Bangladesh Integrated Water Resources Assessment supplementary report: approximate regional water balances

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Executive summary

The overall water balance for Bangladesh is not well known. The recharge to aquifers has not been quantified, except in a few small districts. The overall use of groundwater by irrigation has not been quantified, and this use has not been compared to recharge to test notions of sustainability.

We develop approximate water balances for each of the main regions of Bangladesh (excluding the Chittagong hill tracts). The water balances bring together current information on rainfall, crop areas, evapotranspiration, groundwater levels and river flow to form approximate water balances for each region. The regional water balances are for the water resources internal to each region and do not include the major rivers – the Ganges, Jamuna (the name for the Brahmaputra in Bangladesh) and Meghna.

We use the approximate monthly, seasonal and annual water balances to assess the likely regional responses (at least in direction, if not in absolute magnitude) to changes in water availability under climate change and management to substitute surface water use for irrigation with groundwater.

Climate change projections are uncertain, with increased rain in the wet season likely, but decreased rain also possible. The projections with more rain may lead to increased recharge and runoff, and increased water availability. However, increased projected potential evapotranspiration may also lead to increased irrigation requirement. Climate variability, at least to 2050, is projected to have a greater impact on regional water balances than climate change.

The increased use of surface water, particularly when combined with an increase in irrigation overall, may lead to greater recharge and some restoration of groundwater levels. As a result, it may also lead to greater baseflows from groundwater to the rivers (so some of the water pumped from the rivers in effect recycles back to the rivers).

The simple and approximate water balances developed here should be refined through further studies. They should not be used directly for planning or management: the approximate nature of the results does not give estimates that can be relied on for such purposes.
1 Introduction

1.1 Overview

As described in the main report of the Bangladesh Integrated Water resources Assessment project (CSIRO, 2014), Bangladesh faces great challenges in water resources management, with too much water in the wet season and too little in the dry. Groundwater is used extensively for irrigation in the dry season (e.g., Mainuddin and Kirby, 2014), particularly in areas away from the coastal zone where salinity is less of an issue. There are concerns that groundwater may be overused (as reviewed in Kirby et al., 2013, Mainuddin and Kirby, 2014, and Ahmad et al., 2014) and there are plans to use more surface (river) water instead (Mainuddin and Kirby, 2014).

However, notwithstanding the challenges and the plans, the overall water balance for Bangladesh is not well known. An early water balance for Bangladesh (called East Pakistan at the time) by Khan and Islam (1966) focussed on rainfall and soil moisture. They noted that soil moisture was in deficit in the dry season particularly in the west of Bangladesh, whereas rain exceeded the soil storage capacity in the wet season leading to runoff. The National Water Management Plan (Topic Paper No 7 Land and Water Resources and Draft Development Strategy Annex C land and Water Resources) is the main source of water balance information to date. However, it does not give a comprehensive water balance: it treats the groundwater and surface water separately, and does not, for example give the exchange between the two; much of the discussion is in terms of demand rather than actual use, and surface water is often given in terms of dependable flows rather than the actual amount of water available and its variation from wet to dry years.

The recharge to aquifers has not been quantified, except in a few small districts such the area known as the Barind Tract (Rahman and Roehrig, 2006). The overall use of groundwater by irrigation has not been quantified, and this use has not been compared to recharge to test notions of sustainability. If irrigation were to continue on its trend of the last 40 years of increasing area and increasing water use, what would be the consequences for the water table, or for baseflow from the groundwater to the rivers? It is not known.

Water balances, or water accounting, is generally regarded as fundamental to the understanding of water availability in a region and hence to the development of sustainable policies and plans for water management (e.g., Karimi et al., 2013; Molden and Sakthivadivel, 1999). The water accounts of Karimi et al. (2013), Molden and Sakthivadivel (1999) (and others discussed in Kirby et al. 2010) are static water accounts based on a single year, usually an average year. In contrast, Kirby et al. (2010) calculated dynamic monthly water balances which are more suited to assessing dynamic effects such as climate change, land use change and so on.

