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Brahmani model: technical description

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We hope that the results of this study are used to improve the livelihoods of the people of the Brahmani Basin.

1 Introduction

1.1 Background

This technical report is a product of the 'Water Resources Management: Capacity Building in the Brahmani-Baitarni' project (referred to as the Brahmani Baitarni project), which was funded by the Government of Australia and supported by the Government of India. The project ran from July 2013 to June 2016, and was part of Phase 1 of the 'Sustainable Development Investment Portfolio', an Australian government initiative with the goal of increasing water, food and energy security in South Asia. This work was undertaken in the context of a Memorandum of Understanding on water resources management between the Government of Australia and the Government of India, established in 2009 and renewed in 2014.

This report overviews the technical aspects of a river system model for the Brahmani sub-basin, which is part of the Brahmani Baitarni Basin. A separate synthesis report (Pollino et al 2016) overviews the model outcomes. Separate technical project reports have been prepared for agricultural (Mainuddin et al 2016) and groundwater (Schmid et al 2016) trend analyses across the basin.

1.2 Project context and objectives

The primary objective of the Brahmani Baitarni project was on capacity building in water resource management with a focus on basin planning. Project activities included delivering a capacity building program and undertaking a modelling demonstration case. The capacity building program included formal training events and joint dialogues. The demonstration case, documented in this report, uses a river system modelling approach, which was used to explore the current water availability in the Brahmani Basin, and changes to this given potential investments in water infrastructure and management and in changed cropping practices.

This work was done in collaboration with the Government of India from both central and state agencies. The Central Water Commission developed a model for the Baitarni sub-basin, which is reported in Central Water Commission (2016).

1.3 River system models

River system models are analytical tools used to support basin planning and water policy development. Typically they are used to improve the understanding of the availability of water resources and how these may be affected by natural and human interventions. Interventions of interest include potential alterations associated with climate, land use, infrastructure changes and water management policies. The form and focus of the model depends on objectives of basin stakeholders as well as the available information that can be used to support its development. Interventions are typically assessed through the creation of river system model 'scenarios'. In the case of the Brahmani Basin, given the importance of agriculture for supporting the local economy and livelihoods and the potential for irrigation to improve crop productivity, the focus of the model scenarios was to assess changes to irrigated food production. In parallel, we considered energy production, industrial water use and environmental flows.

The model scenarios are described in Chapter 5 of this report.

2 Description of Brahmani Basin

2.1 Geography

The Brahmani Basin is located in the north eastern part of India (Figure 1) and crosses the three Indian states of Chhattisgarh, Jharkhand and Odisha. The Basin is bounded by the Chota Nagpur Plateau on the north, by the ridge separating it from Mahanadi Basin on the west and the south, and by the Bay of Bengal on the east (NRSC and CWC 2011; Asian Development Bank 2013). The physiography of the Basin is defined by four regions: the northern plateau, the eastern ghats, the coastal plains and the central tablelands. The main soil types found in the Basin are red and yellow soils, red sandy and loamy soils, mixed red and black soils and coastal alluvium (Asian Development Bank 2013). The Brahmani River is formed by the confluence of the South Koel and Sankh Rivers. The neighbouring basin is the Baitarni Basin (more information on this Basin is in CWC, 2016). The Brahmani Basin has a total area of is 34,614 sq km and the Brahmani River, with its constituent rivers, is 799 km long.

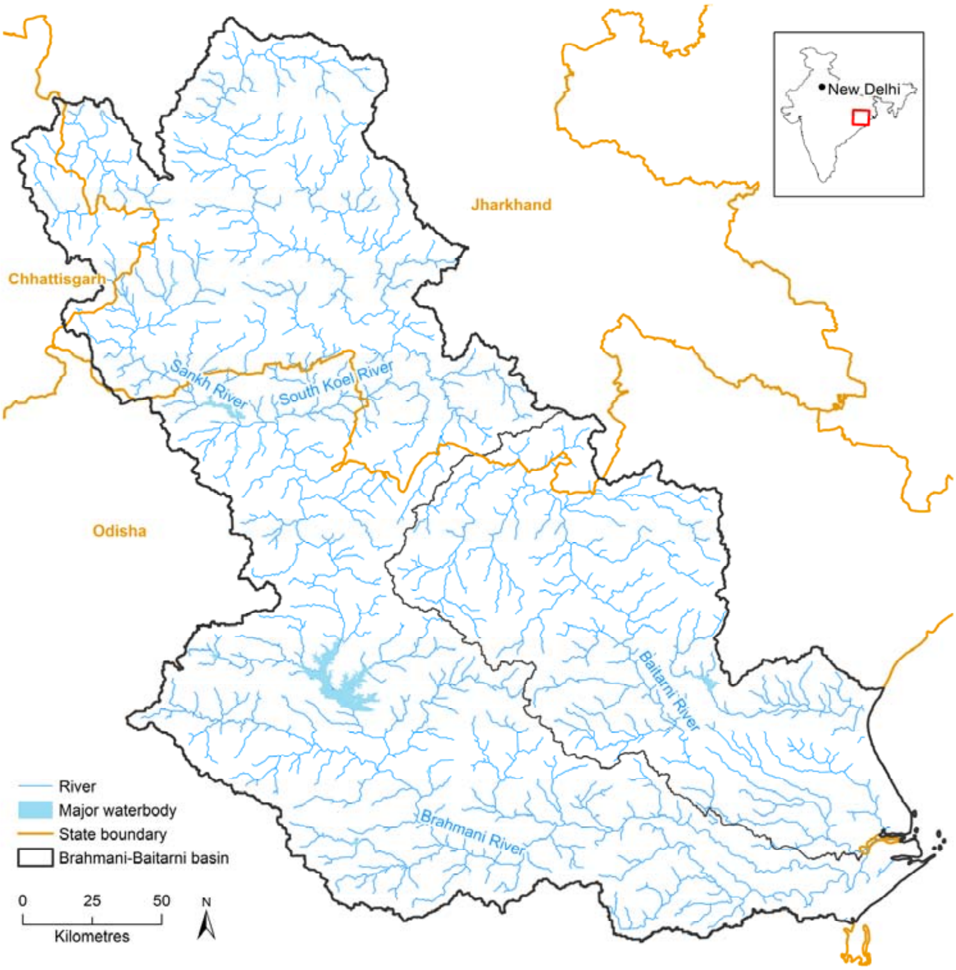

Figure 1 Brahmani Baitarni Basin, showing State boundaries and the inset shows the Basin's location within India. The Brahmani Basin is the larger of the two basins

2.2 Climate

The Brahmani Basin has a tropical monsoonal climate, where rainfall is dominated by the southwest monsoon, between June to October, with 80% of annual precipitation occurring during these months. Maximum temperature rises to 47°C with the minimum being as low as 4°C (NRSC and CWC 2011; Asian Development Bank 2013). Temperatures in the coastal region are moderate with higher humidity (Figure 2).

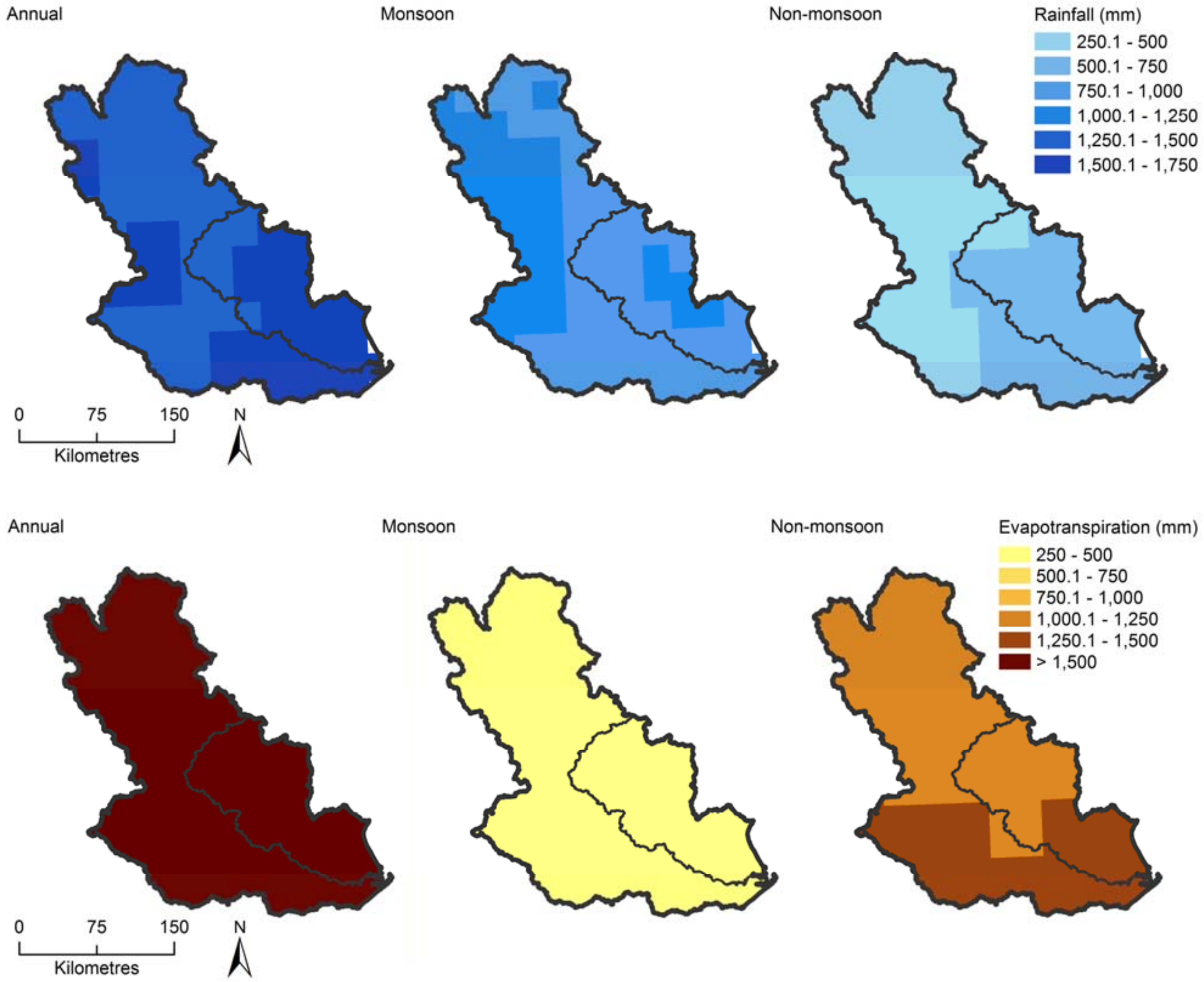

Figure 2 Annual, monsoon and non-monsoon rainfall (top) and evapotranspiration (bottom) for the Brahmani Baitarni Basin, with the Brahmani the larger of the two areas

2.3 Basin land use

The land use of the Brahmani Basin is a mix of forest and agriculture (Figure 3). Agricultural land covers approximately 52% of the basin. In the remaining part of the Basin, the dominant land use is forest. The forest land area is rapidly degrading (Asian Development Bank 2013).

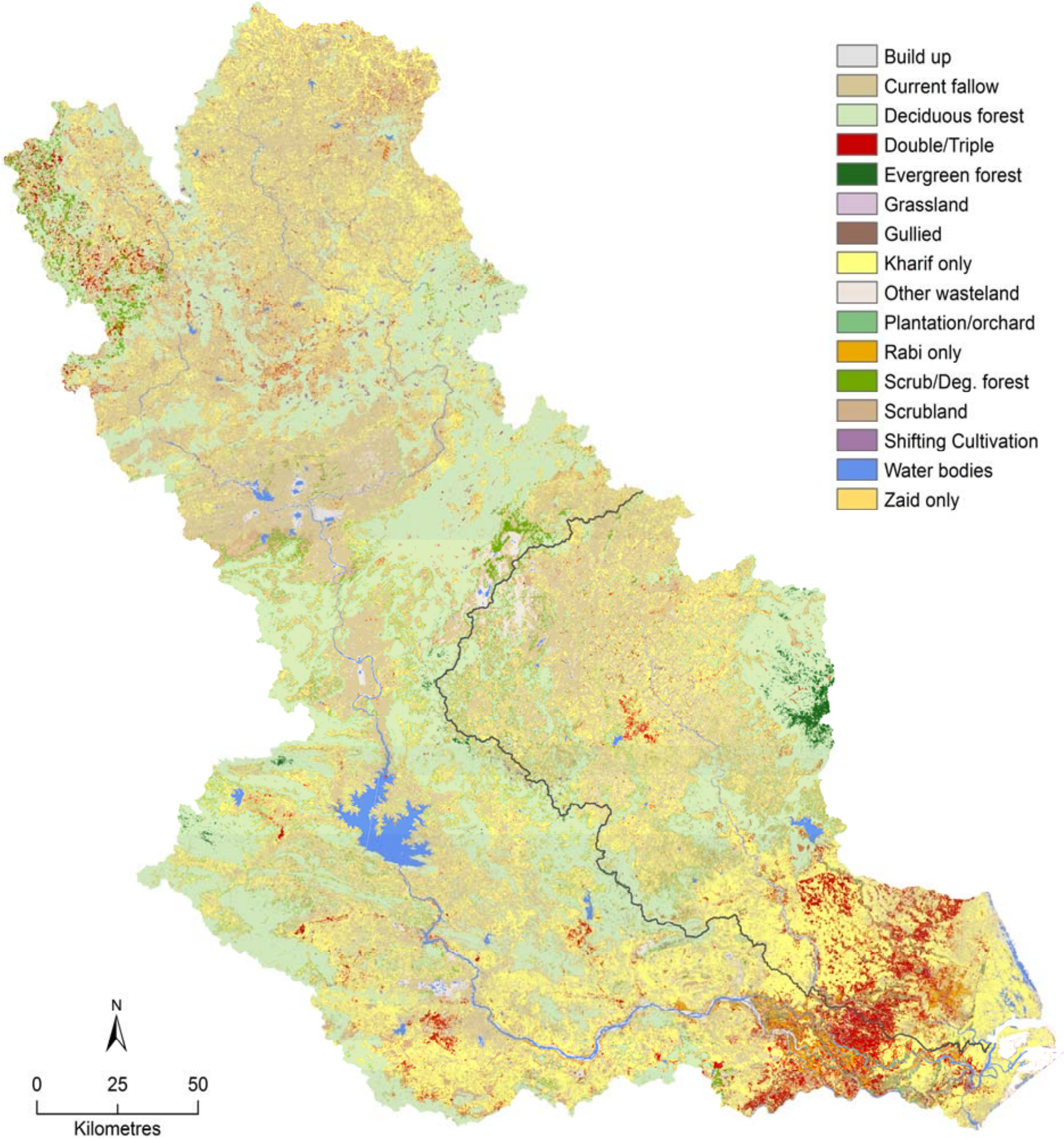

Figure 3 Land use mapping for the Brahmani Baitarni Basin (2007–2008), with the Brahmani the larger of the two areas

2.4 Basin agriculture and infrastructure

Agriculture plays a critical role in the economy and livelihood of people in the Brahmani Basin and has a critical contribution to food security and socioeconomic development. Agricultural districts are located throughout the Basin and also across Basin boundaries. These districts are made up of both irrigated and rainfed agriculture. A full analysis of agriculture results is available in a companion technical report (Mainuddin et al 2016). The results below provide an overview.

In total, the landmass of the three Basin states covers 20.2% (8.65 million hectares (Mha)) of the total cultivated area of India. The states combined produce 14.7% (14.1 million tonnes (MT)) of the total rice production within all of India. Only 6% of the total rice production from the states is from irrigated rice cultivation. Whilst the basin states are among the highest in India for total rice cultivated area, they are ranked amongst the lowest for productivity (Mainuddin et al 2016).

The cropping seasons in the Basin are Kharif, Rabi and Zaid, where Kharif and Rabi are the main cropping seasons in the Basin (NRSC and CWC 2011). Kharif is dominated by rice, Rabi by safflower and Zaid by groundnut. In the modelling undertaken in this study, we include another irrigated rice crop type – defined as double/triple cropping. This term describes when irrigated rice is cropped multiple times in a single year, and represents where irrigation water is used to extend the Kharif cropping period.

Mainuddin et al (2016) undertook an analysis of the Basin Districts cropping intensity (defined as the number of times a crop is planted per year in a given area). This analysis found that cropping intensity is lower in the northern part of the Basin, relative to the south (Figure 4). The analysis also indicates that the cropping intensity in the south has been increasing over time. The main reason for lower cropping intensity and lower rice yields in the upper northern part of the Basin is historically due to a lack of supplementary irrigation where additional water from irrigation is used to extend crop periods. Other constraints that are also likely to contribute to lower cropping intensity include low yielding crop varieties, lack of nutrients and farming practices.

Irrigated areas in the Basin are predominantly located in Command Areas within agricultural districts, although there are small areas of irrigated crops that source water directly from rivers. Typically a Command Area has a water storage, in the form of weir or dam infrastructure.

In the Brahmani Basin, we modelled 20 water storages (19 medium and 1 major), servicing approximately 500,000 hectares of irrigated land, of which approximately 427,000 hectares is in Odisha.[1]

Both Jharkhand and Odisha have 10 storages with the major storage located in Odisha. The total available water storage (assuming storages at 100%) is approximately 4850 MCM, with 4000 MCM of that in Odisha.

[1] This analysis of areas and associated storages was done using data layers obtained from the Central Water Commission. One data layer showed the locations and areas of the Command Areas, and this was associated with separate longitude and latitude information obtained for the locations of water storage infrastructure.

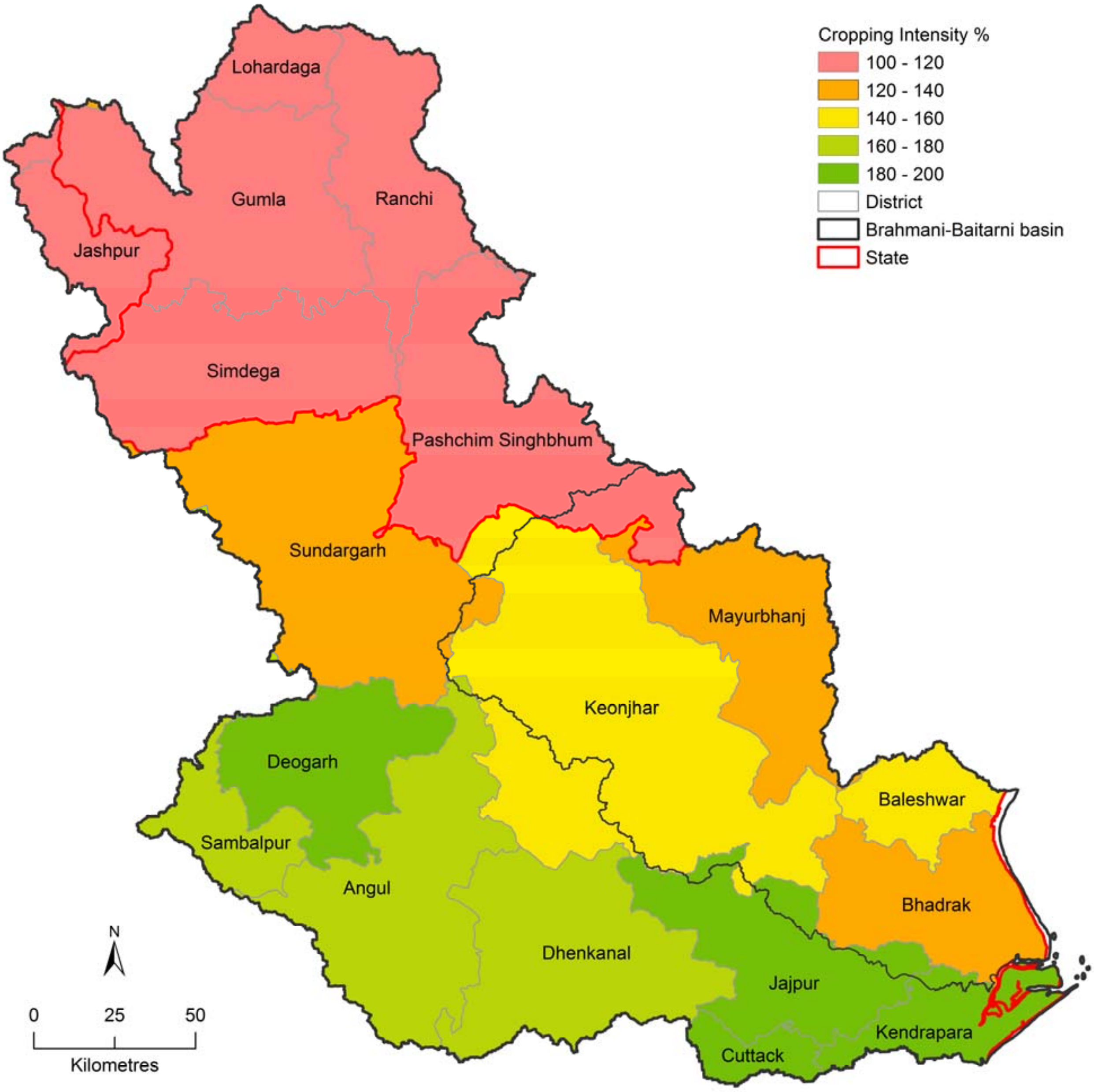

Figure 4 Cropping intensity at the district level (2007–2008) in the Brahmani Baitarni Basin, with the Brahmani being the larger of the two areas

3 The baseline Brahmani river system model

The eWater Source software was used for rainfall-runoff, river system and irrigation modelling (http://ewater.org.au/products/ewater-source/). This software is Australia's National Hydrological Modelling Platform. It is designed to simulate all aspects of water resource systems, and to support integrated planning, operations and governance from urban, catchment to river basin scales including human and ecological influences. Source accommodates diverse climatic, geographic, water policy, and governance settings for both Australian and international conditions.

