Impact assessment of agricultural water management interventions in the Jaldhaka watershed

Devaraj de Condappa, Jennie Barron, Sat Kumar Tomer and Sekhar Muddu
Impact assessment of agricultural water management interventions in the Jaldhaka watershed

Application of SWAT and a groundwater model for current state of water resources and scenarios of agricultural development.

Devaraj de Condappa¹, Jennie Barron¹,
Sat Kumar Tomer² and Sekhar Muddu²

¹ Stockholm Environment Institute – York, Grimston House, University of York, Heslington, York YO10 5DD, United Kingdom
² Indian Institute of Science, Department of Civil Engineering, Bangalore 560 012, India
ABSTRACT

This study contributes to the understanding of potential for Agricultural Water Management (AWM) interventions in the watershed of Jaldhaka river, a tributary to the Brahmaputra river, located in Bhutan, India and Bangladesh. An application of the Soil Water Assessment Tool (SWAT) and of a simple lumped groundwater model was calibrated to reproduce observed time-series of streamflows and groundwater levels. The model step-up was applied to study the current state of hydrology in the Jaldhaka watershed and the impacts of two types of AWM scenarios.

The first AWM scenario assumed a change in landuse in the mountainous upstream part of the watershed: forests are cut down and used for cultivation of rainfed rice. The impact is an increase in flood events and a decrease in groundwater recharge upstream. The decreased recharge consequently gives a reduction of groundwater baseflow during the low flows season which is nevertheless moderated by the buffered nature of groundwater baseflow.

The second AWM scenario supposed a gradual improvement in access to electricity to increase groundwater pumping in the area: 25 per cent, 50 per cent, 75 per cent or 100 per cent of the current rainfed fields will grow additionally irrigated rice during the summer. The results show little impact on groundwater levels in the 25 per cent scenario but with increasing irrigation in the other three sub-scenarios downstream groundwater levels decrease down to a possible 8 meters in the 100 per cent scenario. Throughout the watershed groundwater baseflow reduces from about 15 per cent in the 50 per cent scenario to about 30 per cent in the 100 per cent scenario. Although this entails a small reduction of streamflows during the low flows season, the overall impact on the annual flow of the Jaldhaka river is insignificant.

In both scenarios, crop production increases with little impact on the total water availability, hence there is potential in the watershed to develop water management and increase food security. However, an augmented use of groundwater and a change in landuse can potentially affect the watershed in negative ways through, for example, lower groundwater level in some locations, more floods downstream and an important loss of forest biodiversity in the deforestation scenario. The negative hydrological effects may impact as well on the different river ecosystems and the use of water for other livelihood purposes.
# CONTENTS

Abstract iii

List of abbreviations viii

1 Introduction 1

2 Method 2
   2.1 Biophysical characteristics and data on the Jaldhaka watershed 2
   2.2 Modelling set-up 7
   2.3 Simplifications and limitations of the modelling  8
   2.4 Definition of the scenarios 9

3 Current state of the hydrology 14
   3.1 Comparison of rainfall with reference evapotranspiration 14
   3.2 Water budget 14
   3.3 Streamflows 14
   2.4 Scenario analyses 15

5 Discussion 23
   5.1 Current situation of water resources 23
   5.2 Impacts of the electrification scenario on the water resources 23
   5.3 Impacts of the electrification scenario on rice production 24
   5.4 Enlarging to other issues 24

6 Conclusion 25

Acknowledgements 26

References 27
LIST OF BOXES, FIGURES AND TABLES

Figure 1: Location of the Jaldhaka / Dharla river watershed (in purple). 1
Figure 2: Digital Elevation Model of the Jaldhaka watershed 2
Figure 3: Slope derived from the DEM 2
Figure 4: Topographic profile of the transect defined in Figures 2 and 3 3
Figure 5: Rainfall at Jalpaiguri and Cooch Behar stations (period 1988 - 2008) 3
Figure 6: Landuse map of the Jaldhaka watershed (year 2008) with the 18 sub-watersheds used in the modelling 4
Figure 7: Calendar of the main cropping sequences in the Jaldhaka watershed 5
Figure 8: Irrigation requirement of the different crops in the Jaldhaka watershed 7
Figure 9: Scheme of the modelling 7
Figure 10: Deforestation scenario: consequent landuse 10
Figure 11: Electrification scenario as defined in SWAT and in the groundwater model in each of the 18 sub-watersheds 12
Figure 12: Electrification scenario: consequent landuse 12
Figure 13: Modelled average water budget (period 1998 – 2008) for the Jaldhaka watershed 14
Figure 14: Modelled average water budget (years 01 to 10) for the Jaldhaka watershed in the reference scenario (left) and the deforestation scenarios (right) 15
Figure 16: Electrification scenario, average (years 01 to 10): simulated depletion in piezometric levels in the four sub-scenarios as compared to the Reference scenario 19
Figure 17: Electrification scenario, average (years 01 to 10) 20
Figure 18: Modelled average water budget (years 01 to 10) for the Jaldhaka watershed in the Reference and Electrification scenarios 21

LIST OF TABLES

Table 1: Topographic regions of the Jaldhaka watershed. 3
Table 2: Distribution of landuse in the Jaldhaka watershed (as per Figure 6) 5
Table 3: Average yields in the Jaldhaka watershed, period 1998 – 2008 6
Table 4: Landuse distribution considered in SWAT with respect to the discretisation in HRUs 6
Table 5: Simplifications and limitations of the modelling 8
Table 6: Changes applied to SWAT’s management tables in the scenario of deforestation and electrification 9
Table 7: Terms of the average streamflow modelled for different seasons (period 1998 – 2008) 15
Table 8: Terms of the average streamflow (years 01 to 10) modelled for different seasons in the deforestation scenario 16
Table 9: Area of agricultural lands (A in 1,000 ha) and rice production (P in 1,000 T) in the scenarios 18
Table 10: Terms of the average streamflow (years 01 to 10) modelled for different seasons in the electrification scenario 22
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ArcSWAT</td>
<td>ArcGIS interface for SWAT</td>
</tr>
<tr>
<td>AWM</td>
<td>Agricultural Water Management</td>
</tr>
<tr>
<td>CN2</td>
<td>SWAT parameter, initial soil curve number for moisture condition II [-]</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>ETo</td>
<td>Actual evapotranspiration [L/T]</td>
</tr>
<tr>
<td>ET0</td>
<td>Reference evapotranspiration [L/T]</td>
</tr>
<tr>
<td>FLOW_OUT</td>
<td>SWAT ouput, average daily streamflow out of reach during time step [L/T]</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GW_Q</td>
<td>SWAT ouput, groundwater baseflow contribution to streamflow [L]</td>
</tr>
<tr>
<td>GW_RCHG</td>
<td>SWAT ouput, recharge entering the shallow aquifer [L]</td>
</tr>
<tr>
<td>HRU</td>
<td>Hydrologic Response Unit</td>
</tr>
<tr>
<td>IWM1</td>
<td>International Water Management Institute</td>
</tr>
<tr>
<td>LATQ</td>
<td>SWAT ouput, lateral flow contribution to the streamflow [L]</td>
</tr>
<tr>
<td>masl</td>
<td>Meter above sea level [L]</td>
</tr>
<tr>
<td>mbgl</td>
<td>Meter below ground level [L]</td>
</tr>
<tr>
<td>P</td>
<td>Rainfall [L/T]</td>
</tr>
<tr>
<td>PGIS</td>
<td>Participatory GIS</td>
</tr>
<tr>
<td>SEI</td>
<td>Stockholm Environment Institute</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>SWAT</td>
<td>Soil Water Assessment Tool</td>
</tr>
<tr>
<td>SURQ</td>
<td>SWAT ouput, surface runoff contribution to the streamflow [L]</td>
</tr>
<tr>
<td>WTF</td>
<td>Water Table Fluctuation</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

Agricultural Water Management (AWM) interventions are often a first step to increasing smallholder farmers’ yield levels, their incomes and household food security in many developing countries. Globally, smallholder farming systems may hold a potential to increase current yield levels 2-4 times, and water productivity gains potentially more than double (Rockström 2003).