In this report, we develop dynamic (monthly) approximate water balances for each of the main regions of Bangladesh (excluding the Chittagong hill tracts) shown in Figure 1. The water balances we regard as approximate in the sense that: 1. the groundwater balance for each region is a partial water balance for the shallow unconfined aquifer alone, and ignores exchanges with deeper aquifers and deep lateral flows of groundwater; 2. the water balances for each region are lumped balances that do not account for within-region spatial variation and so average much detail; 3. some terms (whether at the lumped regional scale or finer spatial scales) have not been quantified in any study known to us and so are represented here with simple physically meaningful and plausible expressions (the principal terms so represented are baseflow to rivers and evapotranspiration drawn from groundwater sources via a capillary fringe). The regions have different water issues: groundwater is more intensively used in the northwest; the coastal zone uses less groundwater because of salinity problems; the northeast is extensively flooded every wet season. We develop separate approximate water balances for each.
The water balances bring together current information on rainfall, crop areas, evapotranspiration, groundwater levels and river flow to form approximate water balances for each region. These approximate balances, despite their uncertainties, are helpful in guiding us to propose studies for a better definition of the water balances. They also give us a good indication of the likely regional responses (at least in direction, if not in absolute magnitude) to changes in water availability (such as under climate change) or management (such as the substitution of surface water for groundwater).

However, it should be clear that such approximate water balances cannot be used directly for planning or management: the approximate nature of the results does not give estimates that can be relied on for such purposes.

The regional water balances are for the water resources internal to each region and do not include the major rivers – the Ganges, Jamuna (the name for the Brahmaputra in Bangladesh) and Meghna. The Ganges and Jamuna form the borders between several regions, and their flow is not really attributable to the region on either side. We do account implicitly for exchanges with the major rivers, such as baseflow, but ignore the flow of the major rivers and thus do not present water balances for them. Although they are not part our water balances of the internal resources of each region, they are a major part of the water balance of the country overall. The water balances for the major rivers and impact of climate change on their inflows is described in the companion report by IWM (2014).

Figure 1. The regions of Bangladesh referred to in this report. The South West and South Central are combined into one region called southwest – south central in the regional water balances reported here. The three main rivers, the Jamuna, Ganges and Meghna are at the boundaries of regions for some or all of their length in Bangladesh, and are not included in the regional water balances.

1.2 The aim of this report

The aim of this report is to describe the method and results of modelling approximate regional water balances.
The model and calibration are described in chapter 2, and the results of applying the model to examine climate change impacts and the consequences of management changes are examined in Chapter 3. Following a discussion of the implications in Chapter 4, we conclude by summarising the main messages and suggesting further work in Chapter 5.

Note that throughout the report we use the unit of billion cubic metres or bcm. One bcm equals one cubic kilometre.
Regional water balance top down approach: method

The regional water balance comprises three linked water balances: the land surface, the rivers and the groundwater. The links amongst the balances are the flows of water from one to the next – such as the drainage from the land surface to the groundwater, and the baseflow from the groundwater to the river. The groundwater balance is only a partial balance in which flows to and from the land surface and the rivers are considered, and other lateral groundwater flows (such as inflows and outflows to and from the region) are ignored. In a system in which: (1) The water table goes up and down several metres every wet and dry season indicating a transmissive landscape with rapid and probably primarily vertical exchanges, (2) shallow lateral exchanges with the rivers are likewise probably quite rapid due to the transmissive nature of the landscape, and (3) the vast majority of water use is from shallow tubewells (within the suction limit of say 8 m), we think that it is not unreasonable in a study aimed primarily at resource use to ignore the slower processes of deeper groundwater exchanges.

We consider these linked water balances each as being a single, lumped balance for a region. We assess the balances as dynamic monthly water balances over the period from 1985 – 2009. The water balances are set in a monthly time-stepping calculation: for brevity, however, we drop time indices from the equations except where it is necessary to show the updating of stores from one timestep to the next.

2.1 Surface water balance

The surface water balance is calculated separately for irrigated and non-irrigated land. The areas of irrigated and non-irrigated land change throughout the year.

The water balance of non-irrigated land is calculated through a simple catchment rainfall-runoff model. Bangladesh experiences high rainfall in the monsoon, and a dry season with little rainfall. The groundwater rises and falls several metres with the monsoon and dry season each year. In a mostly flat landscape, this suggests that the monsoon rain rapidly fills the surface soil and a fraction infiltrates downwards to recharge the water table. Much becomes runoff.