The Brahmani model was first constructed using available data and information to define a landscape rainfall-runoff model and a river system model. A baseline scenario was developed that represented current water availability in the Basin with current infrastructure and climate variability.

The following sections describe the input data, model conceptualisation and calibration of the model for the Baseline scenario.

3.1 Sources and overview of input data

At the commencement of the project, we were provided with historic hydrologic, climatic, irrigation and land use data for the Brahmani Basin. The Central Water Commission (CWC) sourced data for the project, provided by the following organisations: Central Water Commission; National Remote Sensing Centre; Mahanadi and Eastern Rivers Organisation; Central Ground Water Board; National Institute of Hydrology; and the Governments of the States of Chhattisgarh, Jharkhand and Odisha.

Specific data types provided include: meteorological, streamflow, water quality, groundwater, storage information, water use/demands, various spatial data sets and information from existing models. Existing models provided were the Basin-wide Holistic Integrated Water Assessment (ICID 2005), a River Basin Simulation (RIBASIM) model for the Odisha portion of the Brahmani Basin (Government of Odisha 2010) and the Space Inputs model (NRSC and CWC 2011). These data were catalogued and their fitness for use in this project evaluated (eWater 2014).

A summary of the data used in developing the Brahmani model is presented in Table 1. More specific information on data use for modelling is also provided in Chapter 3.

3.1.1 Climatic and streamflow data

Gridded rainfall data were obtained from the Indian Meteorological Department (IMD) and converted to Source-compatible time series for the purposes of the model development. We used gridded Princeton data for the evapotranspiration as only point evapotranspiration data were available from IMD. These data were converted to Source-compatible time series. Variation in annual and seasonal rainfall and evapotranspiration across the Basin for the period 1988 to 2012 is shown in Figure 5.

The majority of streamflow gauges used are managed by the CWC. We used data for one gauge managed by the State of Chhattisgarh (Lawa Bomtel). Whilst additional streamflow gauge data were obtained from the State of Jharkhand, discussions with CWC and the State of Jharkhand resulted in a decision that the data were not fit for purpose. This was due to data only being available in the monsoon period and a preliminary evaluation suggested some issues with data quality. Streamflow gauges used in the model development are shown in Figure 6.

The time series for streamflow gauge data extended over the period 1972 to 2012, but not all gauges had this duration of data. Durations of time series data are shown in Figure 7. Some quality checking, primarily using double mass plots, was conducted for the streamflow gauges data (eWater 2014) and showed no unexpected behaviour between flow at neighbouring gauges.

Table 1 Data used to develop the Brahmani model

Model	Dataset	Description	Reference / source of the data
Rainfall-runoff model	PET surface	1948–2008 0.5 degree resolution	Calculated from Princeton using the Morton method
	Rainfall surface	1901 – 2013 0.25 degree resolution	IMD
	Observed streamflow	Available records from: -Altuma, Gomlai, Jaraikela, Jenapur, Panposh, Talcher, Tilga (CWC) -Manoharpur, Nagpheni, Sithio, Torpa, Kochedegaa, Raidih (JH – wet season only) -Lowa Bomtel	CWC State of Chhattisgarh
River system model	Rainfall surface	Daily rainfall surface in 0.25 degree grids 1/1/1980 - 31/12/2012 for scenarios Baseline, P10, P50 and P90	IMD
	PET surface	Daily rainfall surface in 0.5 degree grids1/1/1980 - 31/12/2012 for scenarios Baseline, P10, P50 and P90 Extended past 2008 by assuming mean daily values from the 1948-2008 data set	Princeton
	Subcatchment Runoff	Daily runoff for period 1/1/1980 - 31/12/2012	Rainfall-runoff model - GR4J
	Crop types and area	Spatial data	(NRSC and CWC 2011)
	Command area	Spatial data	(NRSC and CWC 2011)
	Storages	Salient features	(NRSC and CWC 2011)
	Model catchments	Catchments were derived using the HydroSHEDS dataset and location data for the gauges and storages used in the model.	3rd Spiral report (RIBASIM model, Government of Orissa) Government of Jharkhand - .xls Website: www.india-wris.nrsc.gov.in/

3.1.2 Irrigation demands

For representing irrigation demands, the model uses mapped Command Areas, overlapped with land use to identify areas of irrigated crops. Areas of multiple rice crops per year (identified as double/triple) were also considered to be irrigated, some of these sit outside Command Areas. This is the method adopted from a previous study (NRSC and CWC 2011). Storages and associated command and irrigated areas are shown in Table 2.

Crops represented in the baseline scenario model are Kharif (rice), Rabi (safflower) and Zaid (groundnut). Double/triple crops are assumed to be rice. This is consistent with the earlier NRSC and CWC (2011) report.

The demands for irrigation use the window of seasonal planting and information on crop water requirements. These are documented in Chapter 5.

Annual plots

Monthly plots

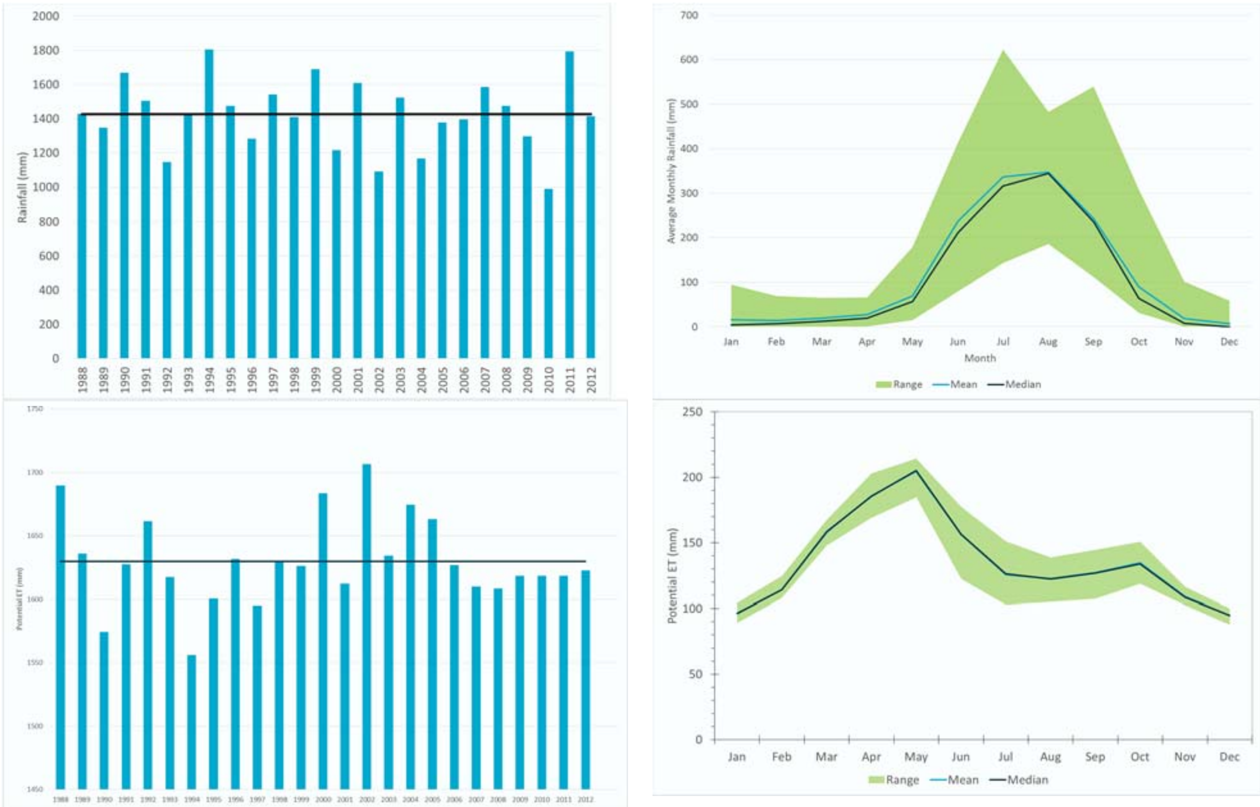

Figure 5 Annual and monthly rainfall (top) and evapotranspiration (bottom) during the calibration and validation periods

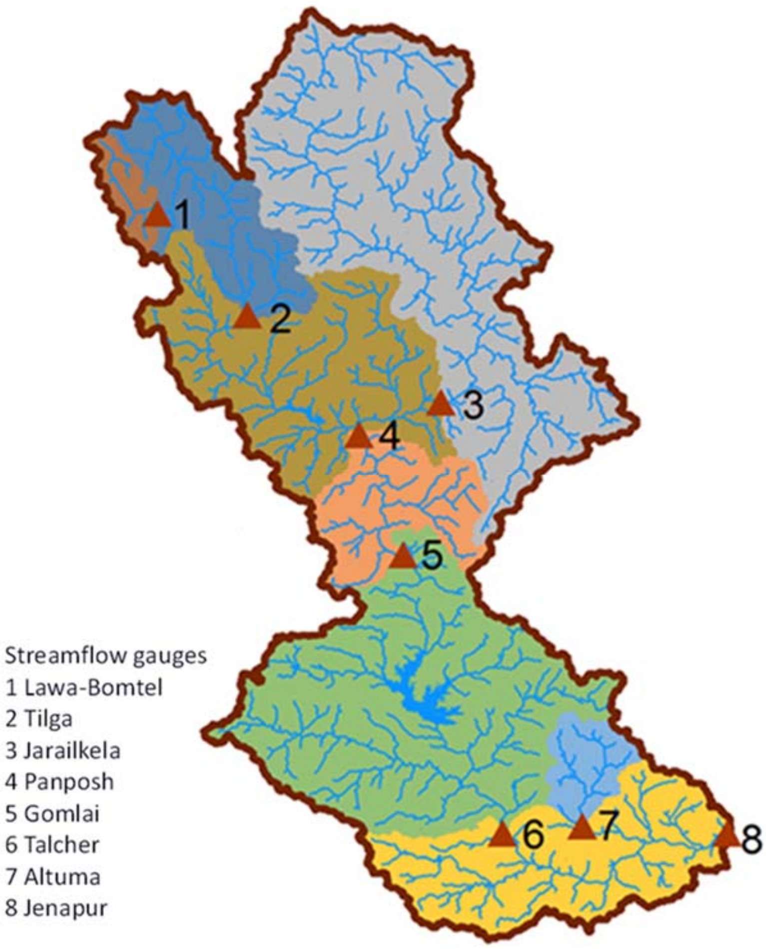

Figure 6 Location of the gauges in the Brahmani Basin

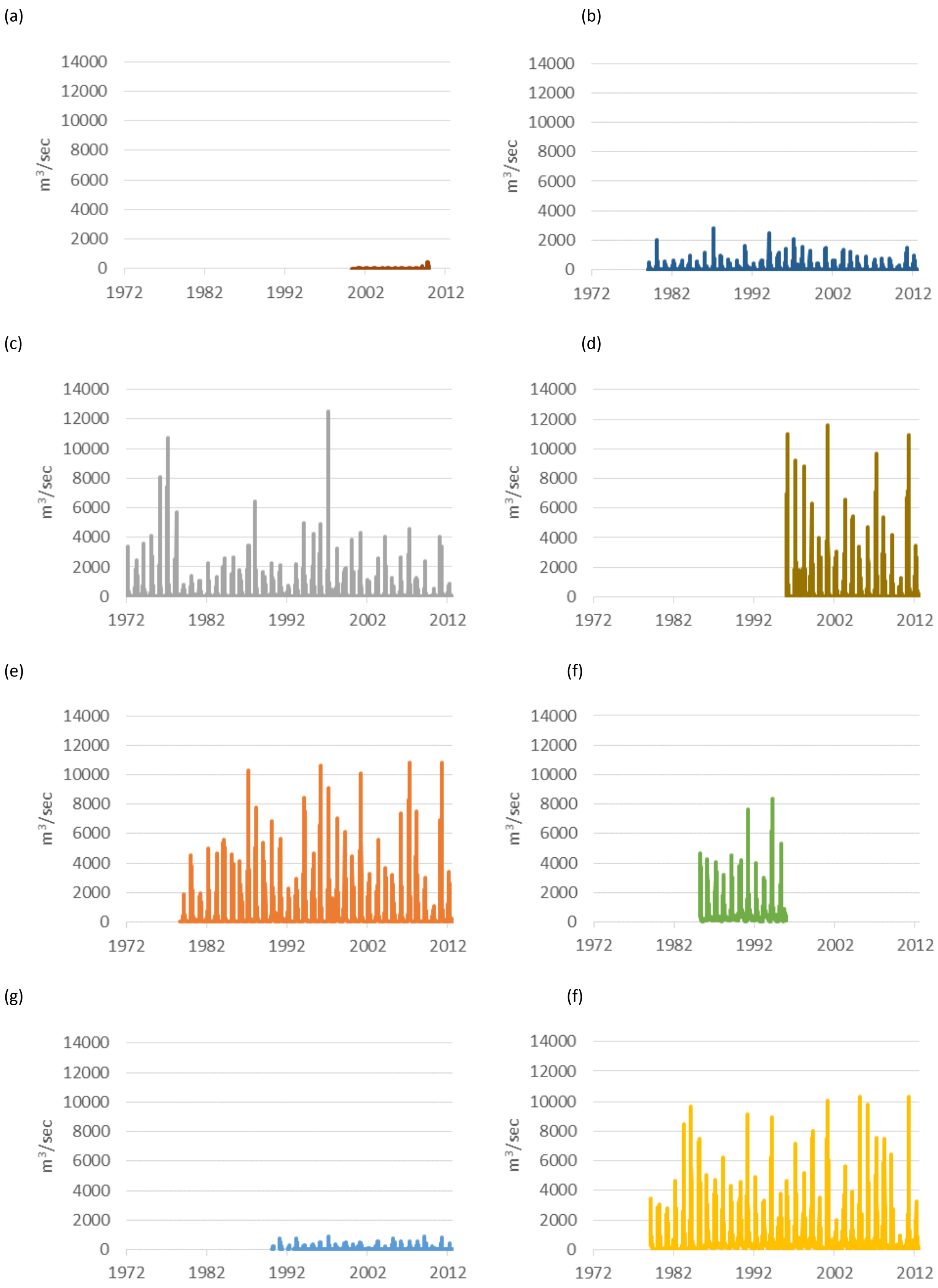

Figure 7 Gauge flow data 1972 to 2012, showing (a) Lawa-Bomtel (b) Tilga, (c) Jaraikela, (d) Panposh, (e) Gomlai, (f) Talcher, (g) Altuma and (f) Jenupur

3.1.3 Other demands

Non-irrigation demands were obtained from a spreadsheet titled 'BBB_Subbasin_Population' (obtained from CWC in December 2013). Domestic demands for urban and rural populations (census from 2007–2008) were also obtained from the spreadsheet.

Based on this information and the NRSC and CWC (2011) report, we estimated:

- water use for domestic demand for a rural population as 70 litres/person/day
- water use for domestic demand for an urban population as 140 litres/person/day
- industrial demands as being 65% of the population demand
- urban and industrial demands as having an 85% return flow.

3.1.4 Infrastructure

Only storages from medium and major storages are considered in the baseline scenario (Table 3). The Calibration chapter (Chapter 4) shows more information on modelled storages. In the model, irrigation demands were assumed to be met by the upstream supply storage.

3.1.5 Environmental flow demands

Environmental flows rules were incorporated into the model for Rengali Dam only – however these were not included in the baseline scenario (i.e. it is assumed that environmental flows were not currently delivered, based on information given). In the scenarios with environmental flows, the rules in the model required that the storage pass 20% of non-monsoon flows and 30% of monsoon flows, where flows are the inflows to the storage. These rules were provided by the CWC verbally.

These demands were modelled as a function in Source, represented as: Storage inflow multiplied by the required percentage for the relevant time period.

Table 2 Storages with associated Command Areas and irrigated areas (in hectares, ha) included in the baseline model

Storage name	Command Area (ha)	Double/triple (ha)	Kharif (ha)	Rabi (ha)	Zaid (ha)
Aradih weir	810.99	1.57	328.42	0.31	0.00
Altuma	1,843.00				
Aunli	5,686.59	428.31	3,097.58	0.31	25.40
Birha weir	1,754.42	15.98	634.41	12.84	0.00
Chinda	6,136.33	89.80	978.66	28.89	0.00
Dadaraghati	19,169.24	223.24	10,042.87	2.51	14.74
Derjang	21,723.80	3,057.83	6,593.04	46.42	159.02
Gohira	15,595.57	616.23	4,467.93	42.34	478.25
Gomlai	527.00				
Jaipur	1,502.00	89.80	402.71	0.63	0.00
Jenapur	10,484.00				
Khatwa	2,608.85	82.11	461.66	15.98	0.00
Kita weir	4,372.09	188.31	890.46	144.44	0.00
Masaria	1,411.25	27.89	419.96	12.54	0.00
Nandini	7,239.59	161.88	2,452.62	113.88	0.00

Storage name	Command Area (ha)	Double/triple (ha)	Kharif (ha)	Rabi (ha)	Zaid (ha)
Naraj Sapuabadjo	132,210.62	4,946.70	47,062.36	1,482.07	714.06
Pitamahal	11,856.51	13.17	196.36	0.00	9.10
Raisa weir	8,645.70	268.83	1,868.92	215.50	0.00
Rengali	1,226.00				
Rengali	198,005.02	4,702.92	98,174.58	2,335.78	495.51
Rukura	9,372.87	1.88	839.74	1.88	5.96

Table 3 Storages and storage features included in the Brahmani model

Name	Full Supply-level (m)	Full supply-volume (MCM)	Full supply-surface area (sq km)	Initial storage-level (m)	Initial storage-volume (MCM)	Dead storage-level (m)	Dead storage-volume (MCM)
Basuki Res	693	37,800	9	693	37,800	685	4,697
Nandani_Weir_Sch	675	19,300	6	672	8,258	669	2,367
31_Latratu	626	46,341	3	620	24,229	610	5,179
28_Paras	674	22,710	4	664	1,590	664	1,590
Katri_Res_Sch	647	22,388	3	640	4,277	637	1,565
Dhansingtoli	536	12,900	2	530	3,848	525	931
Upper_Shankh	768	31,760	2	760	12,154	753	3,880
Ramrekha_Res_Sch	463	17,932	2	460	10,648	452	2,049
Kansjore_Res_Sch	428	23,000	3	428	21,860	427	19,299
Chinda_Res_Sch	409	9,210	3	408	6,912	404	1,247
Mandira	210	316,990	44	200	64,307	194	13,690
Kansabahal	228	43,370	5	222	17,300	220	10,840
Pitamahal	244	24,658	4	234	2,416	234	2,416
Rukura	186	50,016	7	180	17,612	175	5,122
Rengali	124	4,400,000	378	121	3,655,440	110	986,290
Gohira	236	73,000	12	235	68,720	226	13,680
Dadaraghati	119	24,250	8	118	21,488	112	7,220
Ramiala	110	81,540	16	101	17,534	100	15,210
Derjang	150	42,919	9	145	20,075	140	7,811
Tapkara	581	765,570	1	575	253,170	572	105,700

3.2 Baseline model conceptualisation – river system network

The Brahmani Basin baseline model is comprised of six sections (Table 4), where a section is one or more river reaches (refer to Figure 8). Sections were defined using the location of the streamflow gauges (Figure 6).