The AgWater Solution project (http://awm-solutions.iwmi.org/) is systematically assessing opportunities to invest in agricultural water management interventions at local to continental scale, to enhance smallholder farmers’ livelihoods. However, agricultural development and intensification can also unintentionally impact various social and environmental dimensions where the interventions are adopted. This report considers the AgWater Solution project watershed of the Jaldhaka river, also known as Dharla, a tributary of the Brahmaputra river. It is a transboundary river originating in Bhutan, flowing through India and joining the Brahmaputra in Bangladesh (Figure 1). The Jaldhaka watershed is one of four project watershed sites, subject to a suite of assessments on agro-hydrological, livelihood and institutional contexts undertaken to identify what potential opportunities are at a local (watershed scale) and how potential interventions may impact the environment, in particularly water resources, and livelihoods.

This report on the Jaldhaka watershed will present the current agro-hydrological state and two scenarios of agricultural interventions. An application of the Soil Water Assessment Tool (SWAT) and of a simple lumped groundwater model were developed to study the impacts on hydrological balance and crop production under the different scenarios of agricultural interventions. An accompanying working paper reports the methodology deployed to set both models (de Condappa et al. 2011). Here we will report (i) the characteristics of the Jaldhaka watershed and the collected dataset (section 6), (ii) the modelling set-up (sections 12 and 13), (iii) the definition of the AWM scenarios (section 14), (iv) the modelling outputs for the current state of the hydrology and agricultural water management scenarios (sections 19 and 20) and (v) the discussion (section 31).

Figure 1: Location of the Jaldhaka / Dharla river watershed (in purple).
The delineation of the Jaldhaka/Dharla watershed were generated in this work Image adapted from Google Earth.
2 METHOD

2.1 BIOPHYSICAL CHARACTERISTICS AND DATA ON THE JALDHAKA WATERSHED

Jaldhaka watershed has a contrasting topography that can be characterised by three topographic regions (Table 1, Figures 2 and 3):

- mountainous upstream (18 per cent of the watershed), where elevation ranges from 500 to more than 4,000 meter above sea level (masl) and slope from 3 to 40 degree (within the watershed),
- piedmont upstream (22 per cent of the watershed), where elevation ranges from 100 to 500 masl and slope from 1 to 3 degree,
- and plain middle and downstream (60 per cent of the watershed), where elevation ranges from 100 to 18 masl and slope less than 1 degree.

The profile of transect defined on Figures 2 and 3 is placed in Figure 4.

In this work, the delineation considered for the Jaldhaka watershed was not the whole extent until the confluence with the Brahmaputra (6,140 km²) but instead the catchment area upstream of the Kurigram streamflow gauge station (5,800 km²), cf. Figures 2 and 3.

The region receives high rainfall, amongst the highest in India. Values of the annual rainfall fluctuate from 2,000 to almost 5,000 mm/year, with an average of 3,500 mm/year at Cooch Behar station, during the period 1988 to 2008 (Figure 5). The rainfall has a monsoonal seasonal pattern, with a relatively dry season from November to March and a rainy season from April to October. Almost all of the annual rain falls in the rainy season (98 per cent), especially between June to September (80 per cent). Daily rainfall intensities can be very high during the peak of the monsoon, with an average...
Topography Area (km²) Share (%)

<table>
<thead>
<tr>
<th>Topography</th>
<th>Area (km²)</th>
<th>Share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountains</td>
<td>1,031</td>
<td>18</td>
</tr>
<tr>
<td>Piedmont</td>
<td>1,270</td>
<td>22</td>
</tr>
<tr>
<td>Plains</td>
<td>3,494</td>
<td>60</td>
</tr>
<tr>
<td>Total</td>
<td>5,795</td>
<td>100</td>
</tr>
</tbody>
</table>

Source of data: Regional Meteorological Centre, Kolkata
The Jaldhaka river is perennial with high seasonal variation. The low flow season is between November to April and about 11 per cent of the annual flow occurs during this period. The high flow season is between May to October with a sharp raise of the discharge in June. Occurrence of flood is common, often in the month of July. The force of the floods can be such that the main river of the region, the Teesta, shifted its course from the Ganges to the Brahmaputra only in the last three hundred years (Kundu and Soppe 2002).

The distribution of the soils follow the topography:

- mountainous upstream shallow soils, coarse sandy loam,
- piedmont upstream deep soils, sandy loam to loam,
- plains middle and downstream deep soils, sandy loam to silty loam.

The groundwater regime can be categorized into two categories: (i) in the plain downstream and (ii) in the piedmont area middle stream. In the plain downstream, the aquifer system is alluvial and composed of ancient sediments from succession of the Ganga – Brahmaputra river systems (Kundu and Soppe 2002; CGWB 2009). The groundwater levels are shallow, fluctuating from 1 to 5 m below ground level (mbgl) before the monsoon in April to 0 to 3 mbgl during the monsoon in August. In the piedmont area, the aquifer is composed of more recent sediments carried by the tributaries from the mountainous upstream areas (Kundu and Soppe 2002; CGWB 2009). The groundwater levels are also shallow, although some wells indicate a deeper level. The levels fluctuate from 2 to 15 mbgl before the monsoon in April to 1 to 11 mbgl during the monsoon in August.

The landuse map shown in Figure 6 was prepared during this work for the year 2008 (de Condappa et al., 2011). Table 2 summarises the extent of each landuse category. The major crops in the region of the Jaldhaka watershed are:

![Figure 6: Landuse map of the Jaldhaka watershed (year 2008) with the 18 sub-watersheds used in the modelling](de Condappa et al. 2011)
### Table 2: Distribution of landuse in the Jaldhaka watershed (as per Figure 6)

<table>
<thead>
<tr>
<th>Landuse category</th>
<th>In SWAT</th>
<th>Area (km²)</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>FRSJ</td>
<td>1338</td>
<td>23</td>
</tr>
<tr>
<td>Tea or Light Forest</td>
<td>TEAB</td>
<td>510</td>
<td>9</td>
</tr>
<tr>
<td>Small Trees or Shrubland or Settlement</td>
<td>FRMJ</td>
<td>785</td>
<td>13</td>
</tr>
<tr>
<td>Monsoon_Rice -&gt; [Pre-monsoon_Rice]</td>
<td>AAAJ</td>
<td>174</td>
<td>3.0</td>
</tr>
<tr>
<td>Monsoon_Rice -&gt; [Winter Crop] -&gt; [Jute or Pre-monsoon_Rice]</td>
<td>AWJJ</td>
<td>1,841</td>
<td>32</td>
</tr>
<tr>
<td>Monsoon_Rice -&gt; [Winter Crop] -&gt; Summer_Rice</td>
<td>AWBJ</td>
<td>342</td>
<td>6</td>
</tr>
<tr>
<td>Village or Fallow</td>
<td>VIFA</td>
<td>256</td>
<td>4</td>
</tr>
<tr>
<td>Town</td>
<td>URMD</td>
<td>8</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Water</td>
<td>WATR</td>
<td>541</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>5,795</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Figure 7: Calendar of the main cropping sequences in the Jaldhaka watershed**

(de Condappa et al. 2011)
• **Summer_Rice**, locally called *Boro*: irrigated rice grown before the onset of the monsoon, from February to May.

• **Pre-monsoon_Rice**, locally called *Aus*: partly irrigated rice grown at the onset of the monsoon, from April to June.

• **Monsoon_Rice**, locally called *Aman*: rice grown during the rainy season, from June/July to September/October, rainfed or partly irrigated depending on the case.

• **Jute**: rainfed vegetable fibre grown at the onset of the monsoon, from April to June.

• **Winter Crop**: irrigated crop following the rain season, which is Potato (predominantly), Tobacco or Vegetables, from November to February; from now we will consider this crop to be Potato.

• **Wheat**: irrigated during winter, from January to April.