Evapotranspiration from the non-irrigated parts of the landscape remains high even in the driest part of the year (Ahmad et al., 2014). The landscape is underlain in most places by shallow groundwater tables. It is therefore reasonable to assume that the evapotranspiration in the dry season is maintained at high levels by capillary rise from the water table which is accessed by plant roots and consumed as transpiration. Some may also be consumed as evaporation where the groundwater intersects the surface and there are shallow wetlands.

Based on these considerations, we assume that the non-irrigated parts of the landscape can be modelled as shown in Figure 2. The surface water balance is:

\[ P + C_r - ET_s - ET_{cf} - R_o - D + \Delta S_s = 0 \]  

where \( P \) is the rainfall, \( C_r \) is the capillary rise, \( ET_s \) is the evapotranspiration from the soil, \( ET_{cf} \) is the evapotranspiration from the capillary fringe, \( R_o \) is the runoff, \( D \) is the deep drainage from the soil to the water table and \( \Delta S_s \) is the change in the water storage in the soil. Evapotranspiration depletes the soil water store in the dry season, and it is replenished by rain in the monsoon. Plant roots also access the capillary fringe, maintaining high transpiration even in the dry season.

The evapotranspiration from the soil store is governed by a crop coefficient model:
\[ ET_s = ET_o \ MIN[1, \alpha_1 \frac{S_s}{S_{max}}] \quad (2) \]

where \( ET_o \) is the reference evapotranspiration, \( \alpha_1 \) is a coefficient (>1), \( S_{max} \) is the maximum depth of water that can be stored in the soil. The evapotranspiration is at the maximum (reference) rate in wet soil and, when drier than a threshold value given by \( \frac{S_s}{S_{max}} \geq 1 \) declines to zero as the soil dries. The store of readily available water is zero in dry soil, though the soil could still contain some residual moisture unavailable to the plants: implicitly, we consider only the readily available water.

The drainage from the soil store to groundwater is given by a water content dependent leakage rate:

\[ D = \alpha_2 \frac{S_s}{S_{s}} \quad (3) \]

where \( \alpha_2 \) is a coefficient (<1).

The runoff is given as a saturation excess:

\[ R_o = MAX \left[ 0, \left( \frac{t - \Delta t}{s} + \frac{P - ET_s - D}{s} \right) - \frac{S_{max}}{s} \right] \quad (4) \]

The expression in the inner brackets sums soil store and inflows and outflows; if the sum exceeds the maximum water storage of the soil, the excess is runoff.

The soil water storage is updated as:

\[ S_s = S_s^t - \Delta t + P - ET_s - R_o - D \quad (5) \]

The evapotranspiration from the capillary fringe is assumed to be a constant fraction of the potential evapotranspiration, limited to the amount of the potential not consumed by the soil evapotranspiration:

\[ ET_{cf} = MIN \left[ \frac{ET_o - ET_s}{s}, \alpha_3 \frac{ET_o}{s} \right] \quad (6) \]

where \( \alpha_3 \) is a coefficient (<1). The total evapotranspiration is the sum of \( ET_s \) and \( ET_{cf} \).

The water content of the capillary fringe is assumed to remain constant, with water extracted by roots re-supplied by capillary rise. Therefore, \( C_r = ET_{cf} \).
The regional volumes of rainfall, evapotranspiration, runoff, drainage and soil water storage are given by multiplying the values derived from (1) to (6) by the area of non irrigated crops.

The water balance of irrigated land is calculated through a crop coefficient model. Water is assumed to be applied to meet the regional water requirement, WR, summed across the crops and districts in a region, and given by

\[
WR = \sum_{i=1}^{nD} \sum_{j=1}^{nC} \text{MAX} \left( 0, (K_{c_j} ET_{oi} - P_{oi}) A_{ij} \right) + D_{irr}
\]  

(7)

where \( K_{c_j} \) is the crop coefficient for crop \( j \), \( A_{ij} \) is the area of crop \( j \) in district \( i \), and \( nD \) and \( nC \) are the number of districts and crops; \( D_{irr} \) is drainage from irrigated land, assumed to be constant since most of the irrigation is for rice which will drain at a near constant rate from a surface pond through a puddle soil horizon. The evapotranspiration (as a depth of water) of crops under irrigation is thus \( K_{c_j} ETo_i \). The \text{MAX} function sets the water requirement to zero when rain exceeds \( K_{c_j} ET_{oi} \). We had data on the rain, potential evapotranspiration and area of the main irrigated crops for each district in the regions we considered. We considered the crops to be Boro rice (which is the main irrigated crop, occupying on the order of 86% of the area irrigated and, furthermore, growing in the later and warmer part of the dry season and so receiving about 95% of the total water applied to irrigation), wheat, potato, Aus rice (which receives only supplementary irrigation as its growth extends into the rainy season) and “other” (which only occupies about 3% of the total area). The water balance for the irrigated land uses an equation similar to (1) but with a term added for the applied irrigation.