Each section includes:

- inflows (from upstream and the residual catchment area)
- current infrastructure for medium and major irrigation districts
- irrigation demands for Command Areas

• lumped demands for stock/domestic and Industry purposes.

For each irrigation Command Area, the irrigator demand model within the Source software[2] has been used to represent the irrigation requirements of the main basin crop types (rice, safflower and groundnut). This also allows modelling of scenarios that consider the impact of changes in crop area and crop type on water demands and the ability of the current infrastructure to meet demands.

As stated above, the current medium and major irrigation storages across both Jharkhand and Odisha have been included in the model as storage nodes. There were no storages of this size in Chhattisgarh. The major storage is Rengali Dam in Odisha. This dam includes hydropower and environmental demands, as described in Chapter 5 of this report.

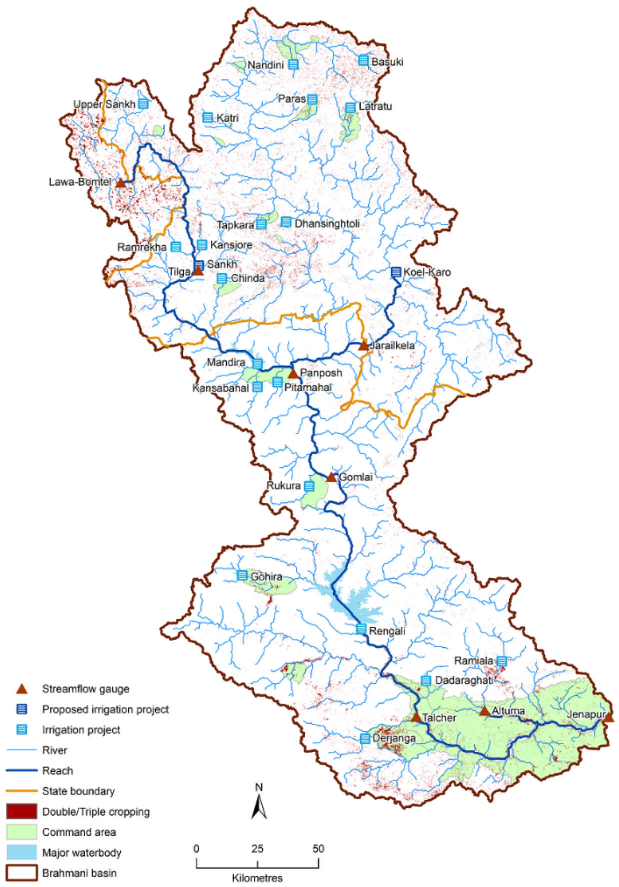

Figure 8 The Brahmani Basin, showing state boundaries, Command Areas, irrigation projects (and associated storages) and streamflow gauges

Reaches are defined by nodes and links. The node-link network details the key features of the river system. The nodes represent the addition or subtraction of flows or temporary storage of water. Common nodes are those that represent:

• inflows to dams or inflows from tributary streams
• the storage of water in dams or weirs and its subsequent release through valves or over spillways
• the extraction of water for irrigation
• the extraction of water for urban water supply
• losses of water through evaporation or seepage to groundwater systems
• outflows to effluent streams or downstream rivers.

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[2] Details relating to the irrigator demand model can be found at <https://wiki.ewater.org.au/display/SD41/Irrigator+Demand+Model>

Key feature types used to characterise the system in the model are:

Links – connects nodes and moves water through the system, where routing is included in a reach, lag and attenuation of flow can be incorporated in to the model, thus modifying the shape of the downstream hydrograph.

Gauging stations – locations where streamflow is measured, provide points for calibration of the model.

Inflow nodes – represent inflows from either upstream reaches or inflows along the reach (referred to as residual catchments). Inflows are required for each of the sub-catchments in the system. In the Brahmani model, 39 sub-catchments have been defined based on the location of gauges and medium and major irrigation schemes.

Confluences – represent locations where tributaries and return flows join a river. In the Brahmani model, the confluences were defined using the river network information.

Storages – are used to hold and regulate water at a point in the river system model. Google Earth and local information were used to set up the storages in the model.

Supply points and Water users – these represent the locations at which extraction demands for water users are generated. Information from the CWC and the states were used to determine demands.

Loss nodes – Loss nodes describe the amount of water lost in the system, a combination of physical processes and compensation for unaccounted modelling errors.

3.3 Baseline model conceptualisation – sections

Sections have been categorised into headwater sections and residual sections, where headwater sections are located in the upstream of the top-most gauging station and residual sections cover the areas between upstream and downstream gauges

Table 4 Brahmani model sections, ordered from top to bottom of the Basin

Section name	Gauge	Section type
Tilga section	Tilga gauge on the Sankh River	headwater
Jaraikela section	Jaraikela gauge on the South Koel River	headwater
Panposh section	Panposh gauge d/s of the confluence of the Sankh and South Koel rivers	residual
Gomlai section	Gomlai gauge on the Brahmani River	residual
Talcher section	Talcher gauge on the Brahmani River	residual
Jenapur section	Jenapur gauge on the Brahmani River	residual

Maps for each section are provided in Figure 9 to Figure 14 and their storages listed in Table 5 to Table 10.

3.3.1 Tilga section

The section to the Tilga gauge is on the Sankh River in the upper part of the catchment and lies partially in the states of Chhattisgarh and Jharkhand. This is a headwater section of the model with no upstream section inflows. It contains several reservoir schemes and areas of double/triple cropping (Table 5; Figure 9). Information supplied indicated that there was one major command area in the Tilga section, the Jaipur irrigation scheme. This irrigation scheme was included as an irrigation demand point for the Upper Sankh Reservoir Scheme. The 2007–2008 population in this section was 446,464.

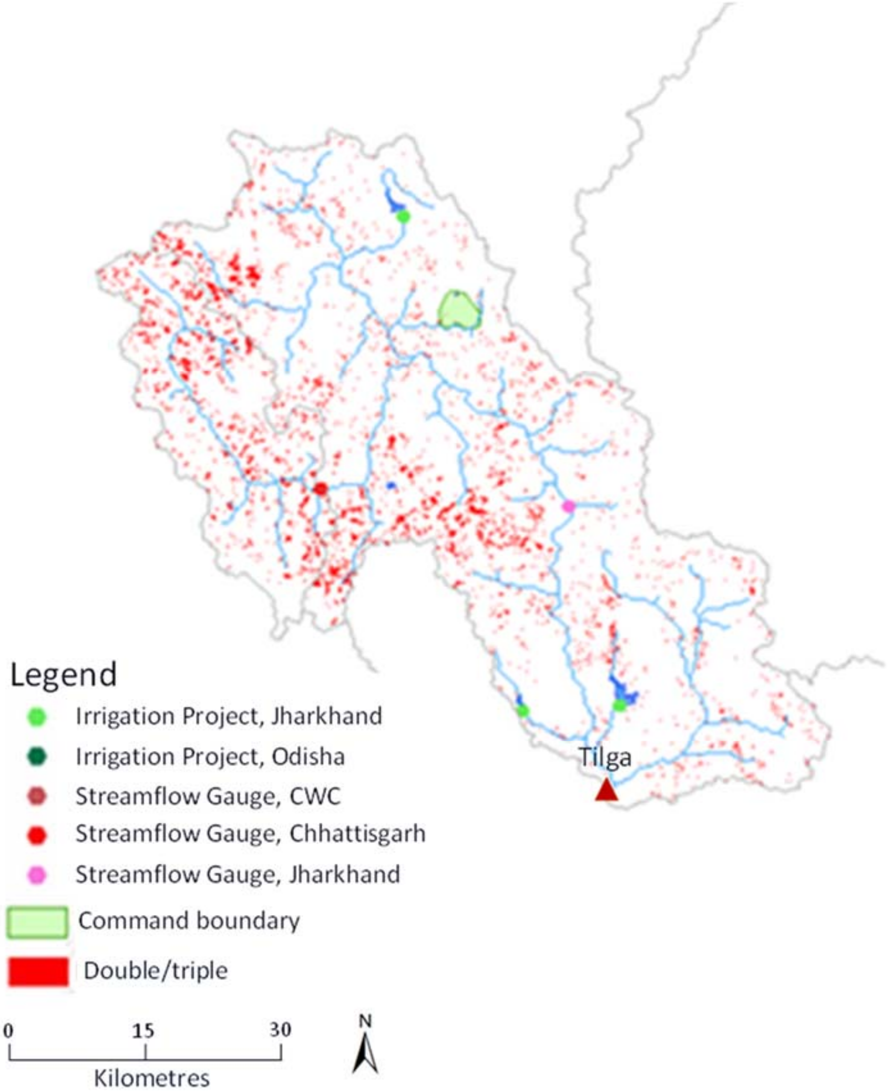

Figure 9 Tilga section showing storages, command areas and areas of double/triple cropping

Table 5 Medium and major irrigation storages in the Tilga section

Irrigation project	Project classification	Culturable Command Area (CCA) (ha)
Upper Sankh	Medium	1502

3.3.2 Jaraikela section

The section to the Jaraikela gauge is on the South Koel River in the upper part of the catchment in the State of Jharkhand. This is a headwater section of the model with no upstream section inflows. It contains several reservoir schemes and areas of double/triple cropping (Table 6, Figure 10). Information supplied indicated that there are seven command areas in this section. Irrigation demand points were included for all but Dhansingh Tola. The 2007–2008 population in this section was 2,295,997.

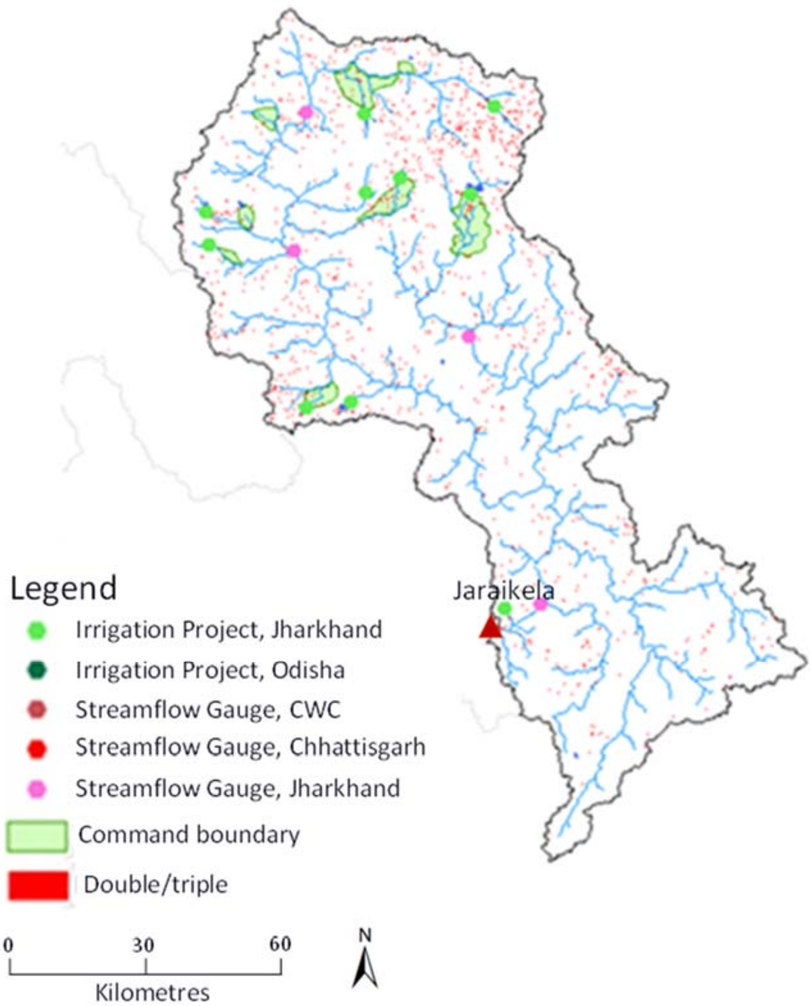

Figure 10 Jaraikela section showing storages, command areas and areas of double/triple cropping

Table 6 Medium and major irrigation storages in the Jaraikela section

Irrigation project	Project classification	Culturable Command Area (CCA) (ha)
Nandani Weir	Medium	7239
Baski	Medium	1754
Latratu	Medium	8645
Tapkara	Medium	2608
Dhansingh Tola	Medium	Not Included
Paras	Medium	4372
Katri	Medium	1411

3.3.3 Panposh section

Panposh is the first residual section. Residual sections have inflows from upstream sections. The Panposh gauge is just downstream of the Sankh and South Koel rivers . The section covers the States of Jharkhand and Odisha and contains four modelled reservoir schemes and two modelled command areas (Table 7, Figure 11). The 2007–2008 population in this section was 1,090,952.

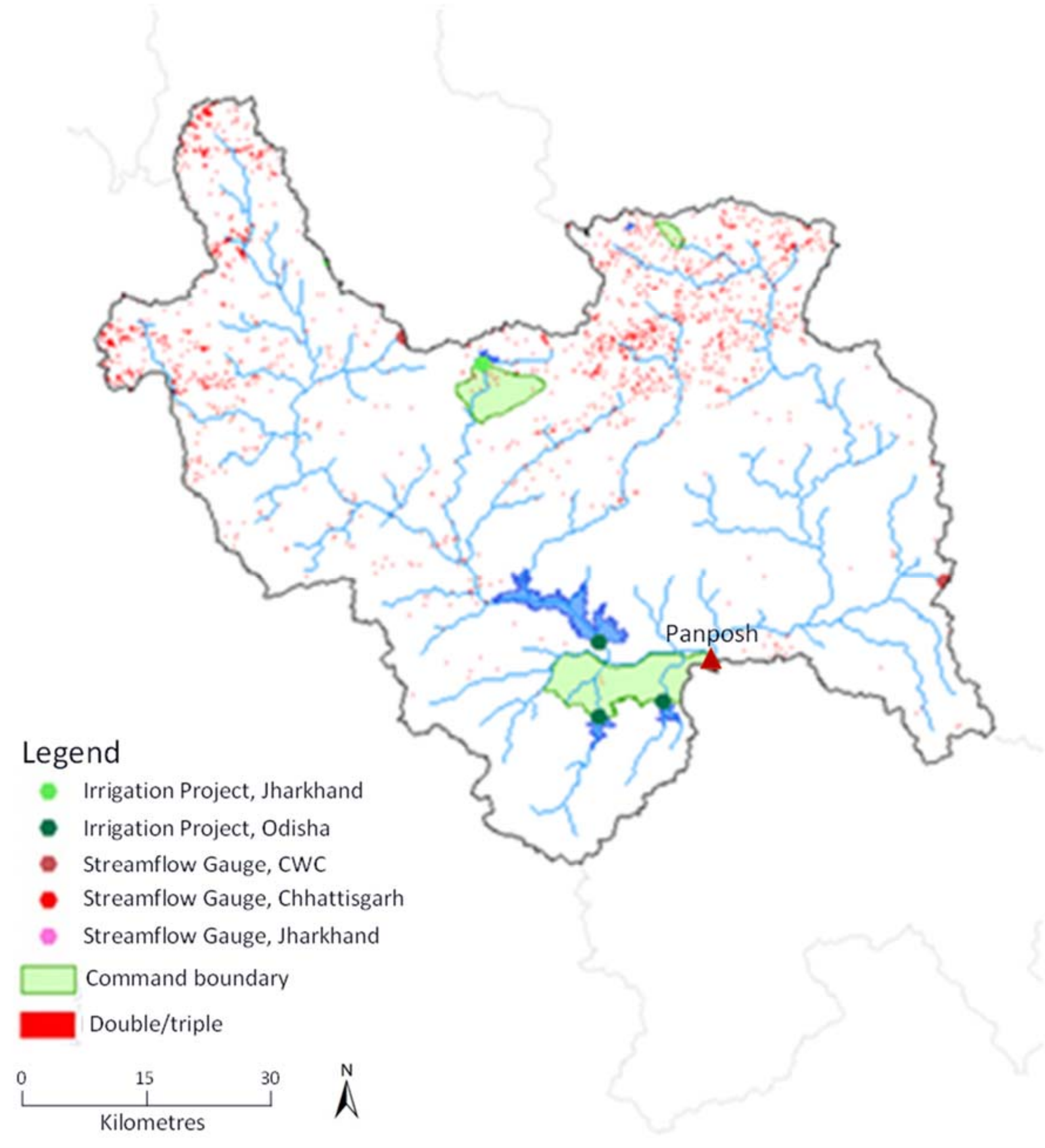

Figure 11 Panposh section showing storages, command areas and areas of double/triple cropping

Table 7 Medium and major irrigation storages in the Panposh section

Irrigation project	Project classification	Culturable Command Area (CCA) (ha)
Pitamahal	Medium	11,856
Kansabahal	Medium	
Chinda	Medium	6,136
Mandira	Medium	N/A – for industrial purposes

3.3.4 Gomlai section

Gomlai is the second residual section and is located in the State of Odisha. The Gomlai gauge is located on the Brahmani River. There is one modelled reservoir and command area in this section (Table 8, Figure 12). The 2007–2008 population in this section was 271,436.