The cropping calendar of these crops is illustrated in Figure 7, the crop yields in Table 3 and their irrigation in Figure 8 (de Condappa *et al.*, 2011). Three categories of habitation zones were identified, from the smallest to the largest: (i) settlements, with few habitations around trees, (ii) villages with a greater number of habitations and sparse vegetation and (iii) towns with urbanised areas.

### Table 3: Average yields in the Jaldhaka watershed, period 1998 – 2008

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Clean yield (T/ha)</th>
<th>Dry yield (T/ha)</th>
<th>Yield (T/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monsoon rice (Aman)</strong></td>
<td>1.5 (2.4)</td>
<td></td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Pre-monsoon rice (Aus)</strong></td>
<td>1.4 (2.0)</td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Summer rice (Boro)</strong></td>
<td>2.2 (2.9)</td>
<td></td>
<td>18.8</td>
</tr>
<tr>
<td><strong>Jute</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wheat</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3: Average yields in the Jaldhaka watershed, period 1998 – 2008**

In bracket the average dry yield of rice for period 2004 to 2008

Source of data: Bureau of Applied Economics and Statistics and Directorate of Agriculture

### Table 4: Landuse distribution considered in SWAT with respect to the discretisation in HRUs

For details on data source, collection and processing please refer to de Condappa *et al*. (2011)

<table>
<thead>
<tr>
<th>Landuse category</th>
<th>Area (km²)</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest (FRSJ)</td>
<td>1,442</td>
<td>25</td>
</tr>
<tr>
<td>Tea or Light Forest (TEAB)</td>
<td>438</td>
<td>8</td>
</tr>
<tr>
<td>Small Trees or Shrubland or Settlement (FRMJ)</td>
<td>805</td>
<td>14</td>
</tr>
<tr>
<td>Rainfed Monsoon_Rice</td>
<td>1,002</td>
<td>17</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Pre-monsoon_Rice</td>
<td>173</td>
<td>3</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Wheat</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Potato – Jute</td>
<td>825</td>
<td>14</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Summer_Rice</td>
<td>342</td>
<td>6</td>
</tr>
<tr>
<td>Village or Fallow (VIFA)</td>
<td>232</td>
<td>4</td>
</tr>
<tr>
<td>Town (URMD)</td>
<td>8</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Water (WATR)</td>
<td>475</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,795</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

**Table 4: Landuse distribution considered in SWAT with respect to the discretisation in HRUs**
Eventually the distribution of the landuse and cropping sequences as represented in SWAT was slightly different from values in Table 2 due to the splitting up of the watershed into Hydrologic Response Units (HRUs), which is reported in Table 4.

2.2 MODELLING SET-UP

The objective of the modelling was to describe the current state of hydrology in the Jaldhaka watershed and to enable insight into a possible change in agricultural water management. The primary hydrological model selected for this purpose was the Soil and Water Assessment Tool (SWAT) developed by the United State Department of Agriculture and Texas A & M University (Arnold et al., 1993), Srinivasan and Arnold (1994), Arnold et al., (1995) and Arnold et al. (1998). We used version 433 of SWAT 2009 that we operated with the interface ArcSWAT version 2009.93.4. SWAT simulates different surface and ground hydrological components as well as crop yields.

Since SWAT’s modelling of groundwater is simplified and groundwater is a prominent water resource for agriculture in the Jaldhaka watershed, the groundwater model developed by Tomer et al., (2010) was also employed to interpret the available groundwater levels, which was not possible with the version of SWAT used in this work. The groundwater model is based on a combination of the groundwater budget and the Water Table Fluctuation (WTF) technique. The WTF technique has widely been applied to link the change in ground water storage with resulting water table fluctuations through the storage parameter (specific yield). The groundwater model has a lumped approach suited to the Jaldhaka watershed since there is little hydrological and geological data available. It is further described in de Condappa et al., (2011).

![Figure 8: Irrigation requirement of the different crops in the Jaldhaka watershed](image_url)

**Figure 8: Irrigation requirement of the different crops in the Jaldhaka watershed**

(de Condappa et al. 2011)

![Figure 9: Scheme of the modelling](image_url)

**Figure 9: Scheme of the modelling**
The strategy of the modelling is illustrated in Figure 9. Both models were run independently but were synchronised so as to model a similar groundwater recharge and baseflow. The groundwater model interpreted the measured groundwater levels, which is not possible with SWAT as it does not simulate piezometric levels, and the streamflow during the low flow season to provide an indication of the magnitude of the recharge and baseflow. At the same time, SWAT gave an indication of the spatial and temporal variation of the recharge, with respect to properties of the overlaying soil cover. Both models were tuned so that they converge to similar outputs.

Data pertaining to the topography, climate, streamflow, soils, groundwater, landuse, agricultural crops and irrigation briefly presented above were obtained from local agencies and international databases. They were filtered and pre-processed for the modelling. A set of 18 sub-watersheds were generated for the modelling (Figure 6). The groundwater model was calibrated against the observed groundwater levels and subsequently guided the setting of SWAT’s groundwater parameters. SWAT was calibrated against the observed streamflows. Please refer to de Condappa et al., (2011) for details.

The current state of the hydrology is derived from the final calibration run and is analysed in section 3

### 2.3 SIMPLIFICATIONS AND LIMITATIONS OF THE MODELLING

Table 5 summarises the simplifications and limitations of the modelling set-up. The current version of this set-up is only valid for monthly or annual average trends at the scale of the whole watershed. In particular, it should not be used to analyse outputs of individual months, years or sub-watersheds (de Condappa et al., 2011).

<table>
<thead>
<tr>
<th>Category</th>
<th>Limitation</th>
<th>Why?</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponding of paddy field should be modelled in SWAT with a pothole</td>
<td>Ignored</td>
<td>Only one HRU per sub-watershed can be a pothole in SWAT 2009</td>
<td>The hydrological functioning of a paddy field is not modelled correctly, which could affect calculations of: rice yield, water budget terms around the paddy field (evapotranspiration, groundwater recharge, surface and sub-surface run-off).</td>
</tr>
<tr>
<td>Domestic &amp; industrial water consumption</td>
<td>Ignored</td>
<td>No data</td>
<td>Should not be an issue as there is no major city nor industries along the Jaldhaka. Moreover these demands usually consume little water as compared to irrigation.</td>
</tr>
<tr>
<td>Deep aquifer</td>
<td>Ignored</td>
<td>Deep aquifer processes in such alluvial context were assumed to be governed by lateral transfers between regions outside of the Jaldhaka watershed.</td>
<td>Should not affect the hydrological modelling of the Jaldhaka river network.</td>
</tr>
<tr>
<td>Crop yield not simulated correctly</td>
<td>Possible bad representation in SWAT of the crops and agricultural practices in the Jaldhaka watershed.</td>
<td>Analysis of the current and scenario contexts ignored SWAT’s simulations for crop yields.</td>
<td></td>
</tr>
<tr>
<td>Snow accumulation and melting upstream</td>
<td>Ignored</td>
<td>No data on snow accumulation and lapse in temperature</td>
<td>Should be negligible as most of the rainfall occurs during the warm period.</td>
</tr>
<tr>
<td>Groundwater pumping for irrigation</td>
<td>Considered constant in SWAT</td>
<td>Cumbersome to enter a varying irrigation in management table (mgt2)</td>
<td></td>
</tr>
<tr>
<td>Streamflow</td>
<td>Available only at 2 locations downstream</td>
<td>Data restriction in India</td>
<td>Not analyses are possible at sub-watershed scale but only for the whole watershed.</td>
</tr>
</tbody>
</table>
Another serious limitation is that, for reasons detailed in de Condappa et al., (2011), the simulated yields were not reliable since the version 2009 of SWAT used in this work was not appropriate to model rice grown under impounded conditions. Therefore, in the followings we did not consider the simulated yields but utilised instead the statistical yields reported in Table 3.