The total regional evapotranspiration is the sum of the irrigated land evapotranspiration (equation 7) and the non-irrigated land evapotranspiration (equations 2 and 6, multiplied by the area of non irrigated land).

### 2.2 Groundwater balance

The groundwater balance comprises drainage inflow, calculated according to equation (3) above, minus baseflow to the rivers, and minus abstractions for irrigation calculated according to the irrigation water requirement in equation (7). As stated in the introduction, no study is known to us that quantifies the exchange of water between groundwater and the rivers. Therefore, we use a simple, physically meaningful and plausible expression for baseflow. The baseflow to rivers, \( BF \), in a single timestep is calculated from:

\[
BF = \alpha_4 H
\]

(8)

where \( \alpha_4 \) is a coefficient, and \( H \) is the height above an arbitrary datum. The change in the volume of groundwater, \( \Delta S_g \), is given by:

\[
\Delta S_g = (D - C_f) - F_{ig} WR - BF
\]

(9)

where the term in brackets is net recharge (drainage minus capillary rise) and \( F_{ig} \) is the fraction of the irrigation water requirement supplied by groundwater, the rest being supplied by river water. We assume that \( F_{ig} WR \) is the net volume pumped; any pumping in excess of this we assume to return by drainage to the groundwater. The height of the groundwater table is updated as:

\[
H = H^t - \Delta t + S_y \frac{\Delta S_g}{A}
\]

(10)

where \( S_y \) is the specific yield and \( A \) is the area of the region.

Strictly speaking, equation (9) should include an “unaccounted or error” term. However, we don’t know what the value of the unaccounted / error term will be and in principle we could set it to any value in any timestep. We could make it exactly the value required to get perfect calibration \textit{for any value of other terms such as baseflow}. What we have implicitly done is to suppose that the unaccounted / error term is zero (ie the unaccounted change in storage is zero), and looked at how well the model then fits; this seems
to be a reasonable Ockham’s Razor approach. We have explicitly discussed that there is little or no information on groundwater – river exchanges and that this is an area requiring further work.

2.3 River water balance

The inflows of all rivers flowing within a region are taken from separate calculations done by the Institute for Water Modelling and described in the companion report (IWM, 2014). They were calculated only for the 1996 year and for the climate change scenarios. Annual variability of river flows is therefore not available. The river outflows (summed for the region), $Q_o$, are the inflows, $Q_i$, plus runoff and baseflow, less extraction for irrigation:

$$Q_o = Q_i + R_o + BF - \left(1 - F_{lg}\right)WR$$

(WR)  

Were river flows and stage heights available, a more refined regional water balance model could use the information in the calculation of river water – groundwater exchanges: this is an area for improvement with further study. Note that the river water balances are those for the rivers that flow within the regions, and do not include the Ganges, Jamuna or Meghna which mostly bound the regions rather than flowing through them. Furthermore, the river water balance for the southwest – south central region (SW-SC) excludes tidal inflows and outflows.

2.4 Input data

The input climate data are taken as weighted averages of district data. The rainfall is taken direct from the Bangladesh Meteorological Department, and potential evapotranspiration is calculated from district temperature and other climate data from the Bangladesh Meteorological Department. The crop coefficients are standard crop coefficients from the FAO. The crop areas are taken from the Ministry of Agriculture (http://www.moa.gov.bd/statistics/statistics.htm), from where the proportion of irrigation supplied by groundwater was also sourced. For scenario exploration, the areas are taken as the 2009-10 areas unless otherwise stated. For calibration, the areas of irrigated crops are assumed to increase threefold from 1985 to 2010, which is the approximate increase of irrigated crops in Bangladesh over that period.

