate change and agricultural development 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 equitably.

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Executive summary

In this report, we describe the development of a simple, lumped, monthly water balance model to assess the impact of climate change and agricultural development scenarios on water balances in the districts of northwest Bangladesh. The model inputs include monthly rain, monthly actual evapotranspiration derived from a daily crop water use model, together with parameters that determine the partitioning of rainfall into evapotranspiration, infiltration and drainage, and runoff.

The calibration of the model with historical groundwater levels (using historical rainfall and modelled historical evapotranspiration) is generally good in all districts except Nawabganj, where the calibration is poor. This might be because Nawabganj is an area partly of river floodplain and partly of the higher ground of the Barind Tract; it may be that a lumped model which treats the area as a single unit cannot capture the overall behaviour.

We used the model to explore ten scenarios:

- five agricultural and water resources development scenarios
- five climate change scenarios.

The agricultural and water resources development scenarios included no development (crop areas held constant at the 1985 level, which is before the recent large increase in dry season irrigated Boro rice), a loss of agricultural land to other uses, increased use of river water, increased cropping intensity and the growing of more fruit trees. The climate change scenarios cover the range from high to low rainfall projections and high to low potential evapotranspiration projections.

The observed groundwater declined in most districts over the period of 1985 to 2015. However, the declines were small in most districts. Large declines were observed in three drier districts of Nawabganj, Naogaon and Rajshahi.

Modelled impacts

In wetter districts with small groundwater declines, the model scenario exploration suggests that groundwater levels are projected to be not much affected by development or climate change.

In drier districts with large groundwater declines (i.e. Nawabganj, Naogaon and Rajshahi), groundwater levels respond to the scenarios as follows:

- Development scenarios with reduced evapotranspiration (resulting from declining crop areas) or supplying 20 percent of the irrigation water from surface supplies lead to improved groundwater sustainability.
- Scenarios with same or more evapotranspiration lead to similar outcomes as at present.
- Climate change scenarios with low potential evapotranspiration or high rainfall lead to less steeply declining groundwater levels than at present – i.e. to a more sustainable position.

Climate change scenarios with high potential evapotranspiration or low rainfall lead to declining groundwater levels– i.e. to a less sustainable position.

Abbreviations, acronyms and terms used in this report

	DESCRIPTION
BIDS	Bangladesh Institute of Development Studies
BWDB	Bangladesh Water Development Board
GCMs	General (climate) circulation models
CEGIS	Centre for Environmental and Geographic Information Services
IWM	Institute of Water Modelling (Bangladesh)
NAM	Nedbor-Afstromnings Model – a rainfall-runoff catchment model
NSE	Nash-Sutcliffe Efficiency, an indicator of goodness-of-fit of the calibration against observed behaviour
PET	Potential evapotranspiration
WARPO	Water Resources Planning Organisation

1 Introduction

The CSIRO project 'Sustainable Development Investment Portfolio, Bangladesh' aims to define the sustainable level of water (particularly groundwater) use for irrigation and its impacts on the socio-economy and livelihood of the farmers (both men and women) in the northwest region of Bangladesh (Figure 1 Map of the study area).

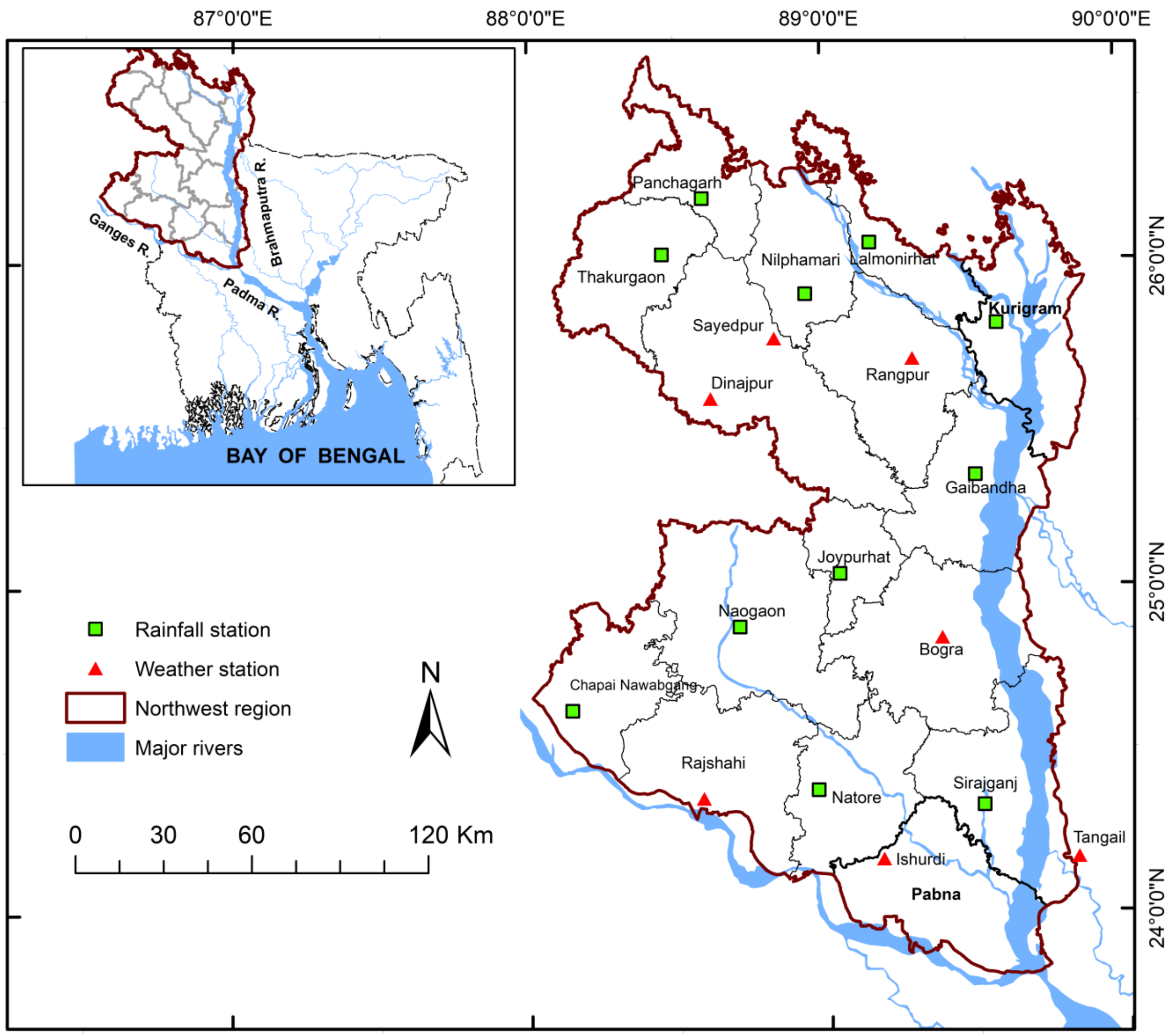

Figure 1 Map of the study area showing administrative districts and locations of meteorological stations in the northwest region of Bangladesh

A key element of the project is to explore changes to water balances under a range of scenarios (including climate change scenarios) for the districts of northwest Bangladesh.

Our aim in this report is to describe a district-scale water balance model, and to discuss using the model results to assess the impact on the water balances of agricultural and water resources development and the impact of climate change. We investigate ten scenarios, five of which are concerned with the impact of agricultural and water resources development, and five of which are concerned with the impact of climate change scenarios on the water balances.

We describe the model and the data used to run the model and the scenarios in Section 2 of this report. We then describe in Section 3 the use of the model to assess the impact on the district water balances of the scenarios. We give overall conclusions in Section 4.

1.1 Companion reports

This report is one of a series of reports from the project. Others describe surface water (catchment and river flow) assessment, groundwater depth trend analysis, groundwater modelling, land cover and cropping system analysis, and socio-economic assessment. The deep drainage estimated by the water balance analysis described in this report was used as an input to the groundwater modelling (Janardhanan et al., 2021). The irrigation demand results were used as an input to the surface water assessment (Karim et al., 2021). The estimated crop evapotranspiration was used to compare with the remote sensing based estimation of crop evapotranspiration (Pena-Arancibia et al., 2021). The groundwater levels collated into a database for use in the trend analysis report (Hodgson et al., 2021) were used in the study described in this report to calibrate the water balance models for each district. The remote sensing evapotranspiration results from Peña-Arancibia et al. (2020a) were used to validate the evaporation results used here.