2.4 DEFINITION OF THE SCENARIOS

The objective of the scenario analysis was to compare the potential impact of a change in an individual parameter, the other factors remaining unaltered, as compared to a reference, called scenario of reference. The scenarios focused on change related to agricultural practice and were of two types: (i) a deforestation upstream in favour of agriculture – noted Deforestation scenario and (ii) farmers gradually get access to subsidized electricity to support groundwater pumping for irrigation – noted Electrification scenario. Each scenario is defined in following sections.

Technically, the scenarios were modelled as follows:

- the duration of each simulation was 10 years;

- the setting of the reference scenario run was similar to the final calibration run (de Condappa et al., 2011) except:
  - the calibration was over the period 1998 to 2008 while the reference run was for years 1999 to 2008 so that the duration of the scenario was 10 years,
  - the groundwater pumping was increasing every year in the calibration phase while it was taken to be equal to the value assessed for 2008 in the reference run, as it will be explained below;
  - the configuration of the two types of scenario was the same as the reference scenario except:
  - deforestation scenario: upstream forests were replaced by agricultural or bare lands,
  - electrification scenario: areas currently growing only Monsoon_Rice gradually start to grow Monsoon_Rice followed by Summer_Rice.

- in all the scenarios:
  - the input climatic data was the time-series of period 1999 to 2008 with year 01 of a scenario having climatic data of year 1999... year 10 climatic data of year 2008,
  - and the run was initiated 5 years earlier, i.e., from 1994 to 2008 (climate data were available since 1988), to stabilise the water budget and avoid effects of initial conditions; the outputs of period 1994 to 1998 were ignored.

The main difference between the reference scenario and the calibration run was the groundwater withdrawals. During calibration, the withdrawals were increasing from 1998 to 2008, reproducing what was

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Modified parameter</th>
<th>Which original land-use category?</th>
<th>Modified values</th>
</tr>
</thead>
</table>
| Deforestation    | mgf1 CN2           | Forests (FRSJ)                   | If slope ≤ 43%:
|                  | mgf2 Management Operations |                         | * soils group A: 70
|                  |                    |                                  | * soils group B & C: 90
|                  |                    |                                  | If slope > 43%:
|                  |                    |                                  | * soils group A: 80
|                  |                    |                                  | * soils group B & C: 90
| Electrification  | mgf1 CN2           | Rainfed Monsoon_Rice             | CN2 = 95                                                                     |
|                  | mgf2 Management Operations |                         | Irrigated Monsoon_Rice - Summer_Rice                                           |
observed in the watershed (de Condappa et al., 2011). As the electrification scenario entailed a change in groundwater pumping and the objective was to clearly identify the impacts of this change, the pumping in the reference scenario should be constant. Consequently, the groundwater withdrawals were fixed and equal to the values assessed for 2008 in the reference scenario, which is different from the setting during the calibration.

Table 6 summarises the parameter changes applied in each scenario. This change was fully applied right from year 01 of a scenario, the models ran for 10 years and the average impact over the 10 years was analysed.

2.4.a Deforestation scenario
The deforestation scenario was chosen to explore the biophysical limits and responses of the watershed, rather than to explore a ‘feasible’ future outlook. We assumed that forests get replaced whether by agricultural land, more precisely by Monsoon_Rice cultivation, or bare land where the slope is steep. In SWAT, we changed the HRUs having the landuse category Forest (FRSJ) to (Figure 10):

- Rainfed Monsoon_Rice (landuse class Monsoon_Rice → [Pre-monsoon_Rice], AAAJ) if the slope was less than 43 per cent,
- bare land, and more precisely to the existing category Village or Fallow (VIFA), if slope was more than 43 per cent.

We modified accordingly the management tables (i) mgt1 by increasing CN2 from forest values to values of agricultural lands or VIFA category (fallows) and (ii)
mgf2 by replacing the forest vegetation with rainfed Monsoon_Rice or bare soil (i.e., no vegetation) (cf Table 6). These alterations were effective right from year 01 of the scenario.

It is noteworthy that this deforestation scenario would entail a massive loss of forest biodiversity in the upstream part of the basin, in Bhutan. This would certainly have additional impacts to those on the water resource studied here.

2.4.2 Electrification scenario

The electrification scenario was based on (i) discussions held during the AgWater Solutions Stakeholders Consultation Workshop organised by IWMI on the 16th of February 2010 in Kolkata, (ii) Participatory GIS (PGIS) livelihood analysis conducted by SEI within the AgWater Solution Project in the Jaldhaka watershed (de Bruin et al. 2010b) and (iii) the discussions organised by the PGIS activity with local experts from Cooch Behar and Jalpaiguri (de Bruin et al. 2010a) in April 2010.

This scenario supposed that the State government gradually provides to farmers access to subsidised electricity for irrigation from groundwater pumping. This would at least affect the way farmers pump water and grow their crops. Two assumptions were taken. First, the PGIS survey reveals that farmers currently pump groundwater largely with diesel pumps, which is confirmed by official statistics (de Condappa et al., 2011). With access to subsidised electricity, farmers could shift to submersible pumps, as these pumps can draw groundwater from greater depth and with a greater yield. Submersible pumps are very common in other Indian locations but where groundwater levels are deeper than in the Jaldhaka watershed. Therefore we assumed in this electrification scenario that farmers would not opt for the technological leap to submersible pump and would continue to use centrifugal pumps as long as the groundwater levels are shallow. Their benefit under this scenario would be access to subsidised electricity to run electrical centrifugal pumps.

Second, in term of change in crops, PGIS analysis showed that if farmers have greater access to irrigation, they would not change their current irrigated crops but would choose to grow additional Summer_Rice as supplementary potatoes would require new cold storage facilities as well (de Bruin et al. 2010a). Hence we assumed that (i) the change would only occur for rainfed fields which are currently growing Rainfed Monsoon_Rice, the others cropping patterns that are currently irrigated being unaffected, and (ii) in these fields Summer_Rice would be additionally grown after Monsoon_Rice, i.e., the fields Rainfed Monsoon_Rice get replaced by Irrigated Monsoon_Rice – Summer_Rice.

More precisely, we considered four sub-scenarios where respectively 25 per cent, 50 per cent, 75 per cent or 100 per cent of the areas currently growing Rainfed Monsoon_Rice would shift to the practice Irrigated Monsoon_Rice - Summer_Rice and the associated increase in groundwater pumping for irrigation would be as defined in de Condappa et al. (2011). It is reminded that in the reference scenario irrigation from river and groundwater is taken to be equal to the value for 2008. Concretely in SWAT the HRUs which were Rainfed Monsoon_Rice in the reference scenario were changed gradually to Irrigated Monsoon_Rice - Summer_Rice as we move from one sub-scenario to the next (e.g., 25 per cent to 50 per cent), choosing the same management operations defined in de Condappa et al., (2011) (Table 6). While applying the change in management operations, we modified the value of the CN2 coefficient as well, entering the value 95 as chosen in the calibration phase. We attempted to alter firstly downstream HRUs, where additional pumping is the most likely. Since the watershed was broken up into HRUs of different shape and area, reproducing the exact percentages 25 per cent, 50 per cent, 75 per cent and 100 per cent as defined above was not possible, so instead the percentages were 28 per cent, 53 per cent, 79 per cent and 100 per cent.

Figure 11 shows the corresponding increase in irrigation, due to additional irrigation, partially for Monsoon_Rice (now being irrigated to a certain extent) and especially Summer_Rice. The magnitude of the increase in groundwater pumping is large, especially in the sub-watersheds 7 (from 195 to 666 mm/year), 9 (100 to 707 mm/year) and 12 (293 to 731 mm/year) middlestream and the sub-watersheds 15 (141 to 857 mm/year) and 17 (623 to 1,054 mm/year) downstream. At the watershed scale, the increase in groundwater withdrawal is from 145 mm/year in the reference scenario to 400 mm/year in the 100 per cent sub-scenario, more than twice as great. As it will be shown in Figure 14, 400 mm/year is close to the 579 mm/year of groundwater recharge in the reference scenario hence we can infer some significant impacts.