2.5 Calibration

The river flows are calibrated as described in the companion report. The regional evapotranspiration for the northwest region was calibrated by comparing the total regional evapotranspiration divided by the area of the region with the evapotranspiration modelled from remote sensing (satellite) observations, as described by Ahmad et al. (2014). The remotely sensed observations are for January to April of the dry season of 2009, and the calibrated modelled evapotranspiration is for those months only. The remotely sensed modelled evapotranspiration is for about half the total area of the northwest region (the part of Bangladesh to the north and west of the Ganges and Jamuna rivers) but, since the fractions of cropped areas and the potential evapotranspiration are similar in the remotely sensed part and the whole region, we think the comparison is likely to be reasonable. The match shown in Figure 3 was obtained by manually adjusting $S_{max}$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ to obtain the best visual match. Values of the fitted parameters for each region are shown in Table 1. The model is fairly sensitive to all the parameters.
Figure 3. Comparison of the 2009 January to April regional water balance model (red squares) and a remotely sensed model (SEBAL) estimate of evapotranspiration for the same period for the northwest region of Bangladesh. The SEBAL results were estimated by Ahmad et al. (2013).

Table 1. Values of the fitted model parameters for each region.

<table>
<thead>
<tr>
<th>Region</th>
<th>$S_{max}$</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$\alpha_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>North west</td>
<td>0.2</td>
<td>2</td>
<td>0.5</td>
<td>0.37</td>
<td>1</td>
</tr>
<tr>
<td>North central</td>
<td>0.2</td>
<td>2</td>
<td>0.5</td>
<td>0.28</td>
<td>1.16</td>
</tr>
<tr>
<td>North east</td>
<td>0.26</td>
<td>2</td>
<td>0.5</td>
<td>0.24</td>
<td>1</td>
</tr>
<tr>
<td>South west – south central</td>
<td>0.2</td>
<td>2</td>
<td>0.5</td>
<td>0.43</td>
<td>2</td>
</tr>
<tr>
<td>South east</td>
<td>0.2</td>
<td>2</td>
<td>0.5</td>
<td>0.25</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Ahmad et al. (2013) estimated the regional average groundwater depths for the main regions in Bangladesh, based on water levels observed in boreholes. The regional average depths were calculated for three times at each of five periods at five year intervals. The groundwater height in equations (8) and (10) is the height above an arbitrary datum. To compare the observed depth with the modelled heights, we subtracted the depths (as a positive number) from a constant, and adjusted the constant to obtain the best match. In addition, we adjusted $\alpha_4$ in equation (8) to obtain the best fit; $\alpha_4$ values are shown in Table 1. We assumed a specific yield of 0.1. The resulting fit for the northwest region is shown in Figure 4. The $R^2$ of the fit is 0.86, the Nash-Sutcliffe Efficiency (NSE) is 0.84.
Figure 4. Comparison of the observed regional average water table heights and modelled monthly water table heights (each above an arbitrary datum) for the north west region. The observed results are regional average water table depths estimated from borehole records by Ahmad et al. (2013).

Figure 5. Comparison of the observed regional average water table heights and modelled monthly water table heights (each above an arbitrary datum) for the north central region (top), northeast region (upper middle), southwest-south central (lower middle) and southeast (bottom). The observed results are regional average water table depths estimated from borehole records by Ahmad et al. (2013).

For the other regions, we have only the groundwater level comparison for calibration, as shown in Figure 5. The $R^2$ and NSE values are 0.71 and 0.71 for the north central region, 0.54 and 0.55 for the northeast region, 0.95 and 0.95 for the southwest – south central region, and 0.88 and 0.88 for the southeast region.

While the fits of the model to the groundwater data appear reasonable, it should be borne in mind that they result from fitting the main parameter of a plausible baseflow expression to the data. However, no study is known to us that quantifies the exchange between groundwater and the rivers, so the values of baseflow must be regarded as tentative. We recommend as part of the overall Bangladesh Integrated Water resources Assessment that the surface water – groundwater exchanges be studied in detail in order to better quantify the sustainable levels of groundwater use or the impact on groundwater and other water balance terms of changed groundwater use.
3 Results: regional water balances

In this section, we present the results of using the regional water balance models for the five regions to assess the likely changes to terms in the water balance under several scenarios. First, however, we briefly describe the regional climates.