1.2 Previous studies

Several other studies have estimated water balances in the northwest Bangladesh.

We used an approach based on that used by Kirby et al. (2015), who studied regional water balances in Bangladesh. Both the current study and that of Kirby et al. (2015) assessed monthly water balances for a sequence of about 30 years. However, there are some key differences between their approach and that adopted here. Firstly, as mentioned, their study was of regional water balances, while here we assess district water balances in the northwest region. The greater detail allows the assessment of areas within the region which are using water sustainably and those which are not. Secondly, they used a simple monthly calculation of actual evapotranspiration, whereas we use here a daily water use calculation, although we aggregate the results to monthly for use in the water balance calculation.

2 Methods: data sources, water balance and scenarios

In this section, we describe data sources used as input to the model, the model, and its calibration. We then describe the scenarios used to assess the impacts of agricultural and water resources development and the impacts of climate change.

2.1 Input time-series data: rainfall, actual evapotranspiration and river water level

The inputs for the district water balance model include two sets of observed time-series data, rainfall and river water level, and one derived dataset, actual evapotranspiration. The datasets are for each district, and cover the 30-year period 1985 to 2015.

The rainfall datasets for 1985 to 2010 were developed during an earlier CSIRO project, the Bangladesh Integrated Water Resources Assessment project (CSIRO et al. 2014), and described in the regional water balance study of Kirby et al. (2015). As part of the current project they have been updated to 2015, using data acquired from project colleagues in Bangladesh. The data from 2010 to 2015 in some cases gave much lower totals than those in the 1985 to 2010 dataset and also had missing data. In addition, not all of the rainfall stations in the earlier dataset were present in the later dataset; in some cases such as Nawabganj, data from another nearby gauge were used for the later period. This must be borne in mind when reviewing the results.

The actual evapotranspiration dataset was developed as part of this project. It is based on a daily crop coefficient model of crops and non-crop vegetation in northwest Bangladesh, as described in Peña-Arancibia et al. (2020a). The one-dimensional evapotranspiration from several crops, crop groups and non-crop vegetation was calculated using that model, and the results multiplied by the area of each crop or vegetation type, and then summed to give the total actual evapotranspiration for the district. The crop and vegetation type areas were developed from agricultural survey data; the areas of the main crop types are shown in Figure 2.

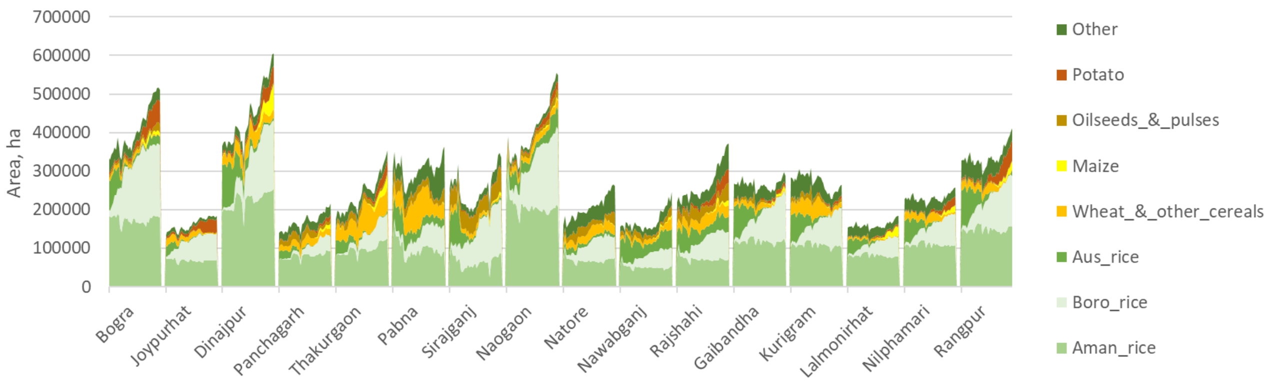

Figure 2 Areas of main crop types from 1979–80 to 2015–16 in the 16 districts of northwest Bangladesh. Data sourced from Bangladesh agricultural survey data. Crop data prior to 2005 were disaggregated from the earlier 5-district data into the 16 districts from that date onwards

Peña-Arancibia et al. (2020a) compared the crop coefficient modelled time-series to time-series developed using remote sensing. The results of the comparison are shown in Figure 3. The comparisons have correlation coefficient between 0.75 in the worst case, and 0.89 in the best; the Nash-Sutcliffe Efficiency varies from 0.36 to 0.77; the maximum absolute bias is 8.36 %; and the greatest difference in mean monthly actual evapotranspiration is 5.4 %. The results of the comparison suggest that the crop coefficient modelled time-series are likely to be reasonable estimates of the actual evapotranspiration, and may be used with reasonable confidence in district water balance modelling.

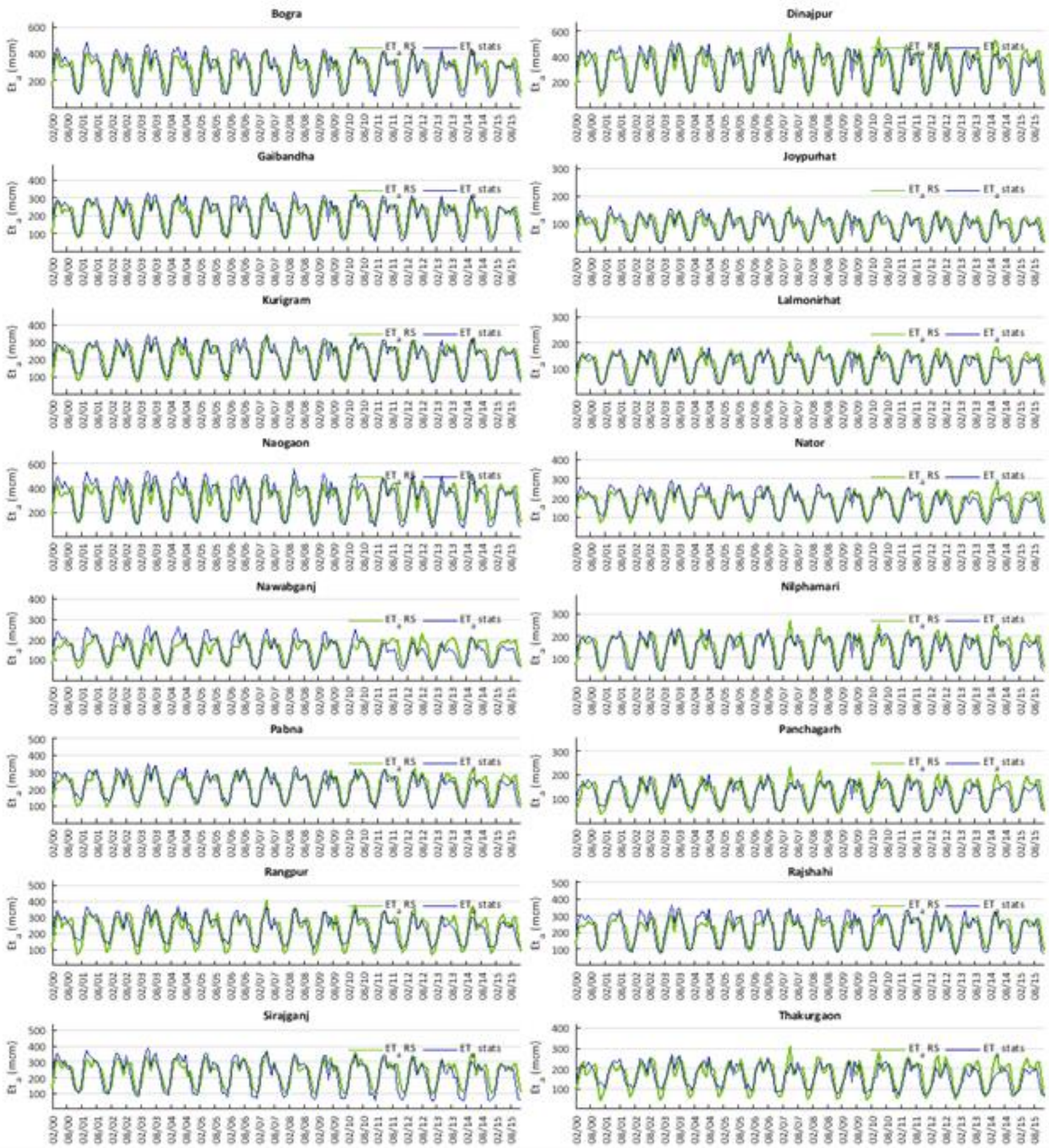

Figure 3 Comparison of actual evapotranspiration time-series from a crop-coefficient model and a remote sensing based model for the 16 districts of northwest Bangladesh from 2000 to 2015 (adapted from Peña-Arancibia et al. 2020a)