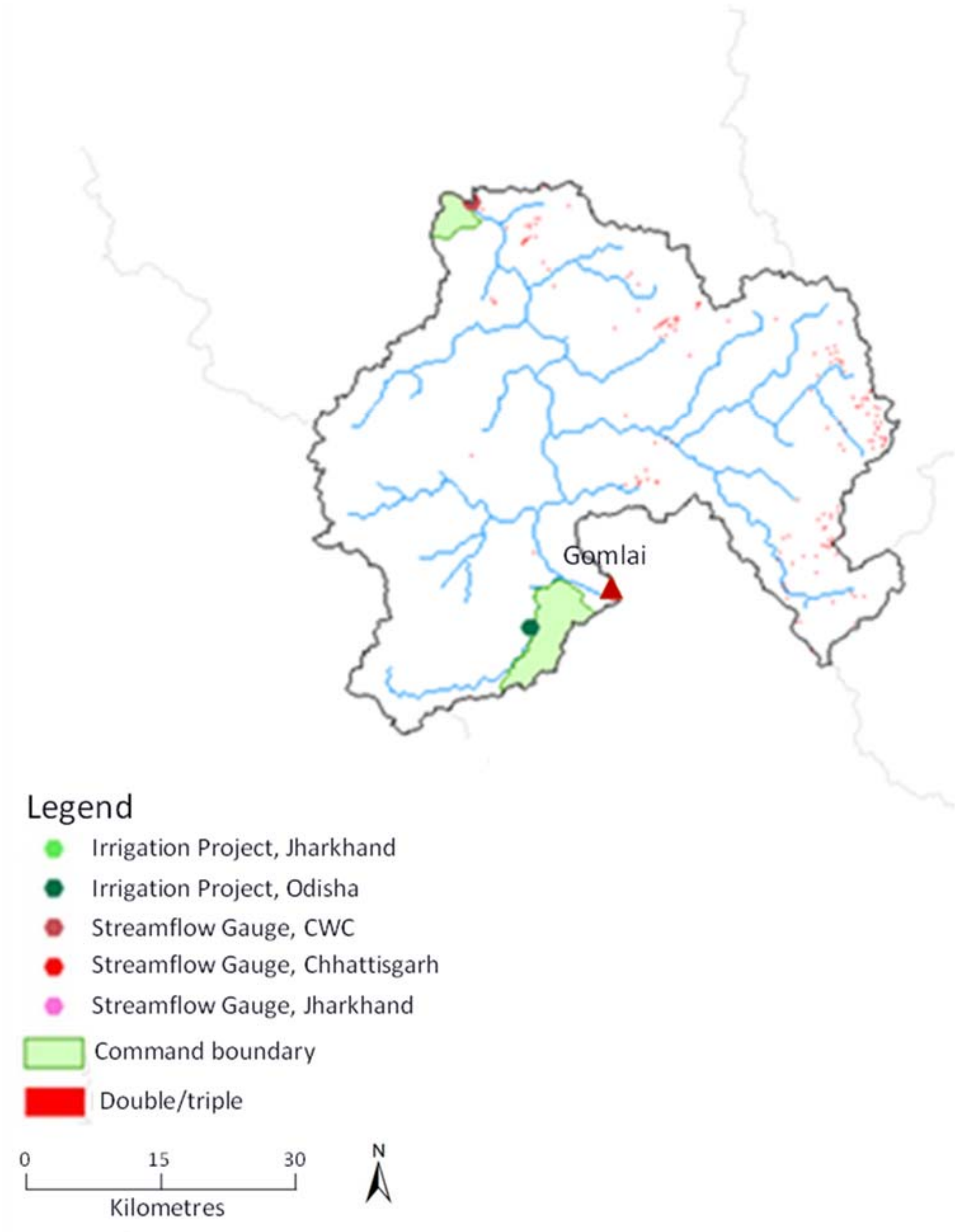

Figure 12 Gomlai section showing storages, command areas and areas of double/triple cropping

Table 8 Medium and major irrigation storages in the Gomlai section

Irrigation project	Project classification	Culturable Command Area (CCA) (ha)
Rukura	Medium	9372

3.3.5 Talcher section

There are three modelled reservoir schemes and three command areas in this section (Figure 13, Table 9). This section has the only major storage (Rengali Dam) in the Brahmani baseline model. The Anuli storage has not been included as the storage delivers water to a minor irrigation scheme. However diversions have been included. There are no population or industrial demands included on this section as these data were not included in the information provided. It is assumed that the population figure at Jenapur incorporates the population between Gomlai and the end of the system.

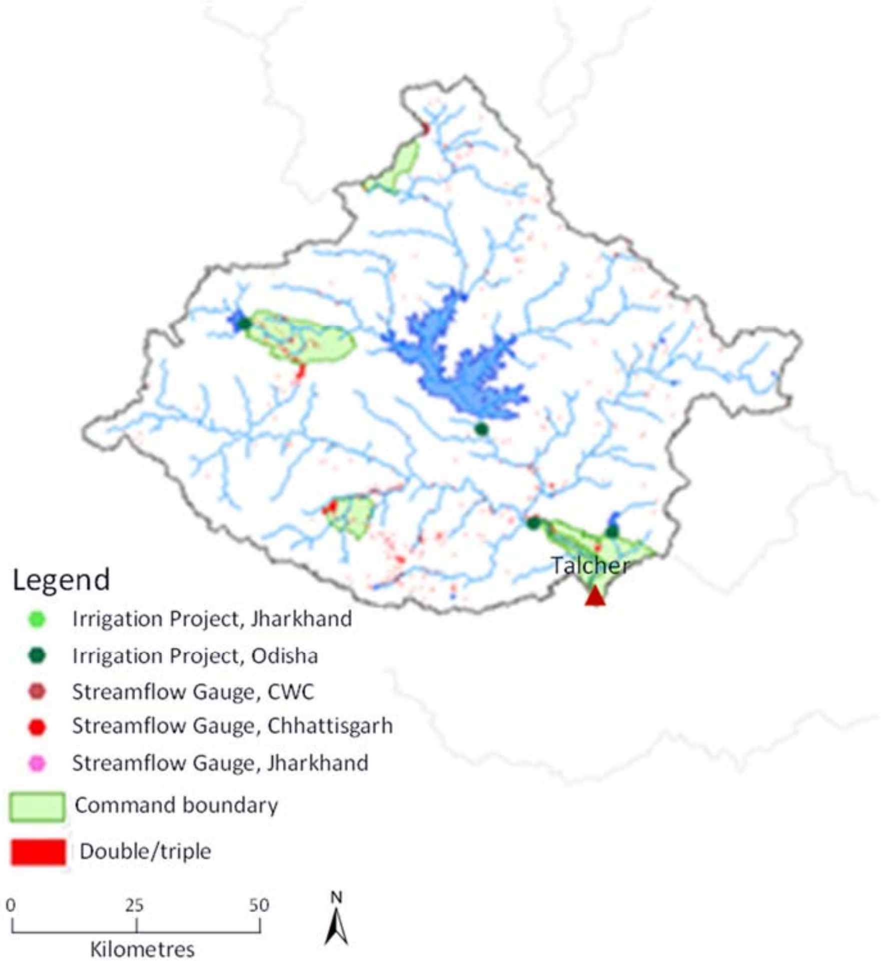

Figure 13 Talcher section showing storages, command areas and areas of double/triple cropping

Table 9 Medium and major irrigation storages in the Talcher section

Irrigation project	Project classification	Culturable Command Area (CCA) (ha)
Gohira	Medium	15,595
Rengali	Major	335,901
Dadaraghati	Medium	19,169

3.3.6 Jenapur section

The Jenapur gauge is on the Brahmani River. The section is in the State of Odisha. There is one modelled reservoir scheme in this section with one command area (Table 10, Figure 14). Most of the water diverted for this area has been included in the model upstream of the Talcher gauge. This is due to the location of the Samal Barrage, this structure re-regulates water released from Rengali Dam for irrigation in the catchment area between Talcher and Jenapur. The 2007–2008 population in this section was 2,558,215.

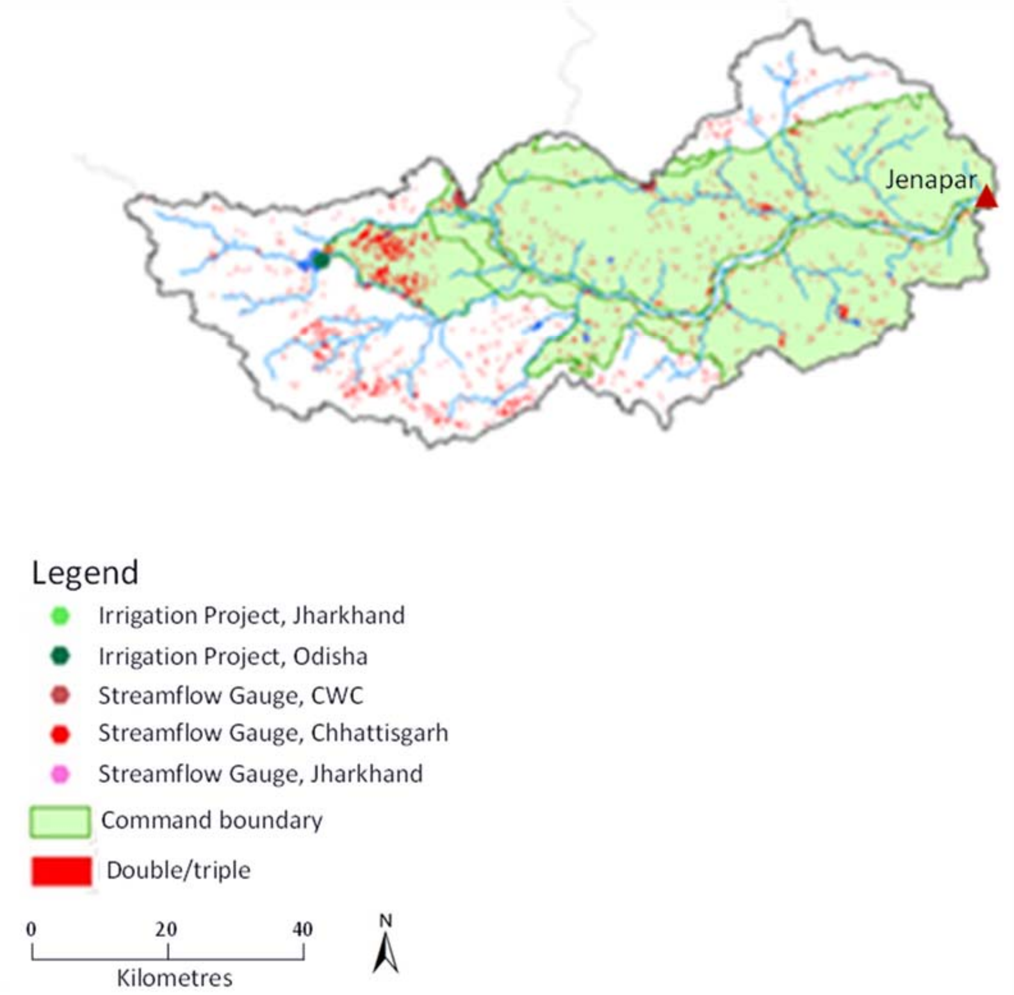

Figure 14 Jenapur section showing storages, command areas and areas of double/triple cropping

Table 10 Medium and major irrigation storages in the Jenapur section

Irrigation project	Project classification	Culturable Command Area (CCA) (ha)
Derjang	Medium	21,723

4 Calibration of the baseline Brahmani river system model

4.1.1 Rainfall-runoff model

Inflows from tributary surface water runoff represent the main source of water incorporated in the baseline model. Where observed data are available for the most upstream inflows, these can be used directly as input to the model. However, as all of the CWC streamflow gauges are located downstream of development, this development needed to be explicitly represented in the baseline model and flows upstream of this development needed to be estimated.

Without-development inflows were estimated using models that convert climate inputs into streamflow. These models are referred to as rainfall-runoff models. In the Brahmani model, the rainfall-runoff models are calibrated using the flow gauges, after taking into account estimates of the upstream demands (irrigation, domestics and livestock, industry and irrigation within the command areas).

We used the GR4J rainfall-runoff model for rainfall-runoff calibration (Perrin et al 2003). This was used because it is a simple model with fewer assumptions than other models in representing runoff at the sub-catchment scale . GR4J uses rainfall and potential evaporation as inputs. It has been well tested and is considered to be robust (Perrin et al. 2003). The parameters of the GR4J model together with default values are shown in Table 11.

The rainfall-runoff models consider runoff generation in headwater sections and residual sections, where headwater sections are located in the upstream of the top-most gauging station and residual sections cover the areas between upstream and downstream gauges.

The values of the parameters for the GR4J rainfall-runoff model were determined for each section by calibrating the model to the downstream gauge. For residual catchments, calibration of the rainfall-runoff model was undertaken using the observed flows at the upstream gauge as opposed to model flows.

Table 11 GR4J model parameters

GGR4J parameter	Description	Units	Default	Range
X1	Capacity of the production soil (SMA) store	mm	350	1-1500
X2	Water exchange coefficient	mm	0	-10.0-5.0
X3	Capacity of the routing store	mm	40	1-500
X4	Time parameter for unit hydrographs	days	0.5	0.5-4.0

See <https://ewater.atlassian.net/wiki/display/SD41/GR4J+-+SRG> for more information.

The performance of the baseline model in reproducing observed flows for each rainfall-runoff model is presented in this section. The basis for this assessment is shown in Table 12. This is not based on any formal evaluation protocol but takes into consideration previous modelling experience and a cursory assessment of gauge accuracy.

Table 12 Model performance evaluation criteria

MODEL PERFORMANCE	DAILY NSE	BIAS	DAILY NSE	BIAS
Excellent	> 0.95	< 1%	> 0.95	< 1%
Good	0.9-0.95	1% - 5%	0.9-0.95	1% - 5%
Average	0.8-0.9	5% - 10%	0.8-0.9	5% - 10%
Fair	0.5 - 0.8	10% - 20%	0.5 - 0.8	10% - 20%
Poor	< 0.5	> 20%	< 0.5	> 20%

The rainfall-runoff models were calibrated over the period 2000–2012 and validated over the period 1988–1999. A summary of rainfall-runoff model results are presented in Table 13 (daily flows) and Table 14 (monthly flows). Detailed results can be found in Appendix A. As can be seen from Table 13 and Table 14, the models reproduce monthly total flows better than for daily flows.

The reproduction of flows at Talcher is not as good as for other sections. This is most likely due to the uncertainties associated with replicating the operation of Rengali Dam and Samal Barrage.

Table 13 GR4J Baseline model rainfall-runoff model performance by section (Whole period daily flows ML/day)

Whole period daily	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Tilga section	Fair	Excellent	Fair	Fair	Fair	Good
Jaraikela section	Poor	Average	Fair	Fair	Fair	Average
Panposh section	Fair	Good	Average	Average	Average	Good
Golmai section	Average	Excellent	Good	Good	Average	Excellent
Talcher section inflows to Rengali	Fair	Good	Fair	Good	Fair	Excellent
Talcher section (Talcher)	Poor	Fair	Poor	Poor	Fair	Poor
Jenapur section	Fair	Excellent	Fair	Fair	Fair	Good

Table 14 GR4J Baseline model rainfall-runoff model performance by section (Whole period monthly flow totals ML)

Whole period monthly	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Tilga section	Average	Excellent	Average	Fair	Good	Good
Jaraikela section	Fair	Average	Fair	Fair	Average	Average
Panposh section	Good	Good	Good	Average	Excellent	Good
Golmai section	Excellent	Excellent	Excellent	Good	Excellent	Excellent
Talcher section inflows to Rengali	Excellent	Good	Excellent	Excellent	Excellent	Excellent
Talcher section (Talcher)	Fair	Fair	Fair	Poor	Fair	Poor
Jenapur section	Average	Excellent	Fair	Fair	Average	Good

4.1.2 River system model

The Brahmani river system model was calibrated using stream flow data from 2000 to 2012. Model validation was done for the period of 1988 to 1999. The model was calibrated using a NSE log Daily + Bias Penalty objective function (eWater 2016a). This objective function focuses on achieving a good reproduction of observed low flows.

Irrigation demands during the calibration and validation period were estimated using a time series developed using the irrigator crop model in eWater Source (eWater 2016b). Population and industrial demands have been set as previously outlined in §3.1.3.

It was not possible to calibrate the observed storage behaviour and the observed demands as required information was not available. These have been estimated using the methods outlined below.

Limitations and assumptions

The model key assumptions are listed below, and expanded in Table 15.

- Stationarity has been assumed – that is, land use, irrigated areas, crop types, irrigation practices, supply efficiencies and population had not changed significantly over the model calibration period.
- Parameterisation of storages is based on limited information and, where necessary, the following were estimated:
  - level, volume, surface area relationships
  - discharge relationship for the outlets.
- Storage behaviour has not been calibrated as there is no information to do this for most storages. Due to time constraints, the demands downstream of Rengali Dam were not able to be adjusted to obtain a better match with observed storage behaviour.

Table 15 Assumptions in the conceptualisation of the Baseline model

ID	Assumption
Infrastructure	• Only storages visible in Google Earth have been included in the model • There are no operating rules for storages (i.e. storages are demand driven), except for Rengali Dam
Irrigation	• Irrigation areas are based on Command Area boundaries for Medium and Major projects (Space report) • Irrigation areas do not necessarily line up with the locations of Medium and Major irrigation storages or the CCA detailed (e.g <http://india-wris.nrsc.gov.in/wrpapp.html?show=D01160>) • Crop areas are based on the land use map from the Space report, and determined by the land use types that fall within the Command areas • Crops are modelled based on an FAO 56 approach with crop factors adopted from NRSC and CWC (2011) • Rice pond levels are based on published literature
Irrigation	• Irrigation support is only provided to crops inside Command Areas. The exception is double/triple crops where irrigation support is provided, regardless of their location (grouped as a single node at end of each reach)
Crops - types and seasons	• Kharif: start date 1/7, harvest date 31/10 (rice needs 120 days) • Double/triple crop 1 (same as kharif): • Double/triple crop 2: start date 1/1, harvest date 3/5 • Rabi (Safflower): November to February • Zaid (groundnut): February to May • (NRSC and CWC, 2011)
Crops – water supply	• Crops grown outside Command Areas are rain-fed and are not modelled. • Water requirements of crops grown within Command Areas are met using irrigation water only i.e. groundwater supplies are not considered • Grams/pulses have insignificant water use • Yield is based on FAO water stress yield approach. Yield sensitivity parameters are based on recommended values in FAO 56. Yields are based on district crops statistics.
Water distribution	• Return flows were included for the population and industrial demands at assumed to be xx% of extraction. • No return flows are included in the baseline model for irrigated areas
Water supply	• There is no allocation scheme, storages are operated to meet demands.
Water supply	• There are no differences in efficiencies for different states • A baseline efficiency in is 65%.
Water supply	• There are no supply constraints for irrigation schemes

The performance of the model in reproducing flows along each section is summarised for daily and monthly flow totals at each of the main streamflow gauges in Table 16 and Table 17. The same performance criteria that was used for rainfall-runoff flow reproduction was also used in river system model flow reproduction (Table 12). In general, reproduction of observed total volume results (volume bias) are superior to that of NSE for both daily and monthly flow totals. Monthly flow reproduction is also superior to that of daily flows.

Detailed flow calibration results for each model section can be found in Appendix B.

Table 16 Baseline river system model performance by section (whole period daily flows ML/day)

Whole period daily	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Tilga section	Fair	Excellent	Fair	Fair	Fair	Good
Jaraikela section	Poor	Average	Fair	Fair	Fair	Average
Panposh section	Fair	Good	Fair	Good	Fair	Good
Golmai section	Fair	Excellent	Fair	Good	Fair	Excellent
Talcher section Inflows to Rengali	Fair	Good	Fair	Good	Average	Excellent
Talcher section (Talcher)	Poor	Fair	Poor	Poor	Fair	Good
Jenapur section	Fair	Poor	Fair	Excellent	Fair	Fair

Table 17 Baseline river system model performance by section (whole period monthly flow totals ML)

Whole period monthly	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Tilga section	Average	Excellent	Average	Fair	Good	Good
Jaraikela section	Fair	Average	Fair	Fair	Average	Average
Panposh section	Average	Good	Good	Good	Good	Good
Golmai section	Average	Excellent	Good	Good	Good	Excellent
Talcher section Inflows to Rengali	Good	Good	Good	Good	Excellent	Excellent
Talcher section (Talcher)	Fair	Fair	Poor	Poor	Average	Good
Jenapur section	Fair	Poor	Fair	Good	Fair	Fair

4.1.3 Storage behaviour at Rengali

An additional check on how well consumptive demands are represented by the baseline model can be made by comparing the observed and simulated storage behaviour for Rengali Dam. This is shown in Figure 15. Whilst the overall storage behaviour has been broadly captured, further calibration of the demands (consumptive and non-consumptive) downstream of Rengali Dam is likely to improve the match of the storage level and releases. Incorporation of a rule curve for operations may also improve the fit of the model.