3.1 Regional rainfall and potential evapotranspiration

The annual average rainfall in the five regions is 1927 mm in the northwest region, 1950 in the southwest – south central, 2133 in the north central, 2447 in the south east and 3091 mm in the north east. The corresponding figures for potential evapotranspiration are 1309, 1327, 1275, 1276, and 1261 mm. Thus the two most westerly regions are the driest and have the greatest potential evapotranspiration, with rainfall greatest and potential evapotranspiration least in the northeast. The monthly distribution of rainfall and potential evapotranspiration is shown in Figure 6. The figure shows the strong monsoon peak of rainfall from May to September or October, with very little rainfall in December and January. The potential evapotranspiration is more evenly distributed, though it is generally higher towards the end of the dry season from March to May.

Figure 6. Monthly distribution of rainfall and potential evapotranspiration in five regions of Bangladesh. The monthly totals are the average monthly totals from 1985-2009.

The annual rainfall from 1985 to 2009 is shown in Figure 7. The figure shows the greater rainfall of the southeast and particularly the northeast region. With the exception of the southeast region, all the annual rainfall totals show a slight decline on average from 1985 to 2009; the decline is 13 mm / year for the NW region, 12 mm / year for the north central, 20 mm / year for the north east, and 7 mm / year for the southwest - south central region.
3.2 Base case scenario

In the base case scenarios, we simulate the water balance of each region under the current irrigation development (that is, with irrigated areas equal to those in 2009-10) and with historic rainfall and potential evapotranspiration. The purpose of the base case is to compare the impacts of climate change and changed management in the other scenarios. We also use the base case to examine the impact of climate variability. It is similar to the calibration scenario, except that the areas under irrigation are assumed to be constant at the 2009-10 values, rather than increasing throughout the period of simulation.

The results are shown in Figure 8 for the five regions, as annual averages. The figure shows the river inflows and outflows are the largest terms in the water balance for the northwest and north central regions. River flow results are not available for the other regions. The flows of the Ganges, Jamuna and Meghna are considerably greater than the internal regional river flows shown in the plots. Figure 9 and Figure 10 show the wet season and dry season water balances.

The rain is the next biggest term in each water balance. The rain partitions into (in decreasing volume) evapotranspiration, runoff, and recharge. The recharge itself is partitioned into the water applied as irrigation and the baseflow. The diversions are the irrigation supplied from surface water rather than groundwater. In the base case in most regions it is less than groundwater pumped for irrigation.

The impact of the dry season with much reduced rainfall, river inflows and groundwater inflows is readily apparent in Figure 10, as is the greater irrigation water use. In the dry season, evapotranspiration exceeds rainfall, partly because vegetation naturally draws on the water stored as groundwater and partly because of the use of groundwater and a lesser volume of river water for irrigation.
Figure 8. Components of the annual average water balance (1985-2010) for the five regions. The river inflows and outflows for the southwest – south central region (SW-SC) excludes tidal inflows and outflows.

Figure 9. Components of the wet season average water balance (1985-2010) for the five regions. The wet season river inflow and outflow for the SW-SC region was not available at the time of writing.
Figure 10. Components of the dry season average water balance (1985-2010) for the five regions. The dry season river inflow and outflow for the SW-SC region was not available at the time of writing. The small negative recharge and groundwater inflows in some regions indicates that a net groundwater discharge is modelled in the dry season.

3.3 Climate variability scenarios

The rainfall varies substantially from year to year, with wet years such as 1988 and drought years such as 1994 (Figure 7). The impact of climate variability on the water balance is shown in Figure 11 to Figure 15 for the two wettest years and the driest year in each region. The changing rainfall substantially alters several terms in the water balance for the wet and dry years, particularly recharge, runoff and baseflow. The two wet years do not necessarily affect the water balance in the same way. In the northwest region, for example, the irrigation application is calculated to have increased in the wettest year (1987) but decreased in the second wettest year (1998). The rainfall was distributed quite differently in the two years, with the very high rainfall of 1987 being particularly concentrated in July and August and so not affecting dry season irrigation demand.