River level data (as a monthly time series) were made available from the work of the Institute of Water Modelling (IWM) within the project. There are gaps in the gauge data which would distort the averages; gaps were filled with the average value obtained by averaging all months for which there were valid data. Some values appeared erroneous, falling completely outside the range of values for the river in question; such values were also replaced by the average from months with valid data. Where more than one gauge was available for a district, we averaged the gauge data for that district. The average is a straight arithmetic average, not weighted for river length. Where a gauge was on or near the boundary between two districts (such as where a river forms a district boundary), we used the values for that gauge in both districts.

2.2 District water balance model

The model is a simple lumped water balance on a monthly timestep. The model is shown schematically in Figure 4.

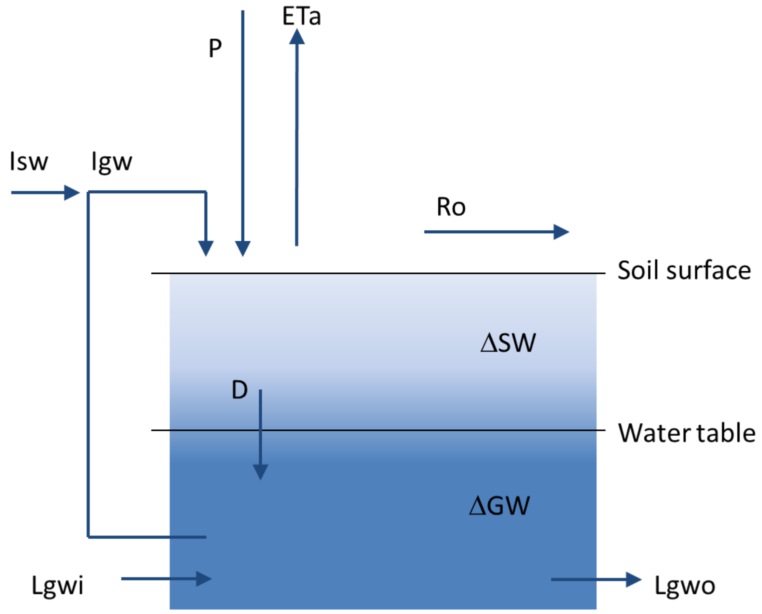

Figure 4 Schematic diagram of the district water balance model. The terms considered in the water balance are rainfall, *P*, actual evapotranspiration, *ETa*, runoff, *Ro*, irrigation from groundwater, *Igw*, irrigation from surface (river) water, *Isw*, drainage from the soil to the groundwater, *D*, change in soil water storage, *ΔSW*, change in groundwater storage, *ΔGW*, lateral inflows to groundwater, *Lgwi*, and lateral outflows from groundwater, *Lgwo*

The soil water balance in a monthly timestep for the setup in Figure 4 is given by:

$$P + Isw + Igw - ET_a - RO - D + \Delta SW = 0 \quad (1)$$

where the symbols are defined in Figure 4. The groundwater balance is given by:

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

where $\Delta Lgw = Lgwi - Lgwo$.

Combining the two, the overall balance is given by:

$$P + \Delta Lgw + Isw - ET_a - RO + \Delta SW + \Delta GW = 0 \quad (3)$$

Rainfall and actual evapotranspiration are input as data (as described further below). The evaluation of the balance equations proceeds by first calculating the difference between rain and actual evapotranspiration. If rain exceeds actual evapotranspiration, the excess can infiltrate the soil surface to add to the soil water storage (i.e., ΔSW is positive). There is a maximum infiltration rate; if the excess rain is greater than the maximum infiltration rate, the infiltration excess goes to runoff. The soil water storage is depleted by evapotranspiration and drainage from the base of the soil to the groundwater. If the soil water storage exceeds the maximum soil water storage after the addition of infiltration and the removal of evapotranspiration and drainage, the excess is added to runoff. The soil evapotranspiration ET_{soil} and soil drainage D_{soil} are considered to be water content dependent, governed by the following two equations:

$$ET_{soil} = (SWC / SWC_{Max})^{ETexp} \quad (4)$$

$$D_{soil} = (SWC / SWC_{Max})^{Dexp} \quad (5)$$

where SWC and SWC_{Max} are the soil water content per unit depth, and the maximum soil water content per unit depth, and ET^{exp} and D^{exp} are adjustable parameters to be fixed by calibration.

In those months with a surface water deficit, with the actual evapotranspiration exceeding rainfall, the soil water is depleted by the smaller of the soil evapotranspiration evaluated according to equation (4) and the surface water deficit. If soil evapotranspiration evaluated according to equation (4) is insufficient to satisfy the surface water deficit, the remainder is taken from groundwater as the term *Igw* in equation (2), except in scenarios where there is an input of surface (river) water. Surface water was used in only two scenarios, to be discussed below; in all other scenarios the surface water term *Isw* in equation (3) was zero. In the two scenarios with surface water, its value was externally defined.

Lateral flows into and out of the groundwater are considered to result from an exchange with the rivers. This follows the evidence in CSIRO et al. (2014) and Mainuddin et al. (2014), and the treatment discussed in Kirby et al. (2015). We used an equation of the same form that they used:

$$\Delta Lgw = C_{lf}\,(RWL - RWL_O - GWL) \quad (6)$$

where GWL is the groundwater level, RWL is the river water level, RWL_O is an offset to account for the difference in datum between measured river level heights and groundwater depths, and C_{lf} is a lateral flow constant. RWL_O and C_{lf} are adjustable constants to be determined by calibration.

Finally, the change in groundwater depth is related to the change in groundwater volume, determined from equation (2), by:

$$\Delta GWL = S_y \Delta GW \quad (7)$$

where S_y is the specific yield, to be determined by calibration.

As we will discuss below, the model as shown above did not calibrate well for some districts. In particular, for those districts where there is a strong trend of declining groundwater levels, the model did not show a trend as great as that observed. Peña-Arancibia et al. (2020a) suggested that the trends of declining groundwater levels may not be fully explained by increased pumping for irrigation (because the consumption of water as actual evapotranspiration has not changed greatly), and that another factor may be the change in landscape infiltration resulting from the large increase in *Boro* rice cultivation in recent years. (Yet other factors could be involved; see Peña-Arancibia et al. 2020b.) Therefore, we assumed that the maximum infiltration rate into the soil was given by:

$$INFL_{max,i} = INFL_{max,0}\ (Area_{Dist} - Area_{Boro,i}) / (Area_{Dist} - Area_{Boro,0}) \quad (8)$$

where the maximum infiltration rate at the start, and at month i are $INFL_{max,0}$ and $INFL_{max,i}$, and the total area of the district and the area of *Boro* are $Area_{Dist}$ and $Area_{Boro}$.

The model is written as a Visual Basic for Application (VBA) macro within an Excel spreadsheet (in Module 2 of the spreadsheet). Input time-series data are given on separate worksheets for rain, actual evapotranspiration, river water level, groundwater level and the area of *Boro* rice. Output time-series data are given on a separate worksheet for each district. Some other worksheets contain summaries of the results. The macro is run separately (and manually) for each district.

2.3 Model calibration

Groundwater level data (Figure 5) were used to calibrate the model. The 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.