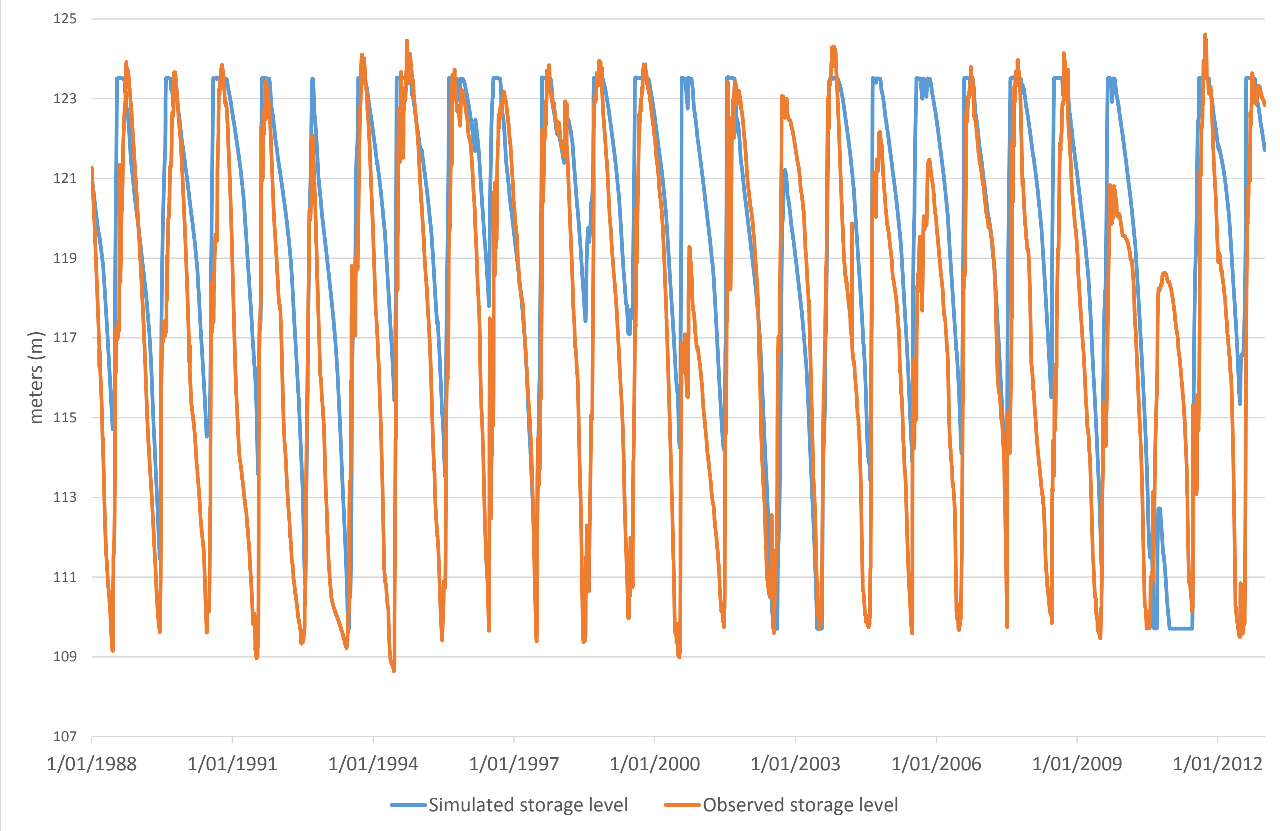

Figure 15 Comparison of observed and simulated storage level behaviour for Rengali Dam

5 Scenarios

5.1 Scenario descriptions

Following calibration, a number of development and climate parameters in the baseline model have been modified in order to assess a series of 12. A without-development and three sets of development scenarios have been created to explore the impact on flows and production throughout the Basin of alternate water management practices, adding new storages (and associated irrigation areas) and new cropping practices. The scenario set is shown in Figure 16 and these are described in Table 18 and Table 19.

Set S1 includes improved supply efficiency, and further development of existing Command Areas, both in terms of planted area and crop mix. This allows for exploration of the effects of increasing each of these separately, and in combination.

Set S2 includes new storages and their associated Command Areas. This set allows for exploration of the impacts of new storages and improved efficiency in delivery of water.

Set S3 is a maximum development set.

Climate change scenarios are overlayed on the twelve model scenarios. Evapotranspiration and rainfall over the Basin, under climate change, have been derived from the Global Climate Models that cover the Basin (Zheng et al 2015). We use the high emission Representative Concentration Pathway (RCP 8.5) which represents the climate pathway currently being tracked (Riahi et al 2011; Van Vuuren et al 2011). These datasets are inputs to the rainfall-runoff model to simulate runoff under likely future climate.

# storages			Efficiency	Crop mix	+Op rules	+Env. Flows
1	Base	•				
	WOD	•				
1	S1	•	•	•		
3	S2	•	•		•	•
3	S3			•	•	•

Figure 16 Scenarios matrix

Table 18 Description of scenarios and their short form names

ID	Description
Baseline	Represents the **most recent level of development**. All storages are present, infrastructure management, operational rules and crop types and areas planted are reflective of today's practices. Comparison of this scenario to the Without Development Scenario allows the extent of change due to water management to be quantified.
WOD	Represents the **hydrology of the river system prior to the construction of storages and the extraction of water**. However, the inflows to the river system network still reflect land use changes that have occurred during the rainfall-runoff model calibration period.
S1	**Baseline with Command Areas developed to the maximum possible extent with existing crop mixes** This scenario allows for assessment of the changes that would occur in both flows and production throughout the Basin, should the existing crop areas (as represented in the Baseline) be developed to their maximum extent. This is achieved through increasing the planted area of each crop while keeping the same relative proportion of each crop as in the Baseline, so that the total crop planted area equals that of the Command Areas. The losses associated with delivery of water from the river to the crop are unchanged.

ID	Description
S1-80	**Baseline with Command Areas developed to the maximum possible extent with existing crop mixes, and improved delivery efficiency** This scenario builds on S1 by reducing water that is lost during the delivery process from the river to the crop. It allows for assessment of the changes that would occur in both flows and production throughout the Basin, should the existing crop areas (as represented in the Baseline) be developed to their maximum extent, and supply efficiency increased to reduce water loss to the crops from 35% (as in Baseline) to 20% (i.e. 80% efficiency). The water loss is to the groundwater system.
S1-80-DT	**Baseline with Command Areas developed to the maximum possible extent with rice (double/triple), and improved delivery efficiency** This scenario builds on S1-80 and allows for assessment of the changes that would occur in both flows and production throughout the Basin if the Command Areas were planted to rice (double/triple) and supply efficiency increased to reduce water loss to the crops from 35% (as in Baseline) to 20% (i.e. 80% efficiency). The rice (double/triple) is grown throughout the year with an area equal to the Command Area of the district.
S2	**Baseline with new storages and associated Command Areas developed to the maximum possible extent with rice (double/triple)** This scenario allows for assessment of the changes that would occur in both flows and production throughout the Basin if new storages were constructed on the Koel, Karo, and Sankh Rivers to generate hydropower and supply water for new rice (double/triple) crops downstream of the storages. Within existing Command Areas, the relative proportion of each crop and planted area is maintained (as in the Baseline), The Command Areas associated with the new storages are fully developed with rice (double/triple). Delivery efficiencies for existing and new Command Areas are assumed to remain at current levels, i.e. 35% of water delivered does not reach the crops.
S2-80	**Baseline with new storages and associated Command Areas developed to the maximum possible extent with rice (double/triple) and improved delivery efficiency** This scenario builds upon the S2 scenario and allows for assessment of the changes that would occur in both flows and production throughout the Basin, if new storages were constructed and improved delivery efficiency were to occur at the same time. Delivery efficiencies for existing and new Command Areas are improved, with the volumes of water that do not reach the crop reduced from 35% to 20%, with no return to the river.
S2-80-OR	**Baseline with new storages and associated Command Areas developed to the maximum possible extent with rice (double/triple) and improved delivery efficiency and flood operation** This scenario builds upon the S2-80 scenario and allows for assessment of the changes that would occur in both flows and production throughout the Basin, if new storages were constructed, improved delivery efficiency were to occur at the same time, and the Rengali, Koel-Karo and Sankh storages were operated to mitigate downstream flooding during the monsoon period from June to September. Flood Operation aims to release water, such that the storages are at their lowest level during June and back at full supply level at the end of September.
S2-80-OR-E	**Baseline with new storages and associated Command Areas developed to the maximum possible extent with rice (double/triple) and improved delivery efficiency and flood operation and environmental releases** This scenario builds upon the S2-80-OR scenario and allows for assessment of the changes that would occur in both flows and production throughout the Basin if Rengali, Koel-Karo and Sankh storages were operated to provide water for agricultural production, flood mitigation and environmental flows. Minimum passing flows have been set equal to 30% of the daily inflow from the beginning of June to the end of September, and 20% of the daily inflow in other months.
S3-80-DT	**Baseline with new storages and all Command Areas developed to the maximum possible extent with rice (double/triple) and improved delivery efficiency** In this scenario, only rice (double/triple) is grown throughout the Basin. Its area equals that of the Command Area for all districts. New Storages are in place on the Koel, Karo, and Sankh Rivers and delivery efficiency has been improved so that only 20% of water is lost in delivery from the river to the crop. This scenario represents the upper limit of production for the Brahmani Basin based on the scenarios that have been evaluated.

ID	Description
S3-80-DT-OR	**Baseline with new storages and all Command Areas developed to the maximum possible extent with rice (double/triple) and improved delivery efficiency and flood operation** This scenario looks at how the upper limit of production in the S3-80-DT scenario is affected by the introduction of flood operation on the major storages. As with the equivalent S2 scenario, flood operation aims to release water, such that the storages are at their lowest level during June and back at full supply level at the end of September.
S3-80-DT-OR-E	**Baseline with new storages and all Command Areas developed to the maximum possible extent with rice (double/triple) and improved delivery efficiency and flood operation and environmental releases.** This scenario looks at how the upper limit of production in the S3-80-DT scenario is affected by the introduction of environmental releases on the major storages. As with the equivalent S2 scenario, minimum passing flows have been set equal to 30% of the daily inflow from the beginning of June to the end of September, and 20% of the daily inflow in other months.

Table 19 Description of scenarios and their storage, supply efficiency and crop area and pattern, highlighting the changes between scenarios (CA=Command Area)

ID	Storages	New storages operation	Supply efficiency	Crop areas	Crop pattern/mixes
Baseline	Existing	N/A	Existing	Existing	Existing
WOD	None	N/A	None	None	None
S1	Existing	N/A	Existing	CAs developed to maximum extent	Existing
S1-80	Existing	N/A	Increase to 80%	CAs developed to maximum extent	Existing
S1-80-DT	Existing	N/A	Increase to 80%	CAs developed to maximum extent	All crops converted to Double/Triple
S2	Existing + 2 new dams	No rules	Existing	Existing in existing CAs, developed to maximum extent in new CAs	Existing in existing CAs, double/triple in new CAs
S2-80	Existing + 2 new dams	No rules	Increase to 80%	Existing in existing CAs, new CAs developed to maximum extent	Existing in existing CAs, double/triple in new CAs
S2-80-OR	Existing + 2 new dams	Operational rules*	Increase to 80%	Existing in existing CAs, new CAs developed to maximum extent	Existing in existing CAs, double/triple in new CAs
S2-80-OR-E	Existing + 2 new dams	Operational rules* + e-flows**	Increase to 80%	Existing in existing CAs, new CAs developed to maximum extent	Existing in existing CAs, double/triple in new CAs
S3-80-DT	Existing + 2 new dams	No rules	Increase to 80%	All CAs developed to maximum extent	Double/triple in all CAs
S3-80-DT-OR	Existing + 2 new dams	Operational rules	Increase to 80%	All CAs developed to maximum extent	Double/triple in all CAs
S3-80-DT-OR-E	Existing + 2 new dams	Operational rules* + e-flows**	Increase to 80%	All CAs developed to maximum extent	Double/triple in all CAs

* Rules. Same operating rules as Rengali Dam

** e-flows. Same seasonal pattern as for Rengali Dam

5.2 Scenario assumptions

Due to data limitations a number of assumptions have had to be made in developing the model scenarios. These are presented in Table 20. In particular assumptions have had to be made in relation to the characteristics of two new storages in the model. These storages are described in more detail in the following section.

Table 20 Assumptions made in development of future development/future climate scenarios

Component	Assumption
Infrastructure	The two dams for the Koel-Karo Hydro Project are modelled as one storage downstream of the confluence of the South Koel and North Karo Rivers
Infrastructure	The new dams have the same height surface area characteristics as Rengali Dam
Infrastructure	The percent distribution of storage volume with height for the new dams is the same as for Rengali Dam
Infrastructure	The Gated spillway relationship for the proposed Koel-Karo dam is a straight proportion (17/24) of the Rengali relationship. The proposed Koel-Karo dam apparently has 17 gates and Rengali has 24. Hence the 17/24 apportionment.
Infrastructure	The proposed Sankh Dam uses the same gated spillway and outlet relationship as the proposed Koel-Karo dam
Hydropower	The Koel-Karo hydropower outlets have been sized to produce 710MW. The same head difference of 28 metres from the valve inlet to outlet that is used for Rengali Dam has been assumed. Eighty Percent Turbine efficiency has been assumed.
Flood operation	New dams use the rule curve logic that exists for Rengali Dam
Crop production	Crop production has been calculated based on the FAO 56 crop yield function. This function compares the actual evapotranspiration with the potential evapotranspiration as well as yield sensitivity parameter to determine the proportion of maximum yield for the crop. This proportion is multiplied by the crop area and the specified maximum yield per hectare to determine the crop production..

5.2.1 New infrastructure

Three new storages have been represented in the Basin - two dams on the Koel and Karo rivers and one on the lower Sankh River. The Koel-Karo Hydro Project involves the construction of two earth dams—one 44 metres (144 ft) high, across the South Koel river near Basia, and the other 55 metres (180 ft) high, across the North Karo river near Lohajima. The two dams will be linked by a trans-basin channel, with six units of 115 mW each in the underground powerhouse at Lumpu-ngkhel and one unit of 20 mW at Raitoli. Due to the linkages between the two dams they have been conceptualised as one storage.

Owing to lack of detailed information concerning the proposed projects, the three new dams represented in the Source Scenario have the same height surface area characteristics as Rengali Dam. The percentage distribution of storage volume with height for the two new dams is also the same as for Rengali Dam.

The Gated spillway relationship for the proposed Koel-Karo dam is a straight proportion (17/24) of the Rengali relationship. The proposed Koel-Karo dam apparently has 17 gates and Rengali has 24, hence the 17/24 apportionment. The proposed Sankh Dam uses the same gated spillway and outlet relationship as the proposed Koel-Karo dam.

Storage and command area characteristics for each dam are presented in Table 21 to Table 23.

Table 21 Command areas associated with new storages

Storage name	Command Area (ha)	Double/triple (Irrigated ha)	Kharif (Irrigated ha)	Rabi (Irrigated ha)	Zaid (Irrigated ha)
Sankh	33603.00	33,603.00	0.00	0.00	0.00
Koel_Karo	172121.00	172,121.00	0.00	0.00	0.00

Table 22 New storage characteristics

Name	Full supply-level (m)	Full supply-volume (MCM)	Full supply-surface area (sq km)	Initial storage-level (m)	Initial storage-volume (MCM)	Dead storage-level (m)	Dead storage-volume (MCM)
Sankh Res	124	774272	378	121	643251	110	173558
Koel_Karo_Res	124	468151	378	121	388932	110	104939

Table 23 Level-volume relationships for new storages

Level (m)	Volume (%)
0	0%
11.22	23%
14.22	35%
17.22	48%
20.22	65%
23.22	84%
23.5	85%
23.72	87%
24.22	90%
24.72	94%
25.22	98%
25.4	100%

5.3 Scenario results

5.3.1 Baseline and Without Development

The baseline scenario shows that annual water availability in the Basin is dominated by monsoonal flows with low flows in the dry (non-monsoon) period. The highest flow volumes in the system are below the confluence of the Sankh and South Koel Rivers in Odisha, where the Brahmani River is formed.

Water use is minimal in the upper Basin, with only minimal differences in flows in the system between the Baseline and the Without Development scenarios (Figure 17), with annual flows being unchanged. The baseline shows reduced flows at the end of the system, reflecting greater water use for consumptive purposes.

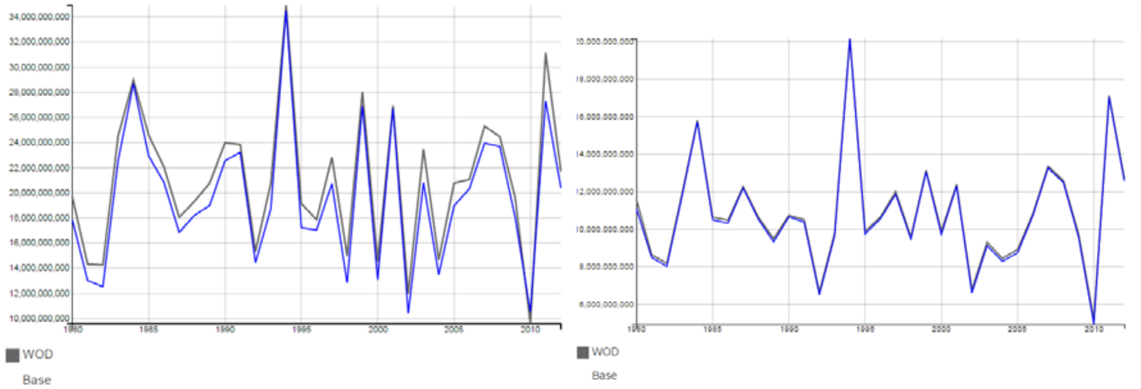

Figure 17 Flows at Panposh gauge (left) just downstream of the confluence of the Sankh and South Koel Rivers, and Jenapur gauge (right) at the end of the system. The Without Development scenario is in grey and the Baseline scenario is in blue.

The bulk of the basin water use is in Odisha, with hydropower being the highest water user. Note that hydropower is a non-consumptive water user, and the water is re-distributed to other users (Figure 18). There is minimal water use in Jharkhand, with 10 MCM being used by each water sector per year.

The dominant crop in the Basin is Kharif rice. The Basin produces approximately 367 kilotonnes of irrigated rice per year, with 99% of that in Odisha.

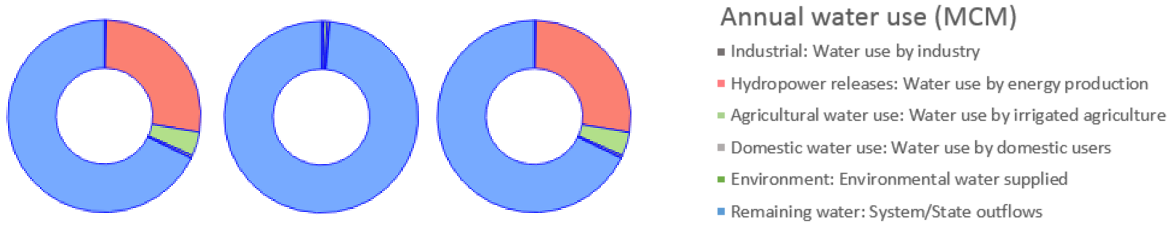

Figure 18 Distribution of water use across water sectors in the baseline scenario, showing the whole of Basin (left), Jharkhand (middle) and Odisha (right)

5.3.2 Cropping areas and patterns (S1 set)

By changing cropping areas and patterns in Odisha, there is a potential to triple rice production from 367 kt/y to 978 kt/y. Command areas in Odisha make up more than 90% of the irrigation areas in the Basin. There is an increase in water use for agriculture in Odisha and the overall availability of water in the river is reduced (Table 24). By contrast, the benefits to Jharkhand are only modest, with production, with production increasing to 17 kt/y from 3 kt/y.