Mapping the changes in agricultural land was not immediate since, as was explained in de Condappa et al., (2011), the spatial information is lost during the generation of the HRUs. We tracked back the approximate HRUs by matching same combination of sub-watershed/landuse/soil/slope-classes – matching cannot be exact as there was a simplification of the
Figure 11: Electrification scenario as defined in SWAT and in the groundwater model in each of the 18 sub-watersheds
Top: increase in area under Irrigated Monsoon_Rice – Summer_Rice. Bottom: associated groundwater pumping with the value representative of the whole watershed in thick black line. Right: spatial distribution of the additional pumping in the 100% sub-scenario as compared with the reference scenario.

Figure 12: Electrification scenario: consequent landuse
The percentages (below the maps) indicate the areas currently growing only Rainfed Monsoon_Rice which would become Irrigated Monsoon_Rice – Summer_Rice in this scenario. Aman: Monsoon_Rice, Aus: Pre-monsoon_Rice, Bora: Summer_Rice.
GIS input information while creating the HRUs. The approximate maps showing the change in agricultural landuse category are placed in Figure 12.

The definition of the sub-scenarios as used in the SWAT approach was not suitable for the groundwater model. The distribution of the areas shifting from Rainfed Monsoon_Rice to Irrigated Monsoon_Rice – Summer_Rice with respect to the HRUs entails indeed sudden spatial changes, when some Rainfed Monsoon_Rice HRUs become Irrigated Monsoon_Rice – Summer_Rice. This is associated with sudden increase in groundwater pumping as we move from one sub-scenario to the next (Figure 11). Although this sudden change might be realistic as similar clusters of socio-economical/cropping pattern/soil/terrain may shift their cropping pattern at the same time, the simulations of the groundwater model would not be correct as it is based on a lumped approach hence it would not model the distributed signal: it would model sudden but local depletion in the groundwater while in reality the alluvial aquifer is a relatively homogeneous system that spatially buffers any local change. In the groundwater model, the shift from the areas Rainfed Monsoon_Rice to Irrigated Monsoon_Rice – Summer_Rice, and in particular its associated increase in groundwater pumping, was linear in each sub-watershed as we move from one sub-scenario to the next. This time the percentage increases were exactly 25 per cent, 50 per cent, 75 per cent and 100 per cent (Figure 11).

In the following, outputs of the groundwater model were used to analyse impacts on the groundwater levels and the groundwater baseflow while SWAT showed consequences on the water budget and streamflow. In both models, the alterations of this electrification scenario, as compared to the reference scenario, were effective right from year 01 of the four sub-scenarios.
3 CURRENT STATE OF THE HYDROLOGY

The average water budget modelled for the period 1998 – 2008 by the final calibration run is shown on Figure 13. This budget represents the current state of the hydrology.

3.1 COMPARISON OF RAINFALL WITH REFERENCE EVAPOTRANSPIRATION

Using the reference evapotranspiration (ET₀) as defined by Allen et al., (1998), the ratio of rainfall P to reference evapotranspiration

\[ \frac{P}{ET₀} \]

provides an indication of the aridity: the smaller it is compared to 1, the more arid (Budyko and Miller 1974). In the Jaldhaka watershed this ratio takes an average value of 2.5 hence the watershed is very humid.

3.2 WATER BUDGET

The water budget shows that the rainfall is partitioned mainly by two processes: as much as 73 per cent of this rain water contributes to streamflows and a smaller 26 per cent of the amount evapotranspires. The small value of this last percentage is once more a particularity of the Jaldhaka watershed as compared to the other watersheds of the AgWater Solutions Project, where evapotranspiration represents the dominant term of the water budget. The restriction for a greater evapotranspiration is not the water availability but the relatively moderate value of the reference evapotranspiration ET₀.

Of the 73 per cent of rainfall that is partitioned into river flow, 51 per cent is from direct runoff at the soil surface: half of the rainfall generates runoff at the soil surface and reaches the river system. This is conceivable with the high intensity of rain events and the low conductivity of soils in the watershed. A consequence is recurrent flood events in the peak of the monsoon. Another consequence is high soil erosion as the intense rainfall events on the steep upstream part creates high speed river flows toward the plains (Kundu and Soppe 2002).

The shallow groundwater baseflow represents 13 per cent of the rainfall and contributes to a minor share of the flow in the river but enables sustained flows during the relative dry season, as shown in the forthcoming section. The last term creating streamflow is the sub-soil lateral flow, which carries 9 per cent of the rainfall and is generated in upstream mountainous sub-watersheds.

The groundwater recharge, which is an internal flux within the Jaldhaka watershed, represents 18 per cent of the rainfall.

3.3 STREAMFLOWS

The surface runoff (SURQ), sub-soil lateral flow (LATQ) and groundwater baseflow (GW_Q) produce the flows of the Jaldhaka river. The contribution of these terms for the whole year and during the dry

<table>
<thead>
<tr>
<th>Water budget terms</th>
<th>(mm/year)</th>
<th>(% of rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>3,179 ± 667</td>
<td>100</td>
</tr>
<tr>
<td>Surface runoff (SURQ)</td>
<td>1,635 ± 406</td>
<td>51</td>
</tr>
<tr>
<td>Sub-soil lateral flow (LATQ)</td>
<td>289 ± 102</td>
<td>9</td>
</tr>
<tr>
<td>Groundwater baseflow (GW_Q)</td>
<td>418 ± 150</td>
<td>13</td>
</tr>
<tr>
<td>Groundwater recharge (GW_RCHG)</td>
<td>571 ± 158</td>
<td>18</td>
</tr>
<tr>
<td>Reference evapotranspiration (ET₀)</td>
<td>1,296 ± 38</td>
<td>41</td>
</tr>
<tr>
<td>Actual evapotranspiration (ETa)</td>
<td>828 ± 40</td>
<td>26</td>
</tr>
</tbody>
</table>

Figure 13: Modelled average water budget (period 1998 – 2008) for the Jaldhaka watershed

The statistical standard deviation is also indicated in mm/year
and wet seasons are compiled in Table 7. Since a very predominant part of the annual streamflow is generated during the wet season, the contribution of each term to the annual flow is similar to the situation during the wet season. Annually and during the monsoon, SURQ generates a very large share of the streamflow.

However, the situation changes significantly during the low flows season where GW_Q becomes the predominant process generating river flow, although SURQ is not negligible. The groundwater baseflow is essential to maintain substantial streamflow during the low flow season.

### Table 7: Terms of the average streamflow modelled for different seasons (period 1998 – 2008)
The statistical standard deviation is also indicated in mm

<table>
<thead>
<tr>
<th>Period</th>
<th>Total streamflow</th>
<th>Surface runoff (SURQ)</th>
<th>Sub-soil lateral flow (LATQ)</th>
<th>Groundwater baseflow (GW_Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(%)</td>
<td>(mm)</td>
<td>(%)</td>
</tr>
<tr>
<td>Whole year</td>
<td>2,342 ± 625</td>
<td>70</td>
<td>289 ± 102</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1,635 ± 406</td>
<td>31</td>
<td>11 ± 8</td>
<td>3</td>
</tr>
<tr>
<td>Low flows: November to April</td>
<td>320 ± 94</td>
<td>99 ± 38</td>
<td>210 ± 71</td>
<td>66</td>
</tr>
<tr>
<td>High flows: May to October</td>
<td>2,022 ± 542</td>
<td>1,536 ± 383</td>
<td>278 ± 98</td>
<td>14</td>
</tr>
</tbody>
</table>

#### 2.4 SCENARIO ANALYSES

##### 2.4.1 Reference scenario

The water budget of the reference scenario is plotted in Figure 14. It is a reminded that the reference scenario and the calibration run are only different on two points. First, the calibration was over the period 1998 to 2008 while the reference run was for years 1999 to 2008 (10 years scenarios). As a consequence, the average rainfall in the reference scenario is less than in the calibration run (Figure 13) as the rainfall was high in 1998 (de Condappa et al., 2011). Second, in the reference scenario the groundwater pumping was constant and equal to the value assessed for
2008, while it was increasing in the calibration phase. This however did not change the share of the different terms of the water budget, in particular the groundwater baseflow (GW_Q) still represents 13 per cent of rainfall.