The calibration was performed using a downhill simplex optimisation method, which is used to maximise the Nash-Sutcliffe Efficiency of the fit of modelled to observed groundwater levels. The optimisation routine is in the VBA macro in Module 1 of the Excel spreadsheet. (Thus, Module 1 is used for optimisation of the water balance coefficients in calibration, and Module 2 is used to evaluate the water balance without optimisation, such as for assessing a scenario.)

A key difficulty with calibrating the district water balance model is the lack of data with which to fully run and test the results. In particular, the lateral flows from the groundwater are somewhat interchangeable with runoff. To achieve a mass balance, a model that suggests greater lateral outflows from groundwater must have lesser surface runoff (for the same soil water storage and groundwater levels). A result of this is that in most districts, many sets of model parameters give similar model fits and similar overall behaviour, but with varying splits between lateral flow and runoff. We have noted this behaviour during calibration, and have allowed for it by starting the optimisation from different starting points (i.e. starting from different sets of initial model coefficients) and keeping track of the Nash-Sutcliffe Efficiencies of the various trial starting points. The calibrations discussed below are those with the highest Nash-Sutcliffe Efficiency, excepting that for the district of Nawabganj, discussed further below. We do not explore this issue further here, but note that it is an area that may repay further investigation.

The results of an initial calibration using a model **without the landscape infiltration effect** given by equation (8) are shown in Figure 5, superimposed on the observed groundwater data. The model provides a reasonable fit to most districts, with the Nash-Sutcliffe Efficiencies (excepting Nawabganj) varying from 0.53 to 0.86 (as shown on Figure 5). However, a close inspection reveals that it does not capture the obvious declining groundwater levels of Joypurhat, Naogaon, Nawabganj, and Rajshahi, and the lesser declines evident in Bogra, Natore, Pabna, and possibly Panchagarh and Thakurgaon.

The calibration was repeated using the model **with the landscape infiltration effect** given by equation (8). The result is shown in Figure 6, superimposed on the observed groundwater data.

Figure 5 Groundwater levels for the 16 districts of northwest Bangladesh based on model with constant infiltration. Observed (orange) and modelled (blue) groundwater levels resulting from calibration for the 16 districts of northwest Bangladesh, using the water balance model that does not include the varying landscape infiltration effect of equation (8). The Nash-Sutcliffe Efficiency (NSE) is shown on each plot

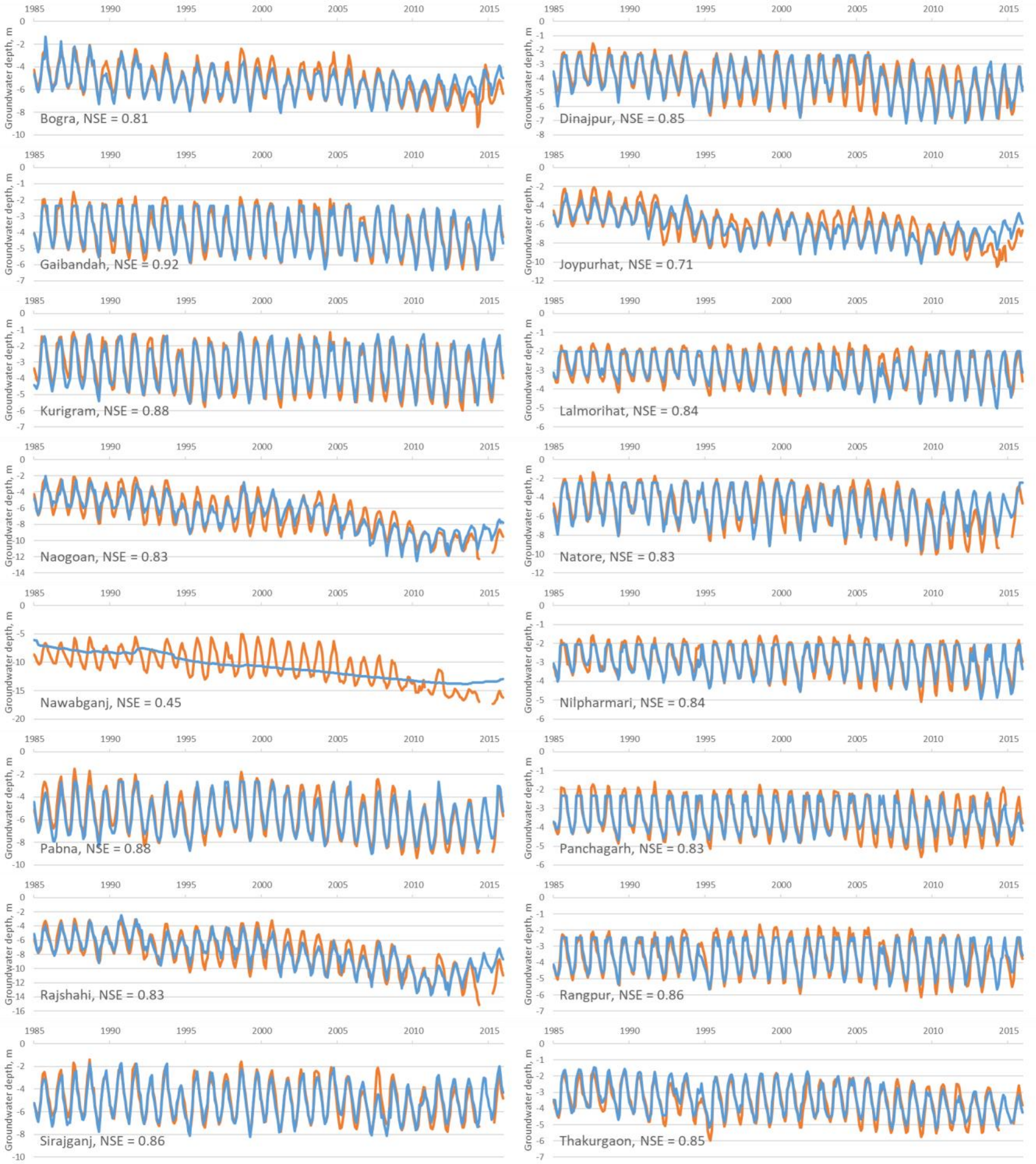

Figure 6 Groundwater levels for the 16 districts of northwest Bangladesh based on model with varying infiltration. Observed (orange) and modelled (blue) groundwater levels resulting from calibration for the 16 districts of northwest Bangladesh, using the water balance model that includes the landscape infiltration effect of equation (8). The Nash-Sutcliffe Efficiency (NSE) is shown on each plot

With the exception of the district of Nawabganj, the fits of the model to the groundwater level data are all reasonable, showing both the seasonal rise and fall of the groundwater, and the trend (if any) over the period. Excepting Nawabganj, the Nash-Sutcliffe efficiencies vary from 0.71 to 0.92 (as shown on Figure 6). Nevertheless, the model simulations show a rise in groundwater levels in the last three years or so that is observed but less pronounced in the measured data in a few districts, particularly Bogra and Joypurha. This mismatch over the last few years could be due to the change referred to in the previous section in the source of rainfall data in the case of Joypurhat (which used the data for CL520 from 1985 to 2010 and for Bogra from 2010 to 2016), but not Bogra, which used the same station (Bogra) throughout.

Nawabganj shows only the trend, but not the seasonal rise and fall, and has a Nash-Sutcliffe Efficiency of 0.45. Other combinations of parameters showed the seasonal rise and fall but did not fit the trend well; in one case the simulation had a higher Nash-Sutcliffe Efficiency (of 0.50), despite lack of fit to the trend. These other solutions all had very low, and unlikely, specific yields of around 0.005 or less, and showed numerically unstable behaviour in the climate change scenarios discussed below. Therefore, we chose the model that showed the trend reasonably well.

The reason for the poor fit of the Nawabganj district is not clear. The district includes both the lower ground around the Mohananda River and, in the east of the district, the higher ground on the western side of the Barind Tract. The water table depths are quite different in the two areas (see Figure 15 of CSIRO et al. 2014 and Figure 3-24 of Hodgson et al. 2014), and the water balance dynamics of the two parts of the district are likely to be quite different. It may be that the differences within the district cannot be captured in a single non-spatial model. However, to some extent this is true of some other districts, so this possible explanation is not altogether satisfactory. On the other hand, the poor fit may result from the mixed rainfall sources referred to in sub-section 2.1; the rainfall data for Nawabganj were from station CL215 for 1985 to 2010 and from Rajshahi for 2010 to 2016. Again, this is also true in other districts.