Table 24 Water use and total rice production considering scenarios of cropping

Scale	Model outputs	Baseline	Cropping area at Command Area same Crop Mix	Cropping area at Command Area + Double/triple Crop Mix
Basin	Water use - agriculture	1170 MCM/y	2397 MCM/y	3305 MCM/y
	Total rice	367 kt/y	811 kt/y	978 kt/y
Jharkhand	Water use - agriculture	10 MCM/y	41 MCM/y	54 MCM/y
	Total rice	3 kt/y	14 kt/y	17 kt/y
Odisha	Water use - agriculture	1160 MCM/y	2356 MCM/y	3252 MCM/y
	Total rice	364 kt/y	797 kt/y	961 kt/y

Water delivery efficiency can be improved by lining of canals to prevent water losses. In the model, we assumed that under current conditions 35% of water released does not reach the crop, but is lost through seepage. By lining canals, it is estimated losses could be reduced to 20%.

With this investment, the model shows no discernible changes to flows in the upper basin. Annual average end of system flows show an increase in water volumes (ranging from 200 to 400 MCM).

5.3.3 New storages (S2 set)

We considered 3 new storages in Jharkhand secure to water supplies. These are represented as two command areas (Koel Karo Reservoir Scheme: 2 major storages on the South Koel and the North Karo Rivers; Sankh Reservoir Scheme: major storage on the Sankh River).

The new storages increase the water storage capacity in Jharkhand from 17% up to 40% of the total Basin water storage resources.

In Jharkhand there is an increase in crop production, from 3 kt/y to 105 kt/y (Table 25). As new storages are hydropower schemes, there is also energy production. There is a reduced reliability of water supply to industry, reduced from 10 MCM/y to 6 MCM/y, due to the increased irrigation demands.

Table 25 Water use and total rice and energy production considering scenarios of new storages

Scale	Model outputs	Baseline	New storages	New storages + flood rules
Basin	Water use - agriculture	1170 MCM/y	2385 MCM/y	2176 MCM/y
	Total rice	367 kt/y	471.4 kt/y	472 kt/y
	Energy production	1814 GWh/y	2628 GWh/y	2517 GWh/y
Jharkhand	Water use - agriculture	10 MCM/y	592 MCM/y	590 MCM/y
	Total rice	3 kt/y	105 kt/y	105 kt/y
	Energy production	0 GWh/y	587 GWh/y	561 GWh/y
Odisha	Water use - agriculture	1160 MCM/y	1792 MCM/y	1586 MCM/y
	Total rice	364 kt/y	367 kt/y	367 kt/y
	Energy production	1814 GWh/y	2040.8 GWh/y	1956 GWh/y

5.3.4 Combination: cropping new storages, and environmental flows (S3 set)

In this scenario, the new storages and changed cropping scenarios are combined. Water use is increased, being almost four times greater than the baseline (Table 26; Figure 19). Rice and energy production are also increased.

With the greater use of water in the Basin, dry season flows are decreased, with an increased number of days where there is no water flowing at the end of the system. The reliability of water supply to domestic and industrial users is also reduced.

Environmental flow demands were implemented, with flow rules introduced for each of the storages with gates. The demand was described as 30% of inflows to the storage being released in the monsoonal period and 20% in the dry season. The flows were subsequently reused for meeting of other demands and there were no changes in the modelled flows further down the river system between scenarios.

Table 26 Water use and total rice and energy production considering scenarios of cropping and new storages

Scale	Model outputs	Baseline	New storages + cropping area + cropping patterns	New storages + cropping area + cropping patterns + flood rules
Basin	Water use - agriculture	1170 MCM/y	4445 MCM/y	4426 MCM/y
	Total rice	367 kt/y	1398 kt/y	1397 kt/y
	Energy production	1814 GWh/y	2595 GWh/y	2480.6 GWh/y
Jharkhand	Water use - agriculture	10 MCM/y	634 MCM/y	633 MCM/y
	Total rice	3 kt/y	121 kt/y	121 kt/y
	Energy production	0 GWh/y	580 GWh/y	556 GWh/y
Odisha	Water use - agriculture	1160 MCM/y	3812 MCM/y	3793 MCM/y
	Total rice	364 kt/y	1275 kt/y	1275 kt/y
	Energy production	1814 GWh/y	2015 GWh/y	1925 GWh/y

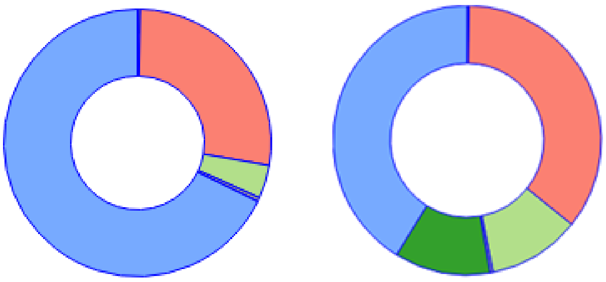

Figure 19 Baseline (left) and combined (right) scenario outcomes, showing relative increases in water use by water sectors (agriculture production: light green; hydropower: pink; environment (dark green)

With cropping intensification and new storage scenarios, water availability is reduced in the basin, with the greatest impacts to non-monsoon flows, with increased days of having no flow in the river.

5.4 Basin water balance under different development scenarios

The water balance of the river basin will change under different development scenarios. Table 27 shows the difference in water balance under the scenarios modelled, where

$$Outflow = Inflow + Return - Storage - Use \quad (1)$$

$$NetET = Evaporation - Rainfall \quad (2)$$

$$Volume_{Change} = Volume_{initial} - Volume_{last} \quad (3)$$

$$Use = Irrigation + Industrial + Domestic \quad (4)$$

The total inflow for the Basin averaged over the period 1990 to 2012 is about 21,175 MCM/year. Under the baseline scenario, total water use accounts for only 6.7% of the total inflow, which is a rather low use of water, relative to the total water resource available. This contrasts to the S3 scenario set where the water use is approximately 22% of the inflow.

Table 27 Basin-scale water balance under different development scenarios (unit: MCM)

Scenarios	Inflow	Storage		Water use				Return	Outflow
		Net ET	Volume change	Irrigation	Industrial	Domestic	Total		
WOD	21,175	0	0	0	0	0	0	0	21,175
Baseline	21,175	18	11	1,166	98	146	1,410	89	19,824
S1	21,175	15	10	2,383	98	146	2,628	89	18,611
S1-80	21,175	16	9	2,006	98	146	2,251	89	18,989
S1-80-DT	21,175	7	11	3,300	98	146	3,545	89	17,701
S2	21,175	102	26	2,410	94	140	2,643	82	18,487
S2-80	21,175	102	27	2,211	94	140	2,445	82	18,684
S2-80-OR	21,175	144	56	2,201	94	139	2,434	82	18,624
S2-80-OR-E	21,175	144	56	2,201	94	139	2,434	82	18,624
S3-80-DT	21,175	87	27	4,446	94	140	4,679	82	16,465
S3-80-DT-OR	21,175	125	57	4,419	93	139	4,652	82	16,423
S3-80-DT-OR-E	21,175	125	57	4,419	93	139	4,652	82	16,424

6 References

Asian Development Bank (2013) Integrated Water Resources Management and the People of Asia, Asian Development Bank.

Central Water Commission (2016) Report on River Basin Planning of Baitarni Sub-Basin. Central Water Commission, Delhi

eWater (2014) Assessment of Data Available for Hydrological & Water Management Modelling of the Brahmani-Baitarani Basin. eWater, Canberra.

eWater (2016a) Calibration Analysis SRG. eWater, Canberra. viewed 20/11/2016 <https://wiki.ewater.org.au/display/sd41/calibration+analysis+-+SRG>

eWater (2016b) Irrigator Demand Model. eWater, Canberra. viewed 20/11/2016 <https://wiki.ewater.org.au/display/SD41/irrigator+demand+model>

Government of Odisha (2010) Perspective and Strategic Plan for Watershed Development Projects, Orissa: 2010-2025, Orissa Watershed Development Mission, Agriculture Department, Orissa.

Government of Odisha (2004) Orissa state water plan, Orissa water planning organisation, Department of water resources, Secha Sdan, Bhubaneswar, India.

Government of Odisha, Department of Water Resources (2002) 3rd Spiral Study report of Brahmani Basin Plan, Volumes 1 and 2, Bhubaneswar, India

International Commission on Irrigation and Drainage (2005) Water resources assessment of Brahmani River Basin, India, Sustainable Economic Development Department, The Government of Netherlands.

NRSC and CWC (2011) Assessment of Water resources at Basin Scale using Space Inputs: Godavari and Brahmani-Baiarani Basins. Water Resources Division, ISRO, Hyderabad.

Mainuddin M, Pollino CA and Merrin L (2016) Agricultural productivity in the Brahmani Baitarni Basin of India, CSIRO, Canberra.

Pandey JS and Devotta S (2005) Assessment of Environmental Water Demands (EWD) of Forests for Two Distinct Indian Ecosystems, Environmental Management, 37(1):141–152.

Pollino CA, Brown A, Parashar A, Barma D, Chen Y, Cuddy S, Mainuddin M, Merrin L, Podger G, Rahman J, Wallbrink P and Zheng, H (2016) Modelling for river basin planning: A demonstration in the Brahmani Basin, India: Synthesis report. Sustainable Development Investment Portfolio (SDIP) Project. CSIRO, Australia.

Pramanik N and Panda RK (2010) One dimensional hydrodynamic modelling of river flow using DEM extracted river cross-sections, Water Resources Management, 24:835-852.

Riahi K, Krey V, Rao S, Chirkov V, Fischer G, Kolp P, Kindermann G, Nakicenovic N and Rafai P (2011) RCP-8.5: exploring the consequence of high emission trajectories, Climatic Change, 10: 1007.

Schmid W, Pollino CA, Merrin L and Stratford D (2016) Groundwater trends in the Brahmani Baitarni Basin, India, CSIRO, Canberra.

Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V and Lamarque J-F (2011) The representative concentration pathways: an overview, Climatic change 109: 5-31.

Appendix A Baseline rainfall-runoff model flow calibration results

A.1 Tilga section

Results from the rainfall-runoff model validation and calibration are shown in Table 28. The flow duration curve shows a poor fit to low flows (Figure 20). This is not surprising given that that there are large uncertainties in flow observations in these low flow ranges. A quality rating has been applied to calibration results. On a daily basis the model calibration is considered to be fair, which on a monthly timestep the model calibration is considered good (Table 29).

Table 28 Results from the GR4J rainfall-runoff model (Tilga section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.74	0.50	0.52	0.89	0.72	-9.62	0.82	0.65	-1.28
Validation (daily)	0.79	0.62	0.75	0.81	0.66	-10.95	0.85	0.72	-1.25
Calibration (monthly)	0.89	0.76	0.40	0.94	0.84	-9.61	0.94	0.89	-1.37
Validation (monthly)	0.93	0.86	0.66	0.89	0.78	-10.75	0.97	0.93	-1.29
Whole period (daily)	0.77	0.57	0.64	0.85	0.70	-10.30	0.84	0.69	-1.26
Whole period (monthly)	0.91	0.82	0.54	0.92	0.82	-10.20	0.96	0.91	-1.33

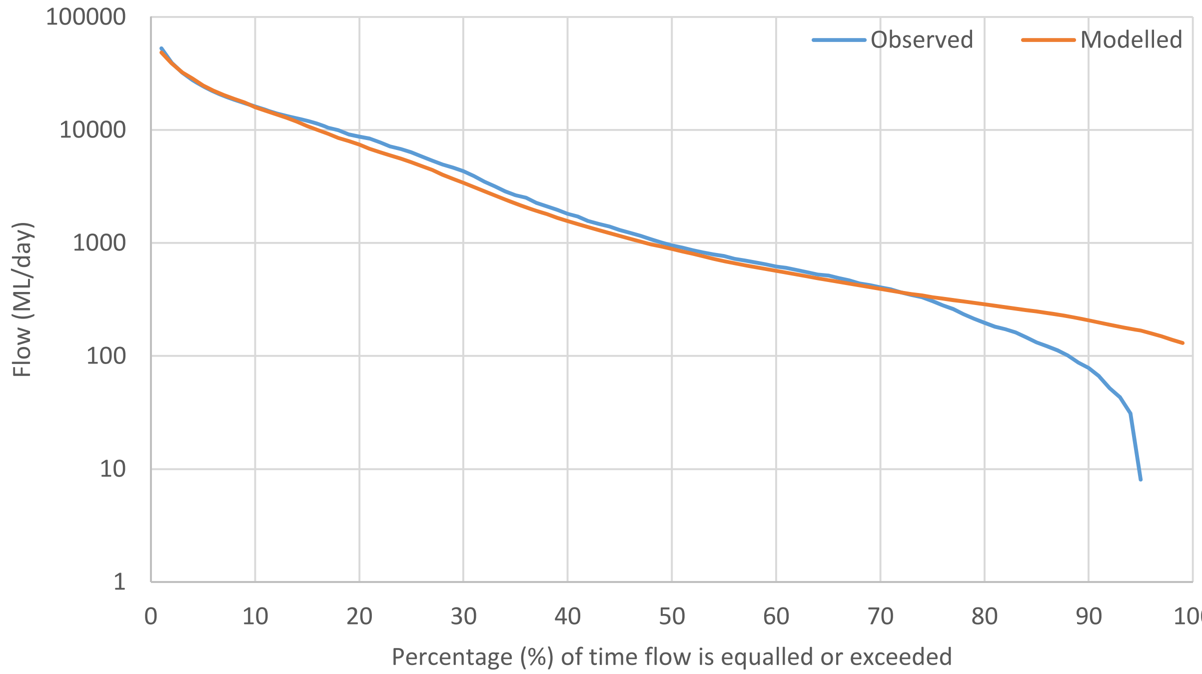

Figure 20 Rainfall-runoff: modelled (orange) and gauged (blue) flow duration curves (Tilga section)

Table 29 Assessment of rainfall-runoff model performance (Tilga section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Fair	Excellent	Fair	Average	Fair	Good
Validation (daily)	Fair	Excellent	Fair	Fair	Fair	Good
Calibration (monthly)	Fair	Excellent	Average	Average	Average	Good

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Validation (monthly)	Average	Excellent	Fair	Fair	Good	Good
Whole period (daily)	Fair	Excellent	Fair	Fair	Fair	Good
Whole period (monthly)	Average	Excellent	Average	Fair	Good	Good

A.2 Jaraikela section

Results from the Rainfall-runoff model validation and calibration are shown in Table 30. The flow duration curve shows a poor fit to low flows (Figure 21).

A quality rating has been applied to calibration results (Table 31). Given the large Volume bias and NSE values of less than 0.5 in both the calibration and validation period, the calibration of this section is considered poor. As this is a headwater catchment, the calibration has implication of the downstream gauges in the river system model. To improve the calibration in this section, a greater understanding of the operations of storages and water demands and use is needed.

On a daily basis the model calibration is considered to be fair, and on a monthly timestep the model calibration is considered average.

Table 30 Results from the GR4J rainfall-runoff model (Jaraikela section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.73	0.44	13.91	0.89	0.69	10.76	0.80	0.57	13.36
Validation (daily)	0.65	0.40	-20.32	0.78	0.48	-41.03	0.73	0.52	-23.75
Calibration (monthly)	0.86	0.55	13.91	0.97	0.82	10.58	0.93	0.77	13.33
Validation (monthly)	0.88	0.66	-20.41	0.94	0.68	-41.06	0.93	0.84	-23.82
Whole period (daily)	0.66	0.42	-5.31	0.79	0.60	-17.58	0.74	0.54	-7.39
Whole period (monthly)	0.84	0.63	-5.48	0.88	0.75	-17.71	0.91	0.82	-7.56

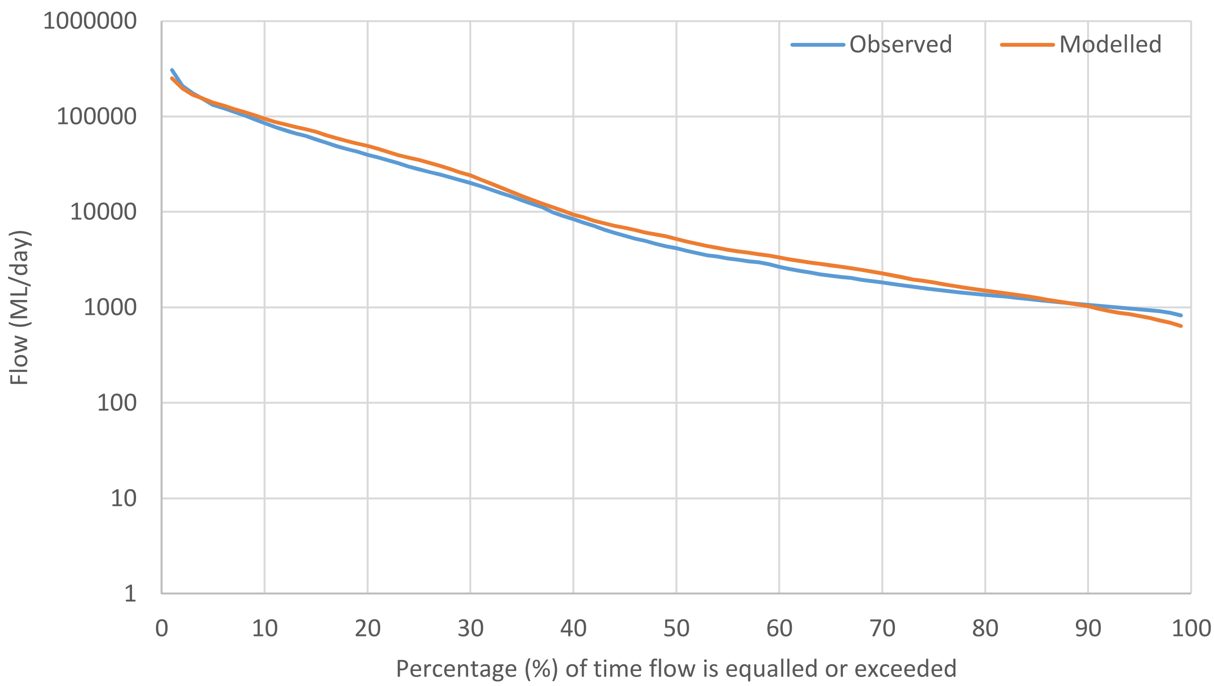

Figure 21 Rainfall-runoff: modelled (orange) and gauged (blue) flow duration curves (Jaraikela section)

Table 31 Assessment of rainfall-runoff model performance (Jaraikela section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Poor	Fair	Fair	Fair	Fair	Fair
Validation (daily)	Poor	Poor	Poor	Poor	Fair	Poor
Calibration (monthly)	Fair	Fair	Average	Fair	Fair	Fair
Validation (monthly)	Fair	Poor	Fair	Poor	Average	Poor
Whole period (daily)	Poor	Average	Fair	Fair	Fair	Average
Whole period (monthly)	Fair	Average	Fair	Fair	Average	Average

A.3 Panposh section

Results from the Rainfall-runoff model validation and calibration are shown in Table 32. The flow duration curve shows a good fit to low flows (Figure 22).

A quality rating has been applied to calibration results (Table 33). The calibration of this section is considered good.