River inflows and outflows were calculated by IWM only for the base year of 1996, and so no information on variability is shown in Figure 11 to Figure 15.
Figure 11. Components of the regional water balance for the northwest region. Top: components shown as annual averages in billion cubic metres (bcm, where 1 bcm = 1 km$^3$). Bottom, components shown as change from the base case, as a percentage in all cases except Diversions from the river which are shown as change in bcm (because the diversions are near zero in the base case, so a percentage change would result in an unwieldy and hard to interpret scale). River inflows are available only for the base case and climate change scenarios only and not for dry and wet years.
Figure 12. Components of the regional water balance for the north central region. Top: components shown as annual averages in billion cubic metres (bcm, where 1 bcm = 1 km$^3$). Bottom, components shown as change from the base case, as a percentage in all cases except Diversions from the river which are shown as change in bcm (for consistency with Figure 5). River inflows are available only for the base case and climate change scenarios only and not for dry and wet years.
Figure 13. Components of the regional water balance for the northeast region. Top: components shown as annual averages in billion cubic metres (bcm, where 1 bcm = 1 km³). Bottom, components shown as change from the base case, as a percentage in all cases except Diversions from the river which are shown as change in bcm (for consistency with Figure 5). River inflows are available only for the base case and climate change scenarios only and not for dry and wet years.
Figure 14. Components of the regional water balance for the southwest – south central region. Top: components shown as annual averages in billion cubic metres (bcm, where 1 bcm = 1 km³). Bottom, components shown as change from the base case, as a percentage in all cases except Diversions from the river which are shown as change in bcm (for consistency with Figure 5). River inflows are available only for the base case and climate change scenarios only and not for dry and wet years.
Climate change may alter the temperature and rainfall within the region, the flow of rivers, and also the crop water demand.

Temperature is projected to increase in the broader Indian subcontinent region (Kumar et al., 2006) and in the Ganges basin in particular (Moors et al., 2011; Mulligan et al., 2011), while the trend for precipitation in the basin is less certain (Moors et al., 2011; Mulligan et al., 2011). Most projections are for some increase in rainfall (eg Yu et al., 2010). There is uncertainty in the magnitude of the increases, which vary with the
climate change scenario and with climate change model, and decreases are possible. Extreme temperatures and precipitation are expected to increase (Kumar et al., 2006). However, natural variability is expected to dominate the climate change signal, at least up to 2050 (Moors et al., 2011).

In view of the uncertainty, we chose to use two climate change projections, one of which shows a wetter future, and the other a slightly drier future. Our aim is to assess a possible wetter and a drier future and compare them with climate variability and with some options for future water resources management (described below), and compare their impacts on the water balance. We used the projections for 2030 and 2050. The projections were supplied by the Institute of Water Modelling and are described in a companion report (IWM, 2014). The wetter year projections were based on the IPCC A1B scenario results from the HADCM3 general circulation model and the slightly drier year results were based on the FGOAL model (IWM, 2014). The annual average rainfall and potential ET for each region and climate scenario are given in Table 2 and Table 3. The tables show that the wetter climate change scenarios are projected to have about 10% more rain in 2030 and 2050, varying across the regions from about a 6% increase to a 14% increase. The slightly drier climate change scenario is projected to have about a -2% increase (i.e., a decrease of 2%) in rain in 2030 (varying from -4% to +1% across the regions) and a 4% increase in 2050 (2% to 6% across the regions). The potential evapotranspiration is projected to increase in the wetter projection by 3% in 2030 (2% to 3% across the regions) and 5% in 2050 (4% to 6%), whereas in the slightly drier projection the potential evapotranspiration is projected to increase by 2% in 2030 (1% to 2% across the regions) and 3% in 2050 (2% to 4%).

The results in terms of annual averages and change from the base case are shown in Figure 11 to Figure 15. The results show that the climate change scenarios affect the terms of the water balance less than climate variability. This is consistent with the findings of Moors et al. (2011).

The wet climate projections lead to increased calculated recharge, runoff and river inflows, and increased water availability. The irrigation requirement is affected by the projected increased rainfall and the projected increased potential evapotranspiration, which leads to a slightly decreased irrigation requirement in the wetter 2030 scenario and a slightly increased irrigation requirement in the wetter 2050 scenario. In

<table>
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<th>2030 wetter</th>
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the wet climate projections, baseflow is projected to increase in 2030, and to decrease slightly in 2050 in most regions but increase slightly in the south west – south central and south east regions.

The slightly drier climate projections generally lead to projections of smaller changes than in the wet climate projections. The projections are for decreased calculated recharge, and in 2050 to decreased runoff. River inflows are projected to increase. The irrigation requirement is affected by the projected increased rainfall and the projected increased potential evapotranspiration, which leads to a generally increased irrigation requirement in the 2030 and 2050 scenarios. In the drier climate projections, baseflow is projected to decrease.