2.4 Scenarios for assessing the impact of agricultural and water resources development and of climate change

We assessed the impact on the water balance of ten scenarios, where the impact is given by the change from a base case scenario of current conditions. The scenarios are summarised in the following table, and described more fully below.

	CROP AREA	SURFACE WATER USE	PET CHANGE	RAINFALL CHANGE
1. Base case	2015	No	No	No
2. No development	1985	No	No	No
3. Loss of agricultural land	Reduced from 2015 such that PET declines 5 %	No	No	No
4. Surface water	2015	20 %	No	No
5. Fruit trees	2015, with 10 % of the rice area converted to fruit trees	No	No	No
6. Increased crop area	33 % increase in crop intensity	Additional water from surface	No	No
7. Climate change				
7.1 AvPAvR	2015	No	Average	Average
7.2 AvPLoR	2015	No	Average	Low
7.1 AvPHiR	2015	No	Average	High
7.1 LoPAvR	2015	No	Low	Average
7.1 HiPAvR	2015	No	High	Average

2.4.1 Current conditions scenario (base case)

This scenario acts as a base case and is the same as the calibrated models for each district described above, except that the areas of crops and other vegetation are held constant at their 2015 values rather than varying throughout the simulation period. The impact of other scenarios will be compared to the current scenario.

2.4.2 No development scenario

Agricultural development, particularly the rise of large areas of irrigated dry season (*Boro*) rice, is seen as responsible for the perceived unsustainable use of groundwater in parts of the northwest region of Bangladesh. We investigate the impact of development with this scenario. The scenario is identical to the current scenario, except that the areas of crops and other vegetation are held constant at their 1985 areas. In particular, this means that the areas of *Boro* rice are small. This scenario was also assessed at the regional level by Kirby et al. (2015).

2.4.3 Loss of agricultural land scenario

In northwest Bangladesh, agricultural land is being converted to other uses (mostly urban and industrial) at a rate of 0.52% per year in the Rajshahi division (the southern half of the northwest region) and at 0.17% per year in the Rangpur division (the northern half) (Rai et al. 2017). Sarker and Wakil (2018) give a similar figure for Rajshahi. If this were to continue at the same rate to 2050, the loss of agricultural land would be about 15% in the southern part of the region and about 5% in the northern part. The urban and industrial land that replaces the agricultural land would presumably have less vegetation and hence a lower actual evapotranspiration. However, the actual evapotranspiration would not be zero. Here, we arbitrarily assumed that the actual evapotranspiration would diminish by 5% in all districts. The scenario is otherwise identical to the current scenario.

2.4.4 Use of surface water scenario

Current agricultural policy in Bangladesh envisages substituting some groundwater use with river water, in order to curb the supposed unsustainable use of groundwater (Government of Bangladesh 2012). In this scenario, we assumed that 20% of the water for irrigation comes from surface water (i.e. local rivers or from storage in ponds and canals) rather than groundwater. This scenario was also assessed at the regional level by Kirby et al. (2015), though based on a 2010 land use, rather than 2015 as here.

2.4.5 More fruit trees scenario

This scenario implements the policy on increasing fruit production / conversion land use to fruit trees. In this scenario, we assumed that 10% of the rice area would be replaced by fruit trees.

2.4.6 Increase in area of crops scenario

As shown in Figure 2, the areas of crops are increasing. However, the area available for crops is decreasing (see the loss of agricultural land scenario in sub-section 2.4.3), so the increase in actual crops is being achieved largely through increasing intensity of cropping – that is, growing more crops per year on the same piece of land. In this scenario we assumed that the cropping intensity would increase such that overall there was a 33% greater area sown to crops. The whole of the increased water demand from the increased area of crops is taken from surface water. This scenario was also assessed at the regional level by Kirby et al. (2015), though based on a 2010 land use, rather than 2015 as here.

2.4.7 Climate change scenarios

The water balance and cropping opportunities will be affected by climate change. For the water balance study reported here, we chose five climate change scenarios, each based on the RCP4.5 emissions scenario and each based on a different general circulation model (GCM). The GCMs were selected as shown in the Appendix A. They were chosen to give contrasting changes in rainfall and potential evapotranspiration in northwest Bangladesh:

- average change in rainfall with average change in potential evapotranspiration (labelled AvPETAvR in the figures in the next section)
- most negative (or least positive) change in rainfall with average change in potential evapotranspiration (AvPETLoR)
- most positive change in rainfall with average change in potential evapotranspiration (AvPETHiR)
- average change in rainfall with most negative (or least positive) change in potential evapotranspiration (LoPETAvR)
- average change in rainfall with most positive change in potential evapotranspiration (HiPETAvR).

We developed projections of changed climates for the period 2046 to 2075 for the districts based on an empirical downscaling or change-factor approach (Zheng et al. 2018), using seasonal scaling factors derived from the five GCMs. More detail on the selection of GCMs and projected climate change time series of rainfall and potential evapotranspiration can be found at Karim et al. (2020).

2.5 Water balance model evaluation of the scenarios

For the agricultural and water resources development scenarios, the area of crops changed from those of the current scenario, with the exception of the surface water use scenario. For these scenarios (except the surface water use scenario), the district actual evapotranspiration was re-calculated by first calculating the new area for each crop, crop group and non-crop vegetation. The new areas were then multiplied by the actual evapotranspiration under the current scenario for each crop or vegetation type, and then summed to give the total actual evapotranspiration for the district. The surface water use scenario and the increased crop areas scenario involved some substitution of groundwater by river water. This was simulated by slightly modifying the model to remove less water from the groundwater, and use in addition an externally defined source – i.e. the river water.

For the climate change scenarios, the area of crops remained the same as those in the current scenario. For these scenarios, the district actual evapotranspiration was re-calculated by re-calculating the one-dimensional evapotranspiration from the crops, crop groups and non-crop vegetation under the changed potential evapotranspiration. The results were multiplied by the current area of each crop or vegetation type, and then summed to give the total actual evapotranspiration for the district.

The actual evapotranspiration for each scenario was then used in the water balance model. For the climate change scenarios, the rainfall was also changed in the scenario model runs. All other model inputs were held the same as for the current scenario.

3 Water balance scenario results

In this section of the report, we outline the results of the water balance scenario assessments.

3.1 Rainfall

The annual rainfall in the various scenarios is summarised in Figure 7. The average annual rainfall over the 30-year period 1985 to 2015 varied from 1,428 mm (minimum 792 mm, maximum 2,062 mm) in Rajshahi district to 2,543 mm (minimum 1,635 mm, maximum 3,599 mm) in Kurigram.

The rainfall in the 5 agricultural and water resources development scenarios (No_Development, Loss_AGLAND, River_water, More_FruitTrees, Area_increase) is the same as that in the current scenario (Current).

In the five climate change scenarios, the average annual rainfall in Rajshahi is projected to vary from 1,403 mm (AvPETLoR, average PET, low rainfall scenario) to 1,741 mm (AvPETHiR, average PET, high rainfall scenario), whereas that of Kurigram is projected to vary from 2,498 mm (AvPETLoR, average PET, low rainfall scenario) to 3,100 mm (AvPETHiR, average PET, high rainfall scenario).

3.2 Actual evapotranspiration

The annual actual evapotranspiration varies much less than the rainfall, both from year to year and from district to district. The annual evapotranspiration totals in the various scenarios are summarised in Figure 8. The average annual evapotranspiration over the 30-year period 1985 to 2015 varied from 1,018 mm (minimum 892 mm, maximum 1,152 mm) in Thakurgaon district to 1,192 mm (minimum 1,036 mm, maximum 1,341 mm) in Joypurhat.