2.4.2 Deforestation scenario

Water budget

The water budget of the deforestation scenario for the whole Jaldhaka watershed is compared to the reference in Figure 14. The difference between the two main components of the water budget, i.e., streamflows and evapotranspiration, hardly changed. However, if we analyse the share between the sub-processes generating the streamflow, we notice that more streamflow is generated through direct surface runoff (SURQ) and less from sub-surface soil lateral flow (LATQ) and groundwater baseflow (GW_Q) (Table 8). Due to deforestation, SURQ becomes the large predominant term of the annual flow, as compared to the reference. There is a reduction in groundwater recharge as agricultural soils are not as permeable as forest soils. Due to the rather homogeneous characteristics of the alluvial aquifer, this reduction is distributed throughout the year, in both the dry and wet seasons. The increase in SURQ and LATQ occurs predominantly during the high flows season. The reduction in LATQ is relatively important as the infiltrating upstream forests in mountainous sub-watershed were replaced by more impermeable agricultural land. The increase in SURQ is a fast process, as compared to the buffered LATQ and GW_Q, hence we can expect increase in flows during the high flows season, hence an increase in floods events and / or magnitude.

Streamflows

The sudden increase in SURQ during the wet season is confirmed while examining the streamflows (Figure 15):

- peak flows are of higher magnitude,
- there are additional peaks,
- hence there is more risk for damaging flood events.

Moreover, the augmentation at the watershed scale of SURQ is a bit less than 300 mm and greater than the reduction of GW_Q (a bit more than 100 mm). Hence the change on the low flows is almost unnoticeable and the major impact of this scenario on the streamflows is the increase of flows during the monsoon.

The impact on the streamflows appears greater compared to the effects on the watershed water budget, i.e., the additional peak flows seem greater than the augmentation of SURQ for the whole watershed. The explanation is that the change in this scenario concerns mainly the upstream mountainous sub-watersheds where (i) precipitation is relatively greater, (ii) the steep slopes and the change in soil cover entails high increase in SURQ, which in turn (iii) creates the higher peaks. However, the change in the water budget of the watershed is weighted by values of all the other sub-watersheds unaffected by the scenario.

Rice production

The Deforestation scenario shows some beneficial impacts in terms of crop productions as this scenario entails an increase in agricultural lands. Indeed, the

<table>
<thead>
<tr>
<th>Period</th>
<th>Scenarios</th>
<th>Total streamflow (mm)</th>
<th>Surface runoff (SURQ)</th>
<th>Sub-soil lateral flow (LATQ)</th>
<th>Groundwater baseflow (GW_Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(mm)</td>
<td>(%)</td>
<td>(mm)</td>
<td>(%)</td>
</tr>
<tr>
<td>Whole year</td>
<td>Reference</td>
<td>2,226 ± 523</td>
<td>1,549 ± 327</td>
<td>271 ± 89</td>
<td>407 ± 141</td>
</tr>
<tr>
<td></td>
<td>Deforestation</td>
<td>2,261 ± 533</td>
<td>1,834 ± 402</td>
<td>134 ± 39</td>
<td>293 ± 114</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Low flows: November to April</td>
<td>Reference</td>
<td>309 ± 85</td>
<td>93 ± 34</td>
<td>11 ± 8</td>
<td>205 ± 69</td>
</tr>
<tr>
<td></td>
<td>Deforestation</td>
<td>263 ± 81</td>
<td>108 ± 45</td>
<td>7 ± 4</td>
<td>148 ± 57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>High flows: May to October</td>
<td>Reference</td>
<td>1,917 ± 449</td>
<td>1,456 ± 311</td>
<td>260 ± 85</td>
<td>201 ± 73</td>
</tr>
<tr>
<td></td>
<td>Deforestation</td>
<td>1,998 ± 464</td>
<td>1,726 ± 381</td>
<td>127 ± 36</td>
<td>145 ± 58</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>

Table 8: Terms of the average streamflow (years 01 to 10) modelled for different seasons in the deforestation scenario

The statistical standard deviation is also indicated in mm.
agricultural land covers about 40 per cent of the watershed in the reference scenario (Table 4) while it becomes more than 50 per cent in the Deforestation scenario (Table 9).

Regarding the production of rice, as mentioned previously, the yields simulated by SWAT were not correct, hence we used the agricultural statistics reported in Table 3 to assess the additional rice crop production, in this case the supplementary production of Monsoon_Rice (Table 9). The area and production of Monsoon_Rice almost double in this scenario while the total increase in rice production in the watershed is about 30 per cent.

Hence, in the Deforestation scenario the increase in rice production is noticeable but at the cost of more frequent flood events and possible negative impacts on the biodiversity and ecology of the watershed, not investigated here.

2.4.3 Electrification scenario

Results from the groundwater model – piezometric levels
The groundwater model was run on 33 modelling wells in the watershed (de Condappa et al., 2011). We analysed the piezometric levels simulated for the months of April, pre-monsoon, and of August, during the monsoon, where the water table is respectively the deepest and the shallowest in the Jaldhaka watershed (de Condappa et al., 2011). The levels calculated at each well for both months were averaged over the 10 years of the sub-scenarios and were subsequently interpolated within the watershed using the Radial Basis Function. In the electrification scenario we supposed that farmers continue to use predominantly centrifugal pumps, which cannot draw groundwater deeper than 8 m below the impeller: the simulated drop in groundwater levels should not be more than 8 m. As the groundwater model was not constrained by this 8 m limit, it predicted greater drops and therefore the interpolated grid was constrained by this limit of 8 m.

The distribution of the average piezometric levels of each sub-scenario were compared with the reference scenario in Figure 16. The impact becomes significant from the 50 per cent sub-scenario with lower piezometric levels, i.e., deeper groundwater levels as compared to the reference situation, downstream of the watershed while there is hardly any change upstream. This is a logical consequence of the definition of the sub-scenarios where there is little increase in pumping upstream. The depletion equals 8 m downstream in the 100 per cent sub-scenario.

The important depression middle stream is located in the sub-watershed number 9 where the increase in pumping is the most important in the sub-scenarios: in this sub-watershed, the groundwater withdrawal rises from 100 mm/year in the reference scenario to 707 mm/year (Figure 11) in the 100 per cent sub-scenario.

Another result is that the depletion is greater in August than April. This may appear surprising as the predominant increase in groundwater pumping occurs during the Summer_Rice cultivation, from February to May. But there is also an augmentation of pumping, though of smaller amplitude, during the Monsoon_Rice cultivation, from June to September, hence the cumulated impact is greatest in August, which is observed on the groundwater levels.

Common results from the groundwater model and SWAT – groundwater baseflow
The results from the groundwater model and SWAT connects through the groundwater baseflow. Both models were run independently for the sub-scenarios defined above. The first gave an indication of the decrease in groundwater baseflow, which is a logical consequence of a declining groundwater table, while the second assessed the impact on the streamflow (Figure 17). The rate of decrease from one sub-scenario to another is variable in each sub-watershed as the increase in pumping is also different from one sub-watershed to another (Figure 11). Similarly as for the piezometric levels, the reduction in groundwater baseflow is appreciable from the 50 per cent sub-scenario, where the watershed’s baseflow has diminished by 15 per cent; in the 100 per cent sub-scenario, the watershed’s baseflow has been reduced by 30 per cent.