In all climate scenarios, the projected changes in water balance terms are less than those due to climate variability. Thus, projected climate change may not be of great concern for regional water balances and should be managed through usual policy and management, since in any event management should cope with the greater impacts of climate variability. However, in the regional water balances we have not considered flooding or sea level rise, which are expected to worsen with climate change.

3.5 Substitution of some groundwater with surface water use

The Bangladesh National Water Management Plan (WARPO, 2001) anticipates several investments which will result some substitution of groundwater with surface water. Here, we assumed that in each region 20 percent of the current groundwater use (as calculated in the base case scenario) would be substituted with water diverted from rivers. The results in terms of annual averages and change from the base case are shown in Figure 11 to Figure 15. The increased diversions result in a greater baseflow return to the rivers in the northwest (Figure 11) and north central regions (Figure 12), which results from the restoration of groundwater levels with lesser pumping and from the recharge from infiltration where river water is used for irrigation.

3.6 Increased irrigation for greater food production

The demand for rice and other grains in Bangladesh (for direct consumption and for feeding animals) is likely to roughly double by 2050, as a result of the increased population and the increased consumption per head (Kirby et al., 2013; Mainuddin and Kirby, 2014). Some of the supply to meet that demand is likely to come from increased yield at the same level of land and water use. However, water use has been increasing throughout the last several decades, and it is likely to increase further for some while, though how much is not clear. Here, we assumed an increase of one third in the area to be irrigated, leading to an increase of one third in irrigation demand. Since there is concern now over the possible over-use of groundwater, and plans to use more surface water, we assumed that the whole of the additional water use would come from water diverted from rivers.

The results in terms of annual averages and change from the base case are shown in Figure 11 to Figure 15. The increased diversions and irrigation water use result in a greater baseflow return to the rivers in the all regions, which results from the restoration of groundwater levels with lesser pumping and from the recharge from infiltration where river water is used for irrigation.
4 Conclusions

4.1 Major findings

The results of the regional water balance scenario modelling discussed above together with results discussed in the literature (Moors et al., 2011; Mulligan et al., 2011; Yu et al., 2010) show that

- Climate variability, at least to 2050, is projected to have a greater impact on regional water balances than climate change. However, this result does not include any impact on the major rivers (Ganges, Jamuna, and Meghna). Thus, management and policy to cope with climate variability impacts on regional water availability will in large measure cope with climate change at least to 2050.

- Climate change projections are uncertain, with increased rain in the wet season likely, but decreased rain also possible. The projections with more rain may lead to increased recharge and runoff, and increased water availability. However, increased projected potential evapotranspiration may also lead to increased irrigation requirement. The extra groundwater pumping may lead to decreased groundwater baseflow to rivers, particularly in the drier climate change scenarios. Overall, climate change does not appear to a simple story of disadvantage at the regional level. However, in the regional water balances we have not considered flooding or sea level rise, which are expected to worsen with climate change.

- The increased use of river water, particularly when combined with an increase in irrigation overall, may lead to greater recharge and some restoration of groundwater levels. As a result, it may also lead to greater baseflows from groundwater to the rivers (so some of the water pumped from the rivers in effect recycles back to the rivers).

4.2 Further work

The study reported here is based on a simple model, using readily available data. As far as we know, it represents the first reported regional water balances for Bangladesh. However, several components of the water balances are not well tested or backed up by measured data, and thus the balances must be regarded as approximate. Notwithstanding, the broad conclusions above, which are based on comparing balances under different scenarios, probably provide a reasonable idea of the likely changes to the water balance, even if the absolute values are uncertain.

However, there remains good reason to develop more precise and accurate water balances. The approximate water balances developed here cannot be used directly for planning or management: the approximate nature of the results does not give estimates that can be relied on for such purposes. More precise and accurate water balances will aid a more accurate assessment of sustainability and of the consequences of changing use (such as the substitution of groundwater with surface water). A particular need is to determine the baseflow to rivers, which could be done from precise water accounting of river reaches, from careful study of groundwater gradients driving flow towards rivers, and possibly from tracer techniques, all backed up by groundwater – surface water modelling.

In addition, three of the water balances are incomplete and lack the river water components. Further, the water balances are for the small rivers that flow through the regions, and a complete water balance for Bangladesh would include the main rivers (Ganges, Jamuna and Meghna).
References


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CSIRO Water for a Healthy Country

Mac Kirby

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