The evapotranspiration in the agricultural and water resources development scenarios varies in a way that depends on the changes to cropping areas, a factor which varies from district to district. The no development scenario has much less cropping (particularly of dry season irrigated *Boro* rice) and has the least evapotranspiration in all districts. The district with the lowest total is Lalmonirhat, at 819 mm. Evapotranspiration also reduced in the loss of agricultural land scenario. The scenario with increased crop areas has the greatest evapotranspiration in all districts. The district with the highest total is Joypurhat, at 1,276 mm. Evapotranspiration also increased, though only marginally, in the more fruit trees scenario; for example, the average annual evapotranspiration increased by 7 mm in Joypurhat, from 1,192 mm in the current scenario to 1,199 mm in the more fruit trees scenario.

In the climate change scenarios, the average annual evapotranspiration in Thakurgaon is projected to vary from 1,016 mm (low PET, average rainfall scenario) to 1,085 mm (high PET, average rainfall scenario), whereas that of Joypurhat is projected to vary from 1,185 mm (low PET, average rainfall scenario) to 1,276 mm (high PET, average rainfall scenario).

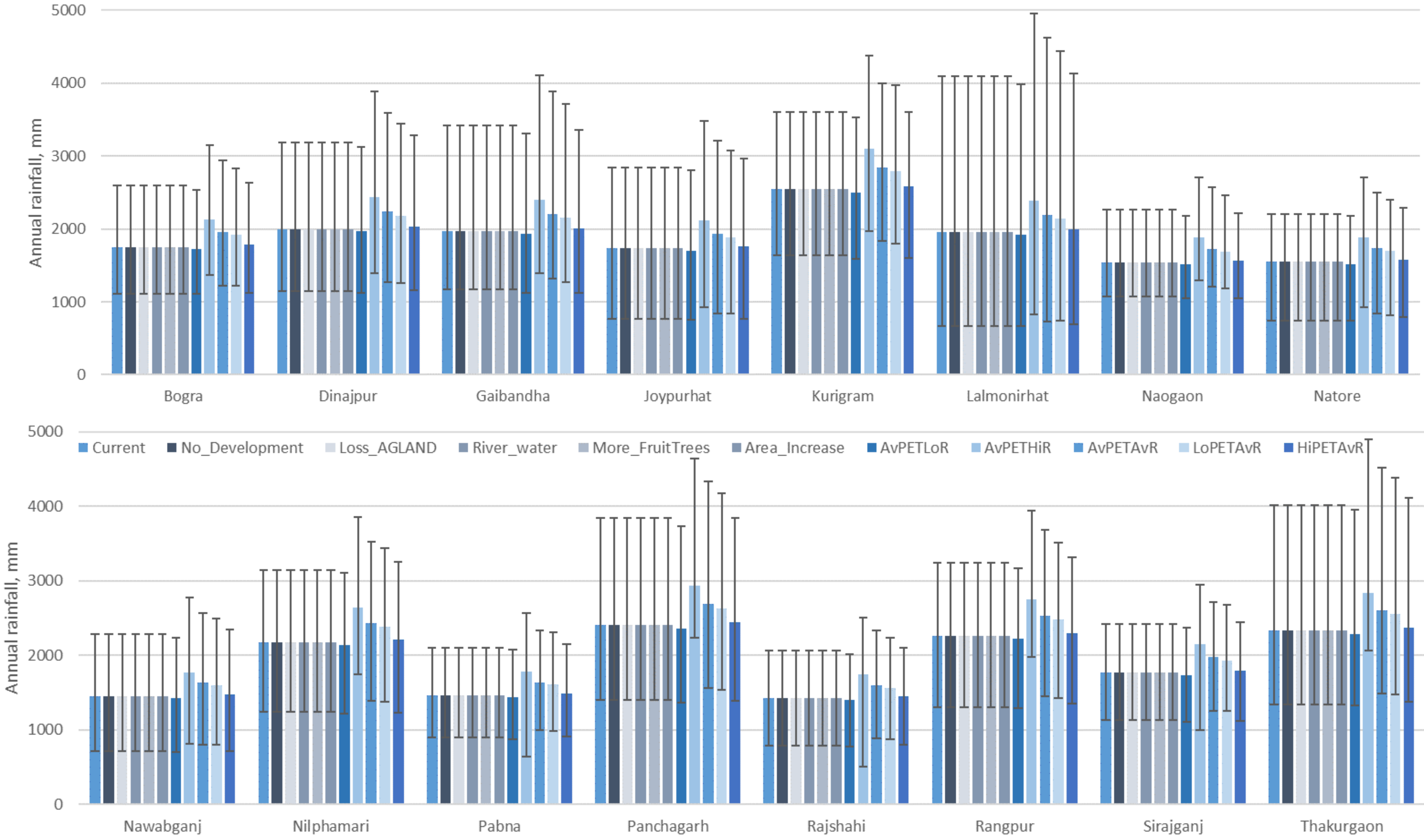

Figure 7 Mean, minimum and maximum rainfall (mm) in the scenarios for each of the 16 districts: The blue bars represent the average annual rainfall in the 30-year period of the simulation, with the black vertical lines representing the greatest and least annual rainfall in the period

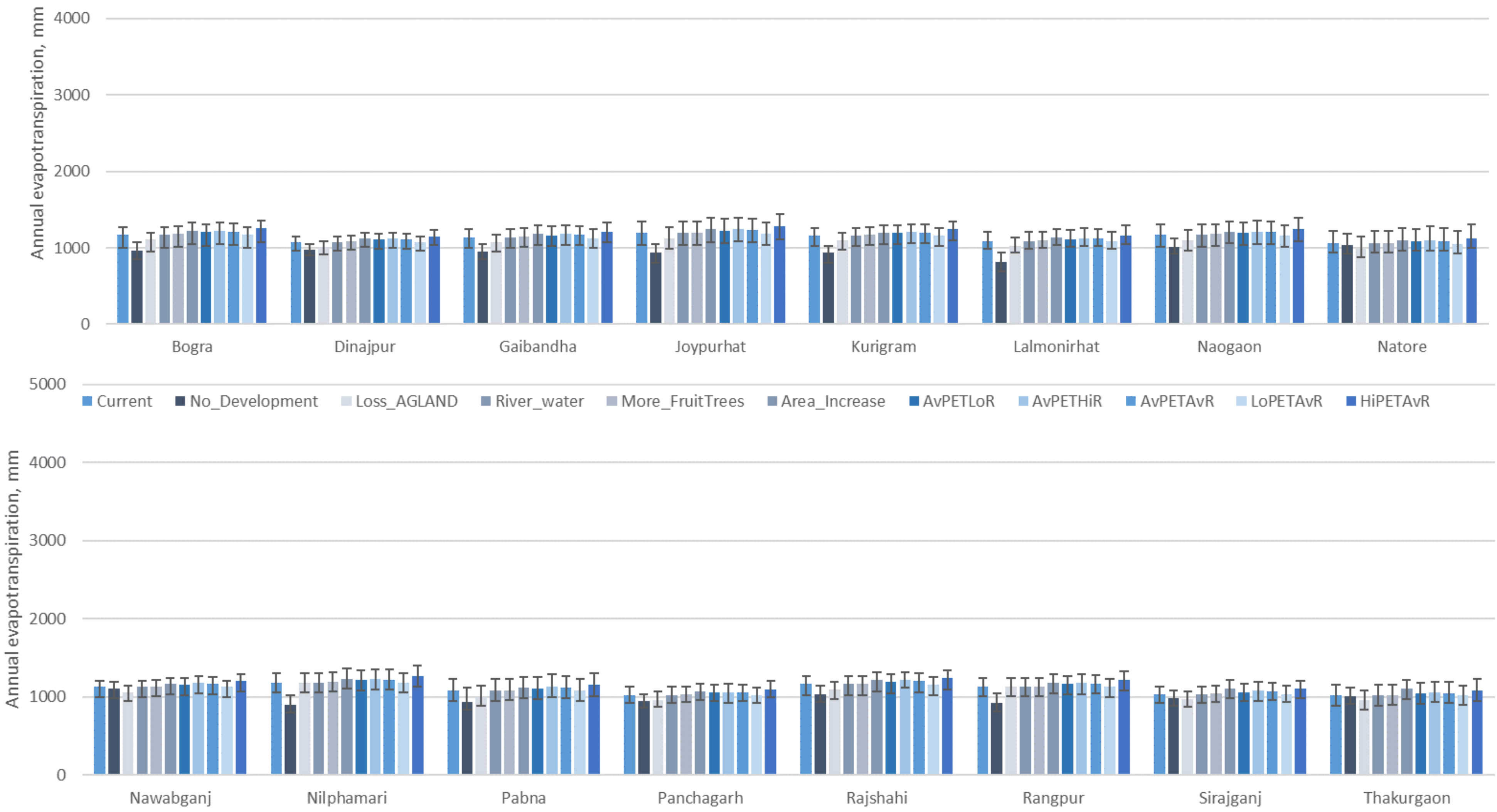

Figure 8 Mean, minimum and maximum evapotranspiration (mm) in the scenarios for each of the 16 districts. The blue bars represent the average evapotranspiration in the 30-year period of the simulation, with the black vertical lines representing the greatest and least annual evapotranspiration in the period. Note that the Y-axis has the same scale as that in Figure 6, for ease of comparison.