The effect on the streamflows is negligible in the 28 per cent sub-scenario. The reduction in the low streamflow is detectable from the 53 per cent sub-scenario, but the magnitude of this reduction is small. There is additionally an apparent slight increase in the high flows, which is due to the more impermeable CN2 chosen for the agricultural practice Irrigated Monsoon_Rice – Summer_Rice, which favour surface runoff.
The number in bracket is the variation in rice production with respect to the Reference scenario

<table>
<thead>
<tr>
<th>Cropping sequence</th>
<th>Clean rice yield (T/ha/year)</th>
<th>Reference</th>
<th>Deforestation</th>
<th>Electrification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>P</td>
<td>A</td>
<td>P</td>
</tr>
<tr>
<td>Rainfed Monsoon_Rice</td>
<td>1.5</td>
<td>100.2</td>
<td>150.3</td>
<td>186.1</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Pre-monsoon_Rice</td>
<td>2.9</td>
<td>17.3</td>
<td>50.2</td>
<td>17.3</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Wheat</td>
<td>1.5</td>
<td>5.3</td>
<td>8</td>
<td>5.3</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Potato – Jute</td>
<td>1.5</td>
<td>82.5</td>
<td>123.8</td>
<td>82.5</td>
</tr>
<tr>
<td>Irrigated Monsoon_Rice – Summer_Rice</td>
<td>3.7</td>
<td>34.2</td>
<td>126.5</td>
<td>34.2</td>
</tr>
<tr>
<td>Total for the watershed</td>
<td>239.5</td>
<td>458.7</td>
<td>325.4</td>
<td>587.6</td>
</tr>
</tbody>
</table>
Figure 16: Electrification scenario, average (years 01 to 10): simulated depletion in piezometric levels in the four sub-scenarios as compared to the Reference scenario.

Up: average for April. Down: average for August.
Results from SWAT – water budget and streamflows

The water budget for the whole Jaldhaka watershed is compared to the reference in Figure 18. There is very little change in the share between the two main components of the water budget, i.e., streamflows and evapotranspiration.

The main change is in one of the sub-processes generating the streamflow: the amount of groundwater baseflow (GW_Q) declines to an extent comparable with the estimation of the groundwater model (Figure 17 and Table 10), i.e., from 407 mm/year to 308 mm/year. As was the case in the deforestation scenario, this diminution is spread throughout the year. Direct surface runoff (SURQ) is slightly augmented during the high flows season owing to more impermeable soils of the Irrigated Monsoon_Rice – Summer_Rice practice. There is no significant change in the sub-soil lateral flux (LATQ) in all the scenarios. Although there is a small reduction noticeable during the low flows and from the 53 per cent sub-scenario, the overall impact on the annual streamflow of the electrification scenario is insignificant as the decrease in groundwater baseflow (GW_Q) is compensated by an increase in direct surface runoff (SURQ).

There is a slight augmentation in groundwater recharge (GW_RCHRG) across sub-scenario as the additional irrigation contributes partly to the groundwater recharge: a part of the additional pumped groundwater returns to the groundwater through percolation.

Rice production

The set of four electrification scenarios assumed that the cropping pattern Rainfed Monsoon_Rice was gradually replaced by the more productive sequence Irrigated Monsoon_Rice – Summer_Rice. The additional production is estimated using the statistical yields of Table 3 (Table 9). The total increase in rice production in the watershed is 13 per cent, 25 per cent, 38 per cent and 48 per cent for the 28 per cent, 53 per cent, 79 per cent and 100 per cent sub-scenarios respectively.
Figure 18: Modelled average water budget (years 01 to 10) for the Jaldhaka watershed in the Reference and Electrification scenarios
The statistical standard deviation is also indicated in mm/year
Figure 18-continued: Modelled average water budget (years 01 to 10) for the Jaldhaka watershed in the reference and electrification scenarios
The statistical standard deviation is also indicated in mm/year

Table 10: Terms of the average streamflow (years 01 to 10) modelled for different seasons in the electrification scenario
The statistical standard deviation is also indicated in mm
5 DISCUSSION

5.1 CURRENT SITUATION OF WATER RESOURCES

Groundwater is the most important resource for agriculture in the Jaldhaka watershed as it is the predominant source for irrigation water: it was estimated to provide 78 per cent of irrigation water in the watershed, i.e., 145 mm/year watershed-wide in 2008, while 22 per cent is estimated to be extracted from the river, i.e., 42 mm/year watershed-wide (de Condappa et al., 2011). A particularly interesting feature of this modelling exercise is to have run interactively two models: SWAT and the groundwater model of Tomer et al. (2010). The groundwater model was required to simulate the groundwater levels, which is not possible with SWAT. Both models converged in the simulation of the groundwater recharge and baseflow, which consequently enabled a description of the interaction between the groundwater and the river system of the Jaldhaka watershed. This showed that the groundwater baseflow from the shallow alluvial aquifer is a significant contributor to the river flow as it enables the perennial flow of the river.

At the watershed scale, the current groundwater exploitation of 145 mm/year appears to be sustainable on average as it is less than the [571 mm/year ± 158 mm/year] estimated for the groundwater recharge in the current situation (Figure 13). This is coherent with the stable shallow groundwater levels observed in the region (de Condappa et al., 2011; Shamsudduha et al., 2009). However, the PGIS analysis carried out in the watershed reports that farmers often complained about depleting groundwater (de Bruin et al. 2010b). A possible explanation could be that the dynamics of a well, with the transmissivity of its surrounding underground material, have to be distinguished from the dynamic of the aquifer. If the well has a low transmissivity, the groundwater level can deplete quickly as it is not recharged in time by the surrounding aquifer. The farmer might have the impression that the groundwater is depleted while the groundwater level in the well may have returned to regional equilibrium the next day.

To summarise on the electrification scenario:

- The groundwater levels are expected to decline downstream and to a lesser extent middlestream to a possible 8 meters in the 100 per cent sub-scenario; in reality induced recharge processes from neighbouring perennial rivers may attenuate this decline.
- As a consequence, the groundwater baseflow would be reduced by 30 per cent in the 100 per cent sub-scenario, and that would impact slightly on the low streamflows; in reality the induced recharge may reduce further the low flows.

If we refer to the assumptions chosen for this scenario and its implication in term of change in agricultural areas, the 25 per cent (or 28 per cent) sub-scenario would mean that about 28,000 ha would grow additionally Summer_Rice after Monsoon_Rice, this additional area would become 53,000 ha in the 50 per cent (or 53 per cent) sub-scenario. The current area under Irrigated Monsoon_Rice – Summer_Rice is 34,200 ha (de Condappa et al., 2011) hence perhaps only the 25 per cent (or 28 per cent) and even 50 per cent (or 53 per cent) sub-scenario could be attainable with respect to the cost for the government to develop the required electrical supply and infrastructure, and the cost for the farmers to acquire additional electric centrifugal pumps.

5.2 IMPACTS OF THE ELECTRIFICATION SCENARIO ON THE WATER RESOURCES

The results from the electrification scenario showed that this sustainable situation may be disturbed, especially in the 100 per cent sub-scenario where the watershed-wide groundwater withdrawal increased from 145 mm/year to 400 mm/year (Figure 11), reaching an amount closer to the groundwater recharge and a simulated depletion of groundwater levels equals to 8 m downstream (Figure 16). However, the magnitude of this depletion has to be moderated by the fact that the groundwater model did not account for at least one process which would restrain the impacts of the Electrification scenario. In a context like the Jaldhaka watershed where rivers are perennial, a decrease in groundwater levels favour what is called induced recharge. A depleting groundwater system near a perennial river actually favours seepage from the river, recharging the groundwater, and eventually the groundwater level may recover after some time at the expense of the streamflow, in particular during the low flow season. Hence the medium to long term impact would not be a sharp decrease in piezometric levels but rather a decrease in flow from neighbouring rivers, in particular during the low season.
5.3 IMPACTS OF THE ELECTRIFICATION SCENARIO ON RICE PRODUCTION

Both the Deforestation and Electrification scenarios entail an increase in rice production. On the watershed scale, the increase in the 25 per cent electrification sub-scenario is smaller than the Deforestation, while the increase is almost the same in the 50 per cent sub-scenario and greater in the 75 per cent and 100 per cent sub-scenarios. However the productivity is not the same: in the Deforestation case, the augmentation in total rice production is due to an increase in agriculture land at the cost of important deforestation upstream, while in the Electrification it is due to an increase in productivity. In this respect, the Electrification scenario is preferable.