Table 32 Results from the GR4J rainfall-runoff model (Panposh section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.89	0.79	1.79	0.93	0.84	10.33	0.92	0.84	3.07
Validation (daily)	0.83	0.68	5.95	0.87	0.76	5.26	0.88	0.77	5.82
Calibration (monthly)	0.96	0.93	1.69	0.98	0.96	10.39	0.98	0.96	2.99
Validation (monthly)	0.97	0.90	7.60	0.96	0.89	5.41	0.99	0.96	7.19
Whole period (daily)	0.88	0.77	2.95	0.91	0.83	8.69	0.91	0.82	3.86
Whole period (monthly)	0.96	0.92	3.29	0.98	0.95	8.77	0.98	0.96	4.16

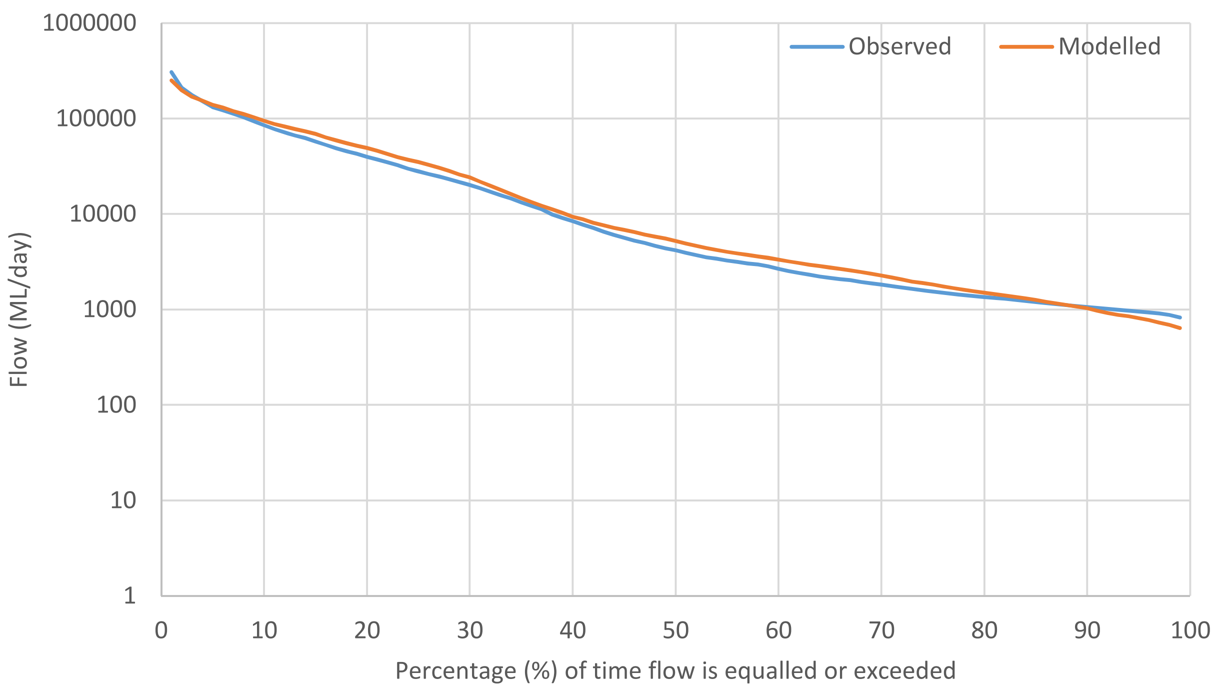

Figure 22 Rainfall-runoff: modelled (orange) and gauged (blue) flow duration curves (Panposh section)

Table 33 Assessment of rainfall-runoff model performance (Panposh section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Fair	Good	Average	Fair	Average	Good
Validation (daily)	Fair	Average	Fair	Average	Fair	Average
Calibration (monthly)	Good	Good	Excellent	Fair	Excellent	Good
Validation (monthly)	Good	Average	Average	Average	Excellent	Average
Whole period (daily)	Fair	Good	Average	Average	Average	Good
Whole period (monthly)	Good	Good	Good	Average	Excellent	Good

A.4 Golmai section

Results from the rainfall-runoff model validation and calibration are shown in Table 34. The flow duration curve shows an excellent reproduction of low flows (Figure 23).

A quality rating has been applied to calibration results (Table 35). Overall the rainfall-runoff modelling for this catchment is considered average on a daily basis and excellent on a monthly basis.

Table 34 Results from the GR4J rainfall-runoff model (Gomlai section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.94	0.88	-0.73	0.97	0.94	1.11	0.96	0.91	-0.46
Validation (daily)	0.93	0.87	2.18	0.93	0.87	5.23	0.93	0.87	2.18
Calibration (monthly)	0.99	0.98	3.09	0.99	0.98	1.15	0.99	0.97	-0.42
Validation (monthly)	0.99	0.98	2.15	0.99	0.98	5.21	0.99	0.98	2.15
Whole period (daily)	0.94	0.89	0.94	0.96	0.91	3.32	0.94	0.89	0.94
Whole period (monthly)	0.99	0.98	0.93	0.99	0.98	3.33	0.99	0.98	0.93

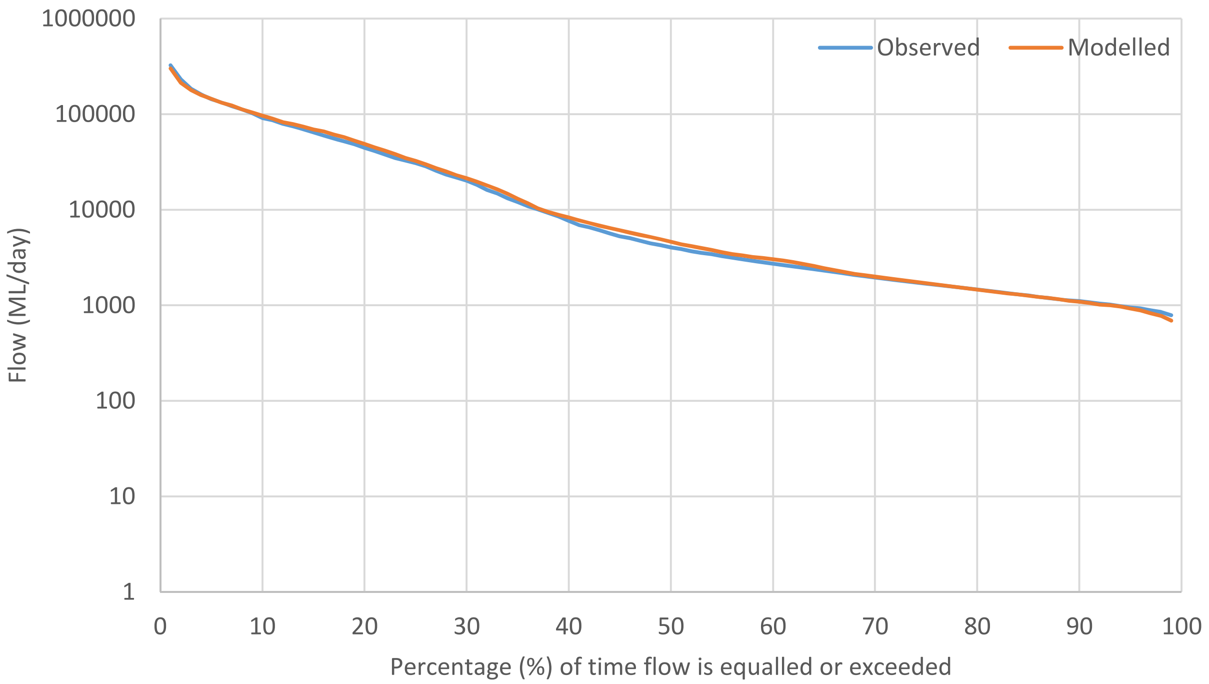

Figure 23 Rainfall-runoff: modelled (orange) and gauged (blue) flow duration curves (Gomlai section)

Table 35 Assessment of rainfall-runoff model performance (Gomlai section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Average	Excellent	Good	Good	Good	Excellent
Validation (daily)	Average	Good	Average	Average	Average	Good
Calibration (monthly)	Excellent	Good	Excellent	Good	Excellent	Excellent
Validation (monthly)	Excellent	Good	Excellent	Average	Excellent	Good
Whole period (daily)	Average	Excellent	Good	Good	Average	Excellent
Whole period (monthly)	Excellent	Excellent	Excellent	Good	Excellent	Excellent

A.5 Talcher section

Results for Rengali and Talcher are cover in this sub-section. The rainfall-runoff model has been calibrated to the inflows to Rengali. Downstream of Rengali the same rainfall-runoff parameters have been used for the area between Rengali to Jenapur. This was done due to there being limited observed streamflow data at Talcher to calibrate the model. Samal barrage is not included in the model as there was insufficient information provided to represent this structure.

Results from the rainfall-runoff model validation and calibration at Rengali are shown in Table 36 and low flow reproduction in Figure 24. A quality rating has been applied to calibration results (Table 37). Overall the rainfall-runoff modelling for this catchment is considered fair on a daily basis and excellent on a monthly basis.

Table 36 Results from the GR4J rainfall-runoff model (Rengali)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.82	0.63	-2.35	0.82	0.64	9.70	0.86	0.72	-0.83
Validation (daily)	0.79	0.58	-0.40	0.89	0.76	-1.13	0.85	0.71	-0.51
Calibration (monthly)	0.99	0.97	-2.08	0.99	0.98	9.03	0.99	0.98	-0.69
Validation (monthly)	0.99	0.99	-0.24	0.99	0.98	-1.23	1.00	0.99	-0.39
Whole period (daily)	0.81	0.61	-1.33	0.85	0.69	3.54	0.86	0.71	-0.66
Whole period (monthly)	0.99	0.98	-1.12	0.99	0.99	-0.53	0.99	0.99	-0.53

Table 37 Assessment of rainfall-runoff model performance (Rengali)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Fair	Good	Fair	Average	Fair	Excellent
Validation (daily)	Fair	Excellent	Fair	Good	Fair	Excellent
Calibration (monthly)	Excellent	Good	Excellent	Average	Excellent	Excellent
Validation (monthly)	Excellent	Excellent	Excellent	Good	Excellent	Excellent
Whole period (daily)	Fair	Good	Fair	Good	Fair	Excellent
Whole period (monthly)	Excellent	Good	Excellent	Excellent	Excellent	Excellent

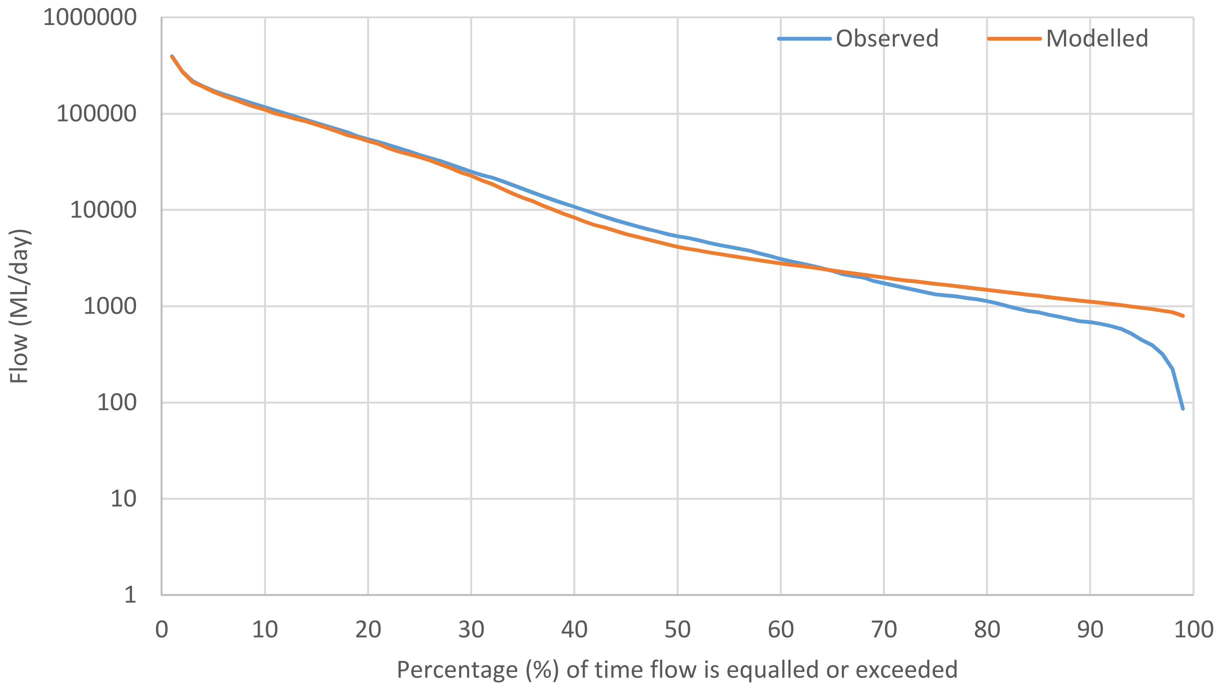

Figure 24 Rainfall-runoff: modelled (orange) and gauged (blue) flow duration curves (Rengali)

Observed outflows from the Rengali Dam were used to replace the flows at upstream gauges. No data were available in our selected calibration period, so the same parameters have been used as for the Jenapur residual section.

Results from the rainfall-runoff model validation and calibration at Talcher are shown in Table 38. The flow duration curve shows a reproduction of low flows (Figure 25).

A quality rating has been applied to calibration results (Table 39). Overall the rainfall-runoff modelling for this catchment is considered poor on a daily basis and poor on a monthly basis.

Table 38 Results from the GR4J rainfall-runoff model (Talcher section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Validation (daily)	0.76	0.48	-19.81	0.81	0.03	-59.31	0.81	0.55	-34.52
Calibration (monthly)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Validation (monthly)	0.83	0.61	-19.69	0.88	0.68	-34.62	0.88	0.68	-34.62
Whole period (daily)	0.76	0.48	-19.81	0.81	0.03	-59.31	0.81	0.55	-34.52
Whole period (monthly)	0.83	0.61	-19.69	0.88	0.68	-34.62	0.88	0.68	-34.62

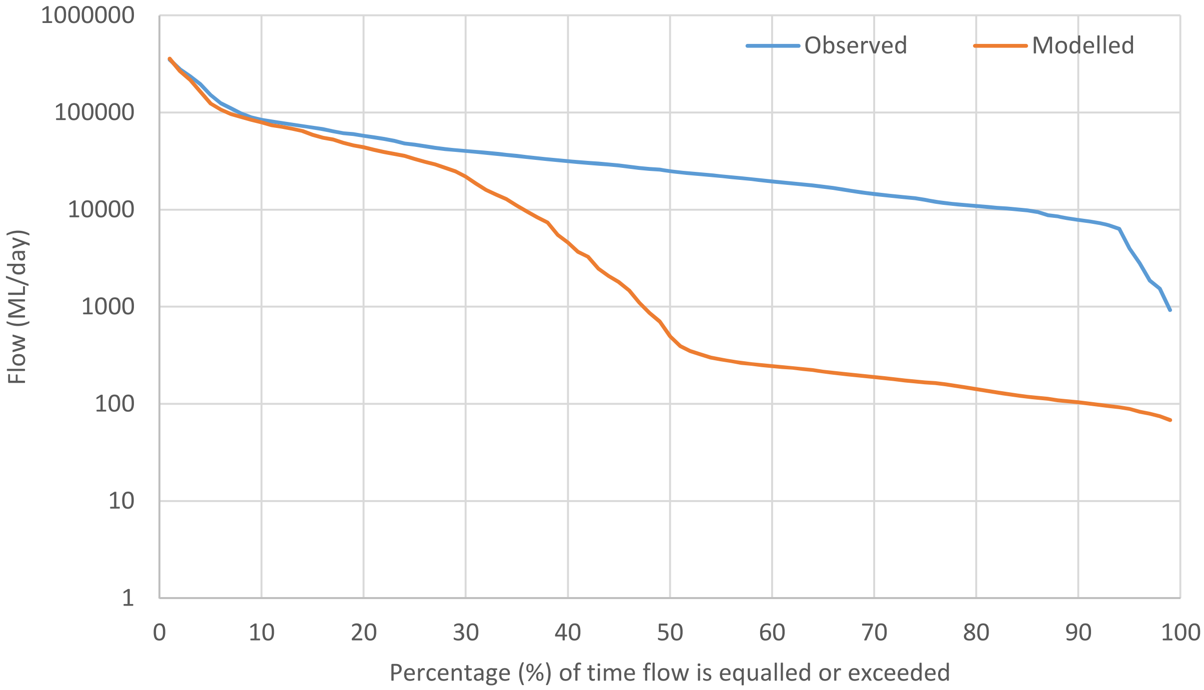

Figure 25 Rainfall-runoff: modelled (orange) and gauged (blue) flow duration curves (Talcher section)

Table 39 Assessment of rainfall-runoff model performance (Talcher section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	NA	NA	NA	NA	NA	NA
Validation (daily)	Poor	Fair	Poor	Poor	Fair	Poor
Calibration (monthly)	NA	NA	NA	NA	NA	NA
Validation (monthly)	Fair	Fair	Fair	Poor	Fair	Poor
Whole period (daily)	Poor	Fair	Poor	Poor	Fair	Poor
Whole period (monthly)	Fair	Fair	Fair	Poor	Fair	Poor

A.6 Jenapur section

Results from the Rainfall-runoff model validation and calibration at Jenapur are shown in Table 40. The flow duration curve shows a reproduction of low flows (Figure 26).

A quality rating has been applied to calibration results (Table 41). Observed flows were used to replace the flows at upstream gauge (Talcher) where available. Overall the rainfall-runoff model for this section is considered average on a fair basis and average on a monthly basis.