3.3 Runoff

Runoff varies considerably, both from year to year and from district to district. The annual runoff totals in the various scenarios are summarised in Figure 9. The average annual runoff from 1985 to 2015 varied from 275 mm (minimum 0 mm, maximum 829 mm) in Rajshahi district to 1,390 mm (minimum 509 mm, maximum 2,486 mm) in Kurigram.

The runoff in the agricultural and water resources development scenarios varies in a way that depends on the changes to cropping areas, due to the impact of cropping areas on evapotranspiration. The no development scenario has much less cropping (particularly of dry season irrigated rice) and has the least evapotranspiration in all districts, and hence the greatest runoff. The district with the largest average is Kurigram, at 1,602 mm. Runoff also increased in the loss of agricultural land scenario. The scenario with increased crop areas has the least runoff in all districts. The district with the lowest average is Rajshahi, at 230 mm; the low total results from the low rainfall and high evapotranspiration in this district, the latter driven yet higher by the increased cropping areas. Runoff also reduced, though only marginally, in the more fruit trees scenario.

In the climate change scenarios, the average annual runoff in Rajshahi is projected to vary from 222 mm (AvPETLoR, average PET, low rainfall scenario) to 528 mm (AvPETHiR, average PET, high rainfall scenario), whereas that of Kurigram is projected to vary from 1,316 mm (average PET, low rainfall scenario) to 1,901 mm average PET, high rainfall scenario).

3.4 Groundwater trends

The groundwater trends vary greatly from district to district (Figure 10). In most districts, the groundwater trend is small in terms of equivalent depth of water in mm per year. In those districts, the variation in groundwater trend with the scenarios is small. Note, however, that a small trend over many years can lead to a significant decline in actual groundwater level. For example, the groundwater trends in Joypurhat (all scenarios) is about 15 mm/year. At a specific yield of 0.1, this results in a decline in average groundwater level of about 4.5 m over 30 years. This is approximately what is shown for Joypurhat in Figure 6 up to about 2013, although the levels recovered somewhat from the long term trend in the final two years of the study period.

The groundwater trend is large – and declining – in Nawabganj, Naogaon and, to a lesser extent, Rajshahi. In these districts, the groundwater trend varies significantly with the scenario. In the agricultural and water resources development scenarios, the no development, loss of agricultural land scenarios and use of river water for irrigation result in a lessening of the declining trend. In other words, the groundwater use becomes more sustainable or less unsustainable. The planting of more fruit trees, and the increase in area do not make much difference, except at Nawabganj where the increase in areas of crops leads to an increase in the decline of groundwater levels.

In the climate scenarios in Nawabganj, Naogaon and, to a lesser extent, Rajshahi, the high rainfall scenario (average PET, high rainfall) and low PET scenario (low PET, average rainfall) result in a lessening of the declining trend. In other words, the groundwater use becomes more sustainable or less unsustainable. The low rainfall scenario (average PET, low rainfall) and high PET scenario (high PET, average rainfall) result in an increase of the declining trend. In other words, the groundwater use becomes less sustainable or more unsustainable.

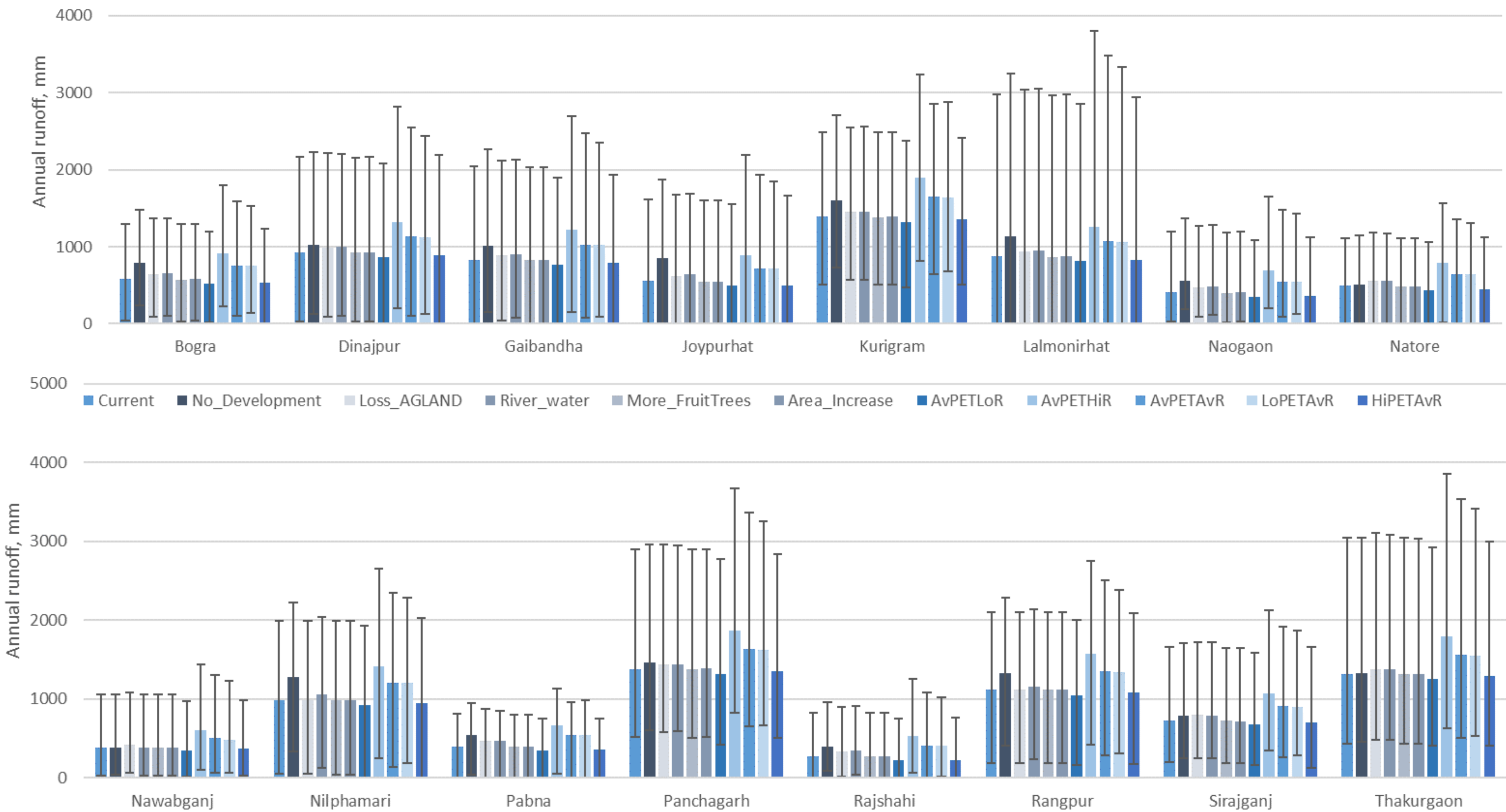

Figure 9 Mean, minimum and maximum annual runoff (mm) in the scenarios for each of the 16 districts. The blue bars represent the average rainfall in the 30-year period of the simulation, with the black vertical lines representing the greatest and least annual rainfall in the period

Figure 10 Annual groundwater level trends (mm) in the scenarios for each of the 16 districts over the 30-year simulation period

3.5 Discussion

The results outlined above are similar to those of the water balance component of the surface water study (Karim et al. 2021). They used the NAM catchment water balance model to examine the water balance at a catchment scale, and then re-mapped the results to the district scale used here. They found calibration of the model less successful in the Nawabganj area, as we did, and they obtained a similar NSE. Similar to the results above, they reported that the groundwater trend is large and declining in Nawabganj, declining at a lesser though still large rate in Naogaon and Rajshahi, and with small trends elsewhere. In our results, some of the other districts show zero or slightly rising trends, though always small, whereas in Karim et al. (2021) all districts show declining trends. Sreekanth et al. (2021) also found that Nawabganj, Naogaon and Rajshahi are the districts within which there are large declines of groundwater.