It was explained in the previous section that only the 25 per cent or at maximum the 50 per cent sub-scenarios are attainable, therefore the overall realistic impact of the Electrification scenario may be small on the water resources of the Jaldhaka watershed, while it may enable farmers of the watershed to produce 13 per cent (25 per cent sub-scenario) or even 25 per cent (50 per cent sub-scenario) additional rice.

5.4 ENLARGING TO OTHER ISSUES

While the electrification scenario is an agricultural water management strategy that could benefit farmers without impacting significantly on the water resources, the energy requirement of supplying the electricity for groundwater pumping would be very costly for the government. Exploiting the surface water resource is generally more economical from an energy perspective and an alternative management practice could for instance attempt to store or divert a fraction of the sudden high river flows for distribution through a network of canals later during the dry season. Storing would however be very difficult in the parts of the watershed located in India or Bangladesh, where the terrain is very flat. A possibility could be in the mountainous part in Bhutan, which would require a careful environmental and social assessment in addition to a formal arrangement between upstream Bhutan and downstream India and Bangladesh.

To enlarge the outcome, it is emphasised that this work confined its analysis to the quantitative impacts on water resources while the scenarios considered may change the quality of the water resources, since additional cultivation of Summer Rice would be logically associated with an increase in agricultural chemical inputs. Moreover, it is important to carry an environmental assessment of the (little) change in quantity of water resources as well as the deforestation scenario.
6 CONCLUSION

This paper contributed to the understanding of potential for development of Agricultural Water Management (AWM) in the watershed of the Jaldhaka river, a tributary to the Brahmaputra river, located in Bhutan, India and Bangladesh. Two models were run interactively: the Soil Water Assessment Tool (SWAT) and the lumped groundwater model developed by Tomer et al. (2010). The groundwater model was required to simulate the groundwater levels while SWAT simulated the streamflows. Both models converged for a satisfactory simulation of hydrological processes in the Jaldhaka watershed. This set-up was applied to study the current state of the hydrology in the Jaldhaka watershed and the impacts of two AWM scenarios.

The main hydrological characteristics of the watershed inferred from the modelling are: (i) as much as about half of the total rainfall is transformed in direct runoff to the rivers, creating recurrent flood events in the peak of the monsoon, (ii) evapotranspiration only represents 25 per cent of the total rainfall, (iii) slightly less than 20 per cent of total rainfall recharges the shallow aquifer and (iv) the groundwater baseflow ensures perennial flow of the main river. In terms of resources, groundwater is the most important for agriculture in the Jaldhaka watershed as it is the predominant source for irrigation water. The current rate of groundwater exploitation is sustainable at the watershed scale as groundwater withdrawals for irrigation is less than the simulated groundwater recharge.

To assess if the water availability could become a restricting factor for agricultural production in the future two types of AWM scenarios were developed. The first scenario assumed a change in landuse in the mountainous upstream part of the watershed: forests are cut down and used for cultivation of rainfed rice. The impact of this landuse change is a sharp increase in the high flows of the Jaldhaka river, with floods of higher magnitude, and a decrease in groundwater baseflow upstream. The decreased recharge consequently gives a reduction of groundwater baseflow during low flows season which is nevertheless moderated by the buffered nature of groundwater baseflow.

The second AWM scenario assumed a gradual improved access to electricity to increase groundwater pumping in the area. Four sub-scenarios were defined: 25 per cent, 50 per cent, 75 per cent or 100 per cent of the fields currently only growing rainfed rice during the monsoon will grow additionally irrigated rice during the summer. The results of the simulations show that the current sustainable exploitation of groundwater may be disturbed from the 50 per cent sub-scenario and downstream groundwater levels decrease up to a possible 8 meters in the 100 per cent scenario. In the 100 per cent scenario, the groundwater withdrawals reach an amount close to the watershed’s groundwater recharge. Throughout the watershed groundwater baseflow reduces from about 15 per cent in the 50 per cent scenario to about 30 per cent in the 100 per cent scenario. Although there is a small reduction of streamflows noticeable during the low flows season, the overall impact on the annual flow of the Jaldhaka river is small. In reality, the process of induced recharge from perennial rivers, not taken into account in the modelling, may temper the drop in groundwater levels upstream. The decreased recharge consequently gives a reduction of groundwater baseflow during low flows season which is nevertheless moderated by the buffered nature of groundwater baseflow.

Both scenarios entail an increase in rice production but not at the same productivity. In the Deforestation case, the augmentation in total rice production is due to an increase in agriculture land at the cost of an important deforestation upstream, while in the Electrification it is due to an increase in productivity. In this respect, the Electrification scenario is preferable with a relatively small impact on the water resources of the Jaldhaka watershed.

To enlarge the outcome, although the electrification scenario is apparently an agricultural water management strategy that could benefit farmers without impacting significantly on the water resources, the energy requirement of supplying the electricity for groundwater pumping would be very costly for the government. Moreover, this work confined its analysis to the quantitative effects on the water resources while the scenarios considered may change the quality of the water resources and have negative impacts on the ecosystem of the watershed.
This work was supported by the AgWater Solutions project, funded by the Bill and Melinda Gates Foundation. We are also thankful to the folersons and people for their contributions (in alphabetical order):

Nyayapati Aakanksh, International Water Management Institute: supporting our request for streamflow data.

Badrul Alam, International Development Enterprises - Bangladesh: supporting our request for streamflow data.


Saswati Bandyopadhyay, State Water Investigation Directorate (West Bengal): providing groundwater data.

Gopal Barma, Assistant Director of Agriculture (Administration, Mathabhanga): providing agricultural statistics.

Salim Bhuiyan, Bangladesh Water Development Board: providing streamflow data.

Suman Biswas, International Development Enterprises India: support during field work.

S. Biswas, Agricultural University of Cooch Behar: providing information on soils.

P. K. Biswas, Assistant Agricultural Meteorologist (Jalpaiguri): providing a copy of Kundu and Soppe (2002).

Aniruddha Brahmachari, International Development Enterprises India: support during field work and data collection.

Annemarieke de Bruin, Stockholm Environment Institute: sharing results of the Participatory GIS in the Jaldhaka watershed.

Xueliang Cai, International Water Management Institute: contributing to the development of the landuse map.

Howard Cambridge, Stockholm Environment Institute, for advice on SWAT.

Yihun Dile, Stockholm Environment Institute: reviewing and improving this report.

D. Dutta, Indian Space Research Organisation: general advice.

Sylvain Ferrant, Indo-French Center for Groundwater Research: extensive advice on SWAT.


Holger Hoff, Stockholm Environment Institute: reviewing and improving this report.

Victor Kongo, Stockholm Environment Institute: advice on SWAT.

Monique Mikhail, Stockholm Environment Institute: sharing results of the Participatory GIS in the Jaldhaka watershed.


Aditi Mukherji, International Water Management Institute: extensive advice on groundwater and data collection.

Rajiv Pradhan, Director of International Development Enterprises - Bangladesh: supporting our request for streamflow data.

Mala Ranawake, International Water Management Institute: supporting our data requests.

Adam Regis, Stockholm Environment Institute: administrative works.

Bhaskar Roy, Assistant Director of Agriculture (Cooch Behar): providing general information.

Bharat Sharma, International Water Management Institute: supporting our request for streamflow data.

Raghuwanshi Narendra Singh, Indian Institute of Technology Kharagpur: providing data from Raghuwanshi et al. (2007).

A. K. Sinha, Agricultural University of Cooch Behar: providing information on soils.


Hua Xie, International Food Policy Research Institute: advice on SWAT.
REFERENCES


The Stockholm Environment Institute

SEI is an independent, international research institute. It has been engaged in environment and development issues at local, national, regional and global policy levels for more than a quarter of a century. SEI supports decision making for sustainable development by bridging science and policy.

sei-international.org