Karim et al. (2021) examined the same climate change scenarios as we did, and also examined increasing use of river water for irrigation. The results of all these scenarios show similar results to ours. The NAM model did not lend itself to examining scenarios of changed crop areas, so there are no results to compare with our scenarios of no irrigation, decreased or increased area of cropland, or more fruit trees.

The results are also similar to those of earlier CSIRO work in Bangladesh. Kirby et al. (2015, 2016) reported the results of irrigation development scenarios and projected climate change scenarios on rainfall, evapotranspiration, runoff and groundwater levels (plus some other water flow terms) for the northwest region as a whole (and other regions of Bangladesh).

In a no irrigation development scenario, Kirby et al. (2015) calculated that groundwater would be shallower than was the case with irrigation development, similar to the result we report here. In scenarios with surface water use, including a scenario with increased cropping intensity, Kirby et al. (2015) calculated that groundwater levels would be somewhat shallower in the northwest region, again similar to the results reported here.

In climate change scenarios, the runoff response to low, medium and high rainfall changes was projected by Kirby et al. (2016) to vary from a modest decrease (relative to the historical case) to a larger increase, as reported here. The groundwater levels likewise varied from slightly less deep to considerably more deep. Overall, the calculations in the earlier study resulted in deeper groundwater levels than those of the study described here. This might result from the different climate change scenarios, the different model, the fact that the earlier work was at the regional level, or the fact that the earlier model simulated a greater impact of irrigation on evapotranspiration than the current model. (Following work reported in Peña-Arancibia et al. (2020a), we now think that irrigation development has not greatly increased evapotranspiration in a wet landscape underlain by mostly shallow water tables.)

4 Conclusions

We have used a simple, lumped, monthly water balance model to assess the impact of climate change and agricultural development scenarios on water balances in the districts northwest Bangladesh. The calibration of the model with historical groundwater levels is generally good in all districts except Nawabganj, where the calibration is poor. This might be because Nawabganj is an area partly of river floodplain and partly of the higher ground of the Barind Tract; it may be that a lumped model which treats the area as a single unit cannot capture the overall behaviour. Developing a sound model for Nawabganj will require further work; it will probably be necessary to split the district into several areas with different hydrological characteristics.

The observed groundwater declined in most districts over the period 1985 to 2015. However, the declines were small in most districts. Large declines were observed in Nawabganj, Naogaon and Rajshahi, in the drier parts of the northwest region.

In districts with small groundwater declines, the model scenario exploration suggests that groundwater levels are projected to be not much affected by management or climate change.

In drier districts with large groundwater declines, namely Nawabganj, Naogaon and Rajshahi, groundwater levels respond to the scenario. Thus, agricultural or water resources management, or climate change, could make groundwater use more or less unsustainable than it is at present in such districts. Management options with reduced evapotranspiration (resulting from declining crop areas) or use of river water for irrigation lead to improved groundwater sustainability.

The study significantly extends the results of previous work at the regional level by providing assessment district by district. This allowed the assessment of which districts are using water less sustainably and are more likely to be affected by future development and also by climate change, and which other districts are using water more sustainably and are consequently less likely to be affected by future development and climate change.

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Appendix A Selection of general circulation models (GCMs) for use in the study

The annual rainfall (P) and potential evapotranspiration (PET) scaling factors of 37 GCMs are shown in Figure A-1. Five GCMS were selected, one to represent the average potential evapotranspiration and rainfall, and four to encompass the range from low to high potential evapotranspiration and low to high rainfall. The chosen GCMs are shown in the figure and listed in Table A-1.

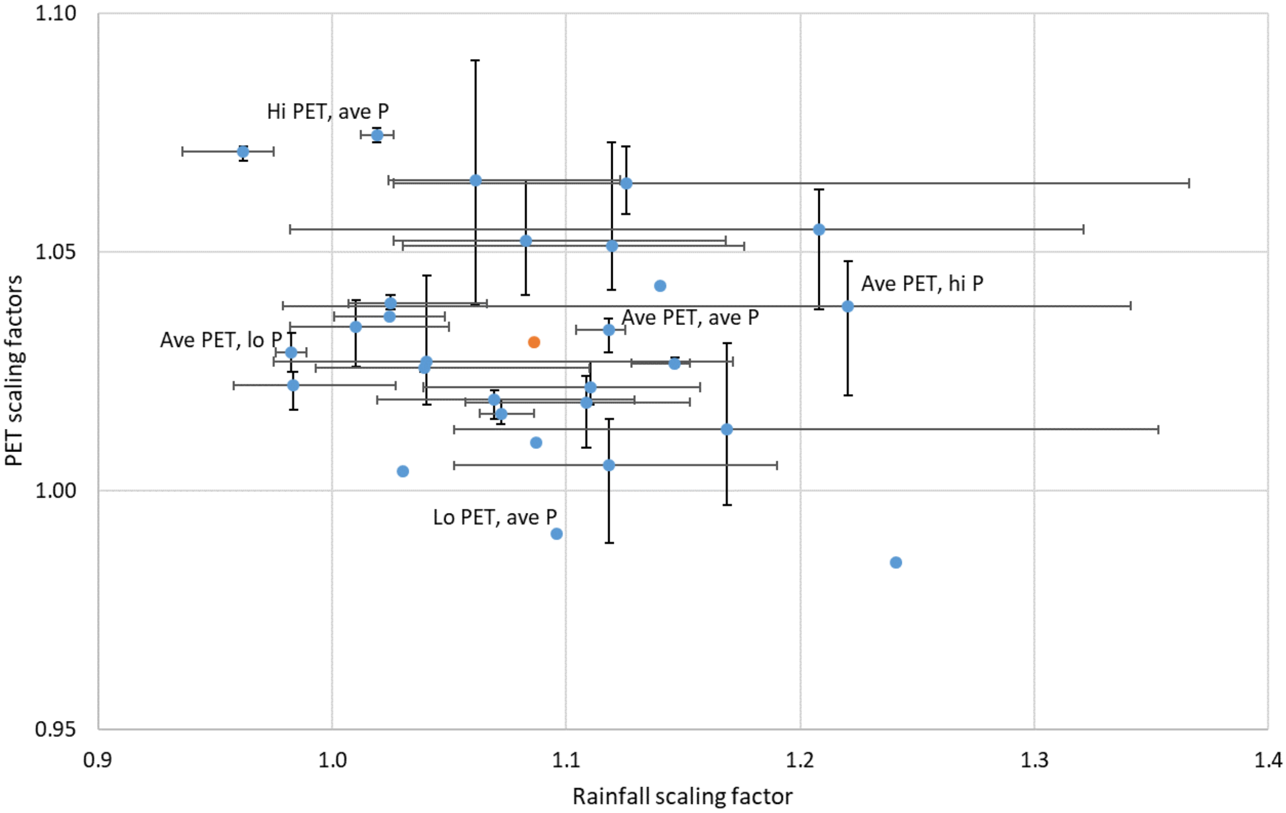

Figure A-1 Annual rainfall and potential evapotranspiration scaling factors. The average scaling factor is shown by the orange point. The blue points show the average scaling factor for each GCM across northwest Bangladesh. The range of scaling factors across the region is shown by the vertical and horizontal lines. Some GCMs encompass the region in a single model grid cell, and so there is no variation in scaling factors

Table A-1 Global Climate Models (GCMs) selected for use in this study

GCM	PET	Rainfall
gfdl-esm2g	Average	Low
miroc-esm	Average	High
bcc-csm1	Average	Average
giss-e2-h-cc	Low	Average
ipsl-cm5a-lr	High	Average

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