Table 40 Results from the GR4J rainfall-runoff model (Jenapur section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.88	0.69	-3.64	0.87	0.55	-38.52	0.90	0.74	-14.02
Validation (daily)	0.84	0.63	4.34	0.87	0.70	4.04	0.88	0.73	4.24
Calibration (monthly)	0.93	0.81	-3.56	0.95	0.59	-38.84	0.95	0.86	-14.06
Validation (monthly)	0.95	0.84	4.40	0.93	0.76	3.98	0.96	0.90	4.26
Whole period (daily)	0.86	0.67	0.40	0.87	0.63	-15.58	0.89	0.74	-4.59
Whole period (monthly)	0.94	0.83	0.47	0.93	0.68	-15.73	0.96	0.88	-4.60

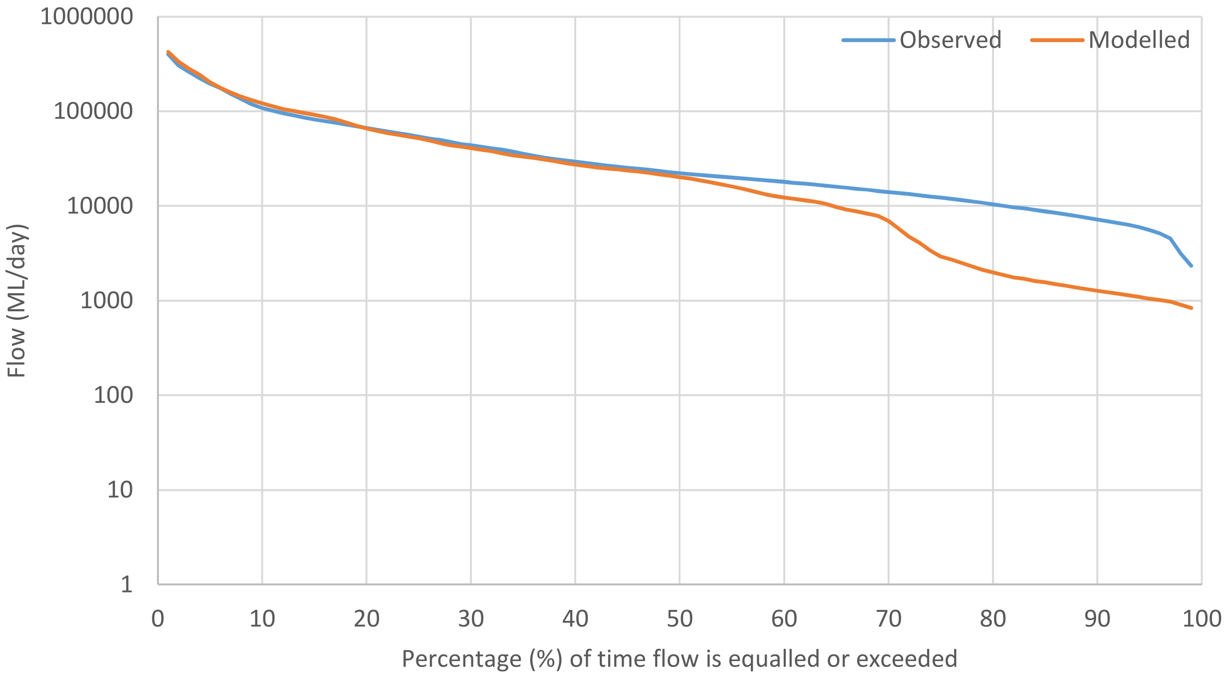

Figure 26 Rainfall-runoff: modelled (orange) and gauged (blue) flow duration curves (Jenapur section)

Table 41 Assessment of rainfall-runoff model performance (Jenapur section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Fair	Good	Fair	Poor	Fair	Fair
Validation (daily)	Fair	Good	Fair	Good	Fair	Good
Calibration (monthly)	Average	Good	Fair	Poor	Average	Fair
Validation (monthly)	Average	Good	Fair	Good	Average	Good
Whole period (daily)	Fair	Excellent	Fair	Fair	Fair	Good
Whole period (monthly)	Average	Excellent	Fair	Fair	Average	Good

Appendix B Baseline river system model flow calibration results

B.1 Tilga section

As Tilga is a headwater catchment, upstream flows were modelled using the observed data with gaps infilled with modelled data. Results from the baseline river system model validation and calibration are presented in Table 42 and Figure 27. On a daily basis the model calibration is considered to be fair, and on a monthly timestep the model calibration is considered good (Table 43).

Table 42 River system model statistics (Tilga section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.74	0.50	0.34	0.89	0.72	-11.17	0.82	0.65	-1.71
Validation (daily)	0.79	0.62	0.60	0.81	0.66	-12.32	0.85	0.72	-1.61
Calibration (monthly)	0.89	0.76	0.22	0.94	0.84	-11.17	0.94	0.88	-1.80
Validation (monthly)	0.93	0.86	0.51	0.89	0.78	-12.13	0.97	0.93	-1.65
Whole period (daily)	0.77	0.57	0.48	0.85	0.70	-11.76	0.84	0.69	-1.66
Whole period (monthly)	0.91	0.82	0.37	0.92	0.81	-11.67	0.96	0.91	-1.72

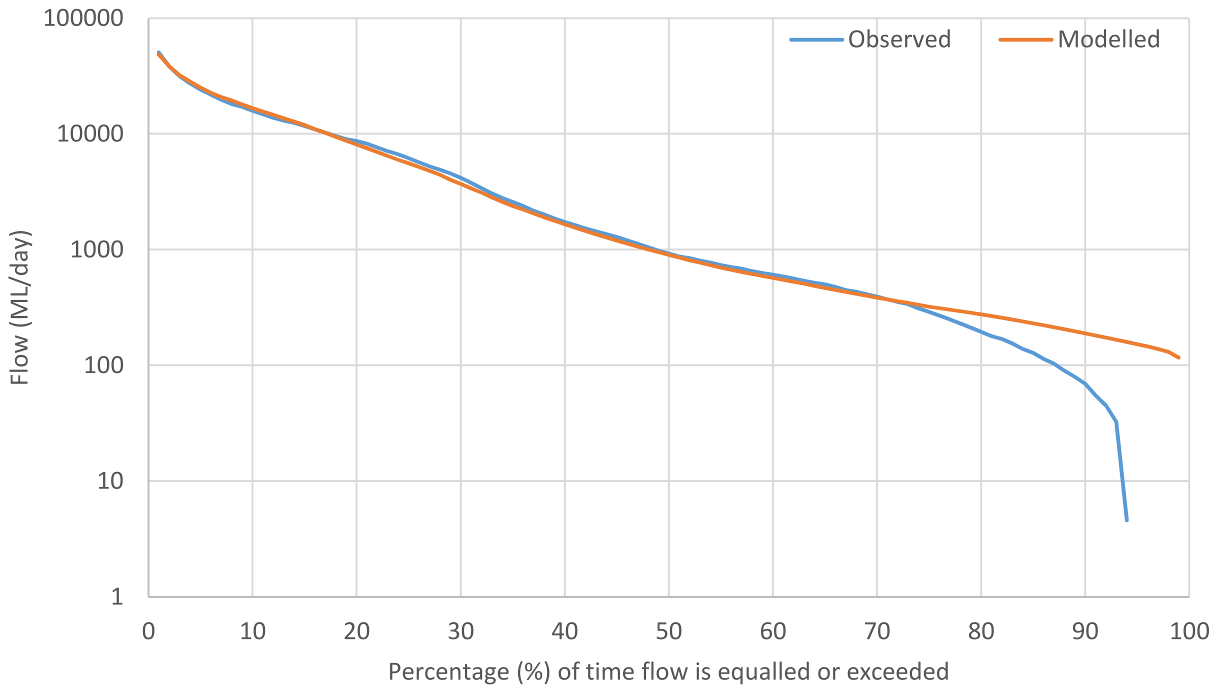

Figure 27 River system model: modelled (red) and gauged (blue) flow duration curves (Tilga section)

Table 43 Assessment of river system model performance (Tilga section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Fair	Excellent	Fair	Average	Fair	Good
Validation (daily)	Fair	Excellent	Fair	Fair	Fair	Good
Calibration (monthly)	Fair	Excellent	Average	Average	Average	Good
Validation (monthly)	Average	Excellent	Fair	Fair	Good	Good
Whole period (daily)	Fair	Excellent	Fair	Fair	Fair	Good
Whole period (monthly)	Average	Excellent	Average	Fair	Good	Good

B.2 Jaraikela section

As Jaraikela is a headwater catchment, upstream flows were modelled using the observed data. Results from the baseline river system model validation and calibration are presented in Table 44 and Figure 28.

Slight differences are seen in the Volume bias compared to rainfall-runoff model due to slight change in demands as a result of the time series being replaced by a crop model. On a daily basis the model calibration is considered to be fair, which on a monthly timestep the model calibration is considered average (Table 45).

Table 44 River system model statistics (Jaraikela section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.73	0.45	13.69	0.89	0.69	10.76	0.80	0.57	13.18
Validation (daily)	0.65	0.40	-20.49	0.78	0.48	-41.02	0.73	0.52	-23.89
Calibration (monthly)	0.86	0.55	13.70	0.97	0.82	10.57	0.93	0.77	13.15
Validation (monthly)	0.88	0.66	-20.58	0.94	0.68	-41.06	0.93	0.84	-23.96
Whole period (daily)	0.66	0.42	-5.51	0.79	0.60	-17.58	0.74	0.54	-7.55
Whole period (monthly)	0.84	0.63	-5.67	0.88	0.75	-17.71	0.91	0.82	-7.71

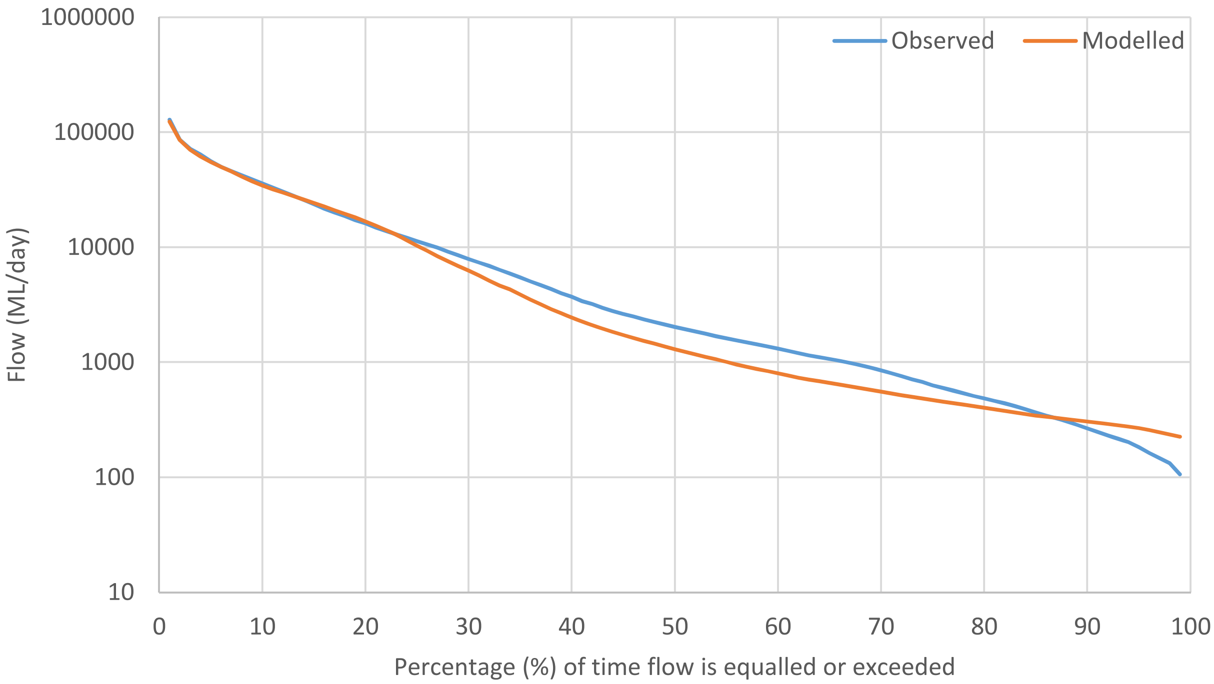

Figure 28 River system model: modelled (red) and gauged (blue) flow duration curves (Jaraikela section)

Table 45 Assessment of river system model performance (Jarakiela section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Poor	Fair	Fair	Fair	Fair	Fair
Validation (daily)	Poor	Poor	Poor	Poor	Fair	Poor
Calibration (monthly)	Fair	Fair	Average	Fair	Fair	Fair
Validation (monthly)	Fair	Poor	Fair	Poor	Average	Poor
Whole period (daily)	Poor	Average	Fair	Fair	Fair	Average
Whole period (monthly)	Fair	Average	Fair	Fair	Average	Average

B.3 Panposh section

Results from the baseline river system model validation and calibration are presented in Table 46 and Figure 29. As can be seen flow reproduction is excellent across all flows.

The inflows to this section from Tilga and Jaraikela are based on modelled data. Consequently, errors in the upstream catchment propagate into this. Overall the river system flow modelling for this catchment is considered fair on a daily basis and good on a monthly basis (Table 47).

Table 46 River system model statistics (Panposh section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.83	0.69	6.95	0.87	0.76	9.75	0.87	0.76	7.37
Validation (daily)	0.82	0.64	-7.60	0.77	0.51	-30.79	0.86	0.72	-11.76
Calibration (monthly)	0.94	0.86	6.79	0.98	0.95	9.71	0.97	0.93	7.23
Validation (monthly)	0.96	0.92	-6.09	0.94	0.76	-30.59	0.98	0.96	-10.65
Whole period (daily)	0.83	0.68	2.89	0.84	0.71	-3.37	0.87	0.75	1.90
Whole period (monthly)	0.94	0.88	3.31	0.95	0.91	-3.36	0.97	0.93	2.24

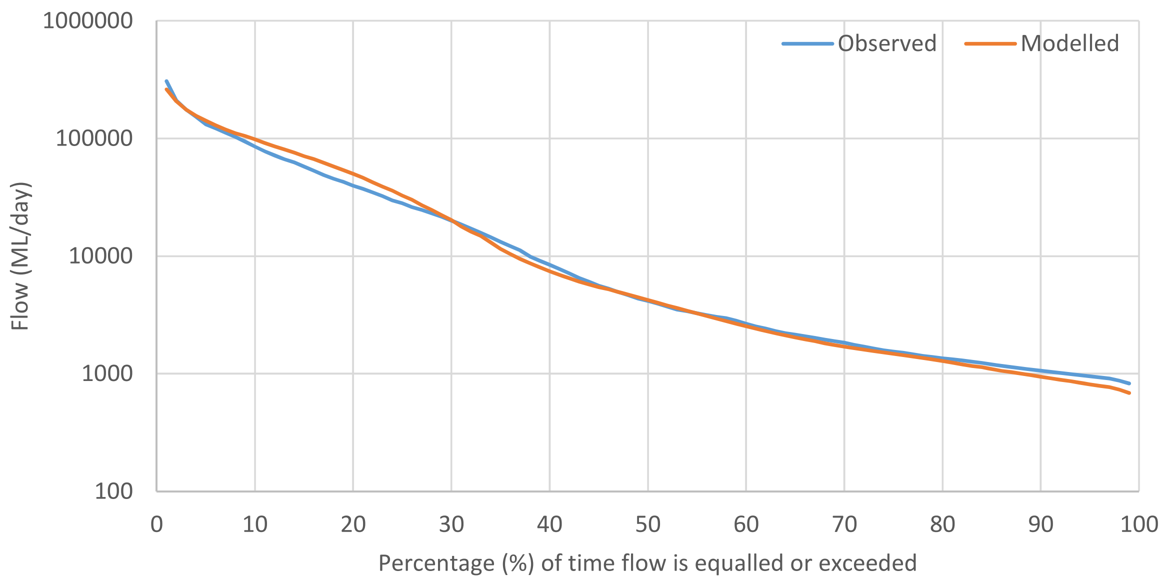

Figure 29 River system model: modelled (red) and gauged (blue) flow duration curves (Panposh section)

Table 47 Assessment of river system model performance (Panposh section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Fair	Excellent	Fair	Average	Fair	Average
Validation (daily)	Fair	Average	Fair	Poor	Fair	Fair
Calibration (monthly)	Average	Average	Good	Average	Good	Average
Validation (monthly)	Good	Average	Fair	Poor	Excellent	Fair
Whole period (daily)	Fair	Good	Fair	Good	Fair	Good
Whole period (monthly)	Average	Good	Good	Good	Good	Good

B.4 Golmai section

Results from the baseline river system model validation and calibration are presented in Table 48 and Figure 30. As can be seen flow reproduction is excellent across all flows. River system model results are impacted by the upstream gauge, which is evident in the changes in the Volume bias, particularly in the non-monsoon period. Overall the river system model for this catchment is considered fair on a daily basis and good on a monthly basis (Table 49).

Table 48 River system model statistics (Gomlai section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.85	0.72	5.98	0.90	0.81	10.79	0.89	0.79	6.68
Validation (daily)	0.84	0.69	-4.88	0.85	0.70	-16.85	0.89	0.78	-6.70
Calibration (monthly)	0.93	0.85	5.86	0.96	0.93	10.79	0.96	0.92	6.59
Validation (monthly)	0.96	0.91	-5.01	0.97	0.91	-16.80	0.98	0.96	-6.80
Whole period (daily)	0.84	0.71	0.26	0.88	0.77	-4.01	0.89	0.78	-0.38
Whole period (monthly)	0.94	0.87	0.14	0.96	0.92	-4.00	0.97	0.94	-0.48

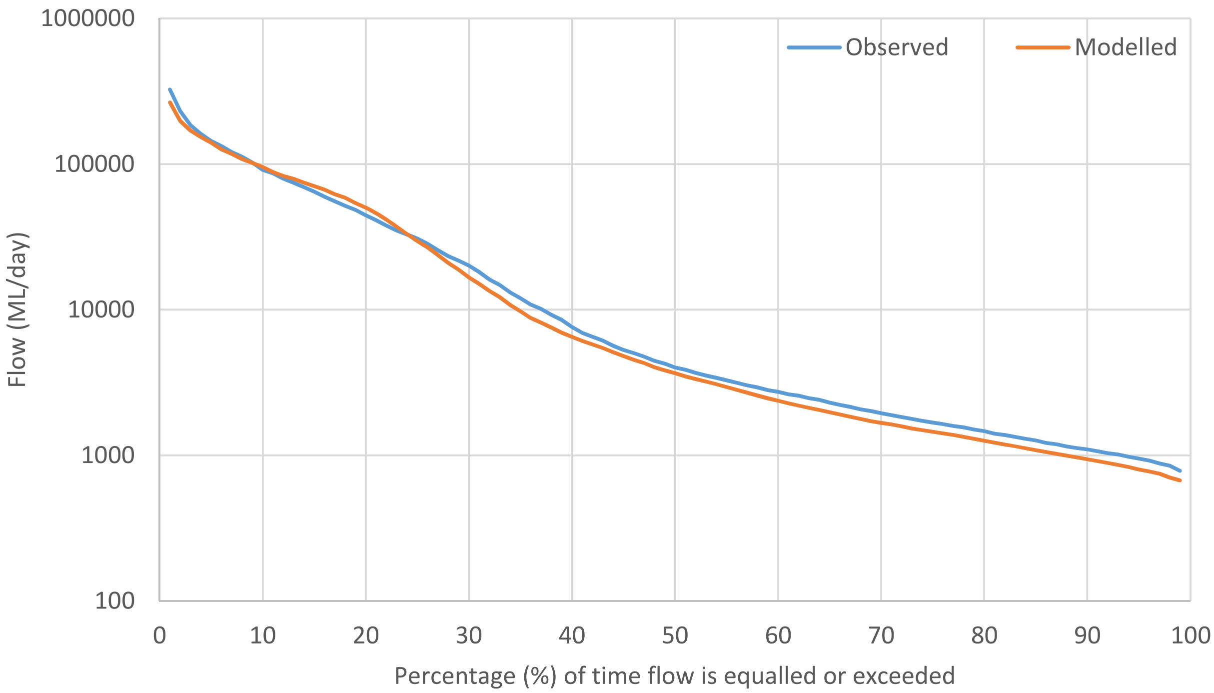

Figure 30 River system model: modelled (red) and gauged (blue) flow duration curves (Gomlai section)

Table 49 Assessment of River System model performance (Gomlai section)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE		NSE	Volume bias (%)
Calibration (daily)	Fair	Average	Average	Fair	Fair	Average
Validation (daily)	Fair	Good	Fair	Fair	Fair	Average
Calibration (monthly)	Average	Average	Good	Fair	Good	Average
Validation (monthly)	Good	Average	Good	Fair	Excellent	Average
Whole period (daily)	Fair	Excellent	Fair	Good	Fair	Excellent
Whole period (monthly)	Average	Excellent	Good	Good	Good	Excellent

B.5 Talcher section inflows to Rengali

Results from the baseline river system model validation and calibration are presented in Table 50 and Figure 31. Overall the river system model for this section is considered average on a daily basis and excellent on a monthly basis (Table 51).

Table 50 River system model statistics (Rengali)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.87	0.76	2.30	0.92	0.85	25.48	0.91	0.83	5.23
Validation (daily)	0.84	0.70	-5.03	0.86	0.74	-13.30	0.89	0.79	-6.26
Calibration (monthly)	0.96	0.93	2.22	0.98	0.95	25.60	0.98	0.96	5.16
Validation (monthly)	0.97	0.92	-5.15	0.97	0.94	-13.36	0.98	0.97	-6.37
Whole period (daily)	0.86	0.73	-1.52	0.89	0.80	3.42	0.90	0.81	-0.84
Whole period (monthly)	0.96	0.93	-1.62	0.97	0.94	3.39	0.98	0.96	-0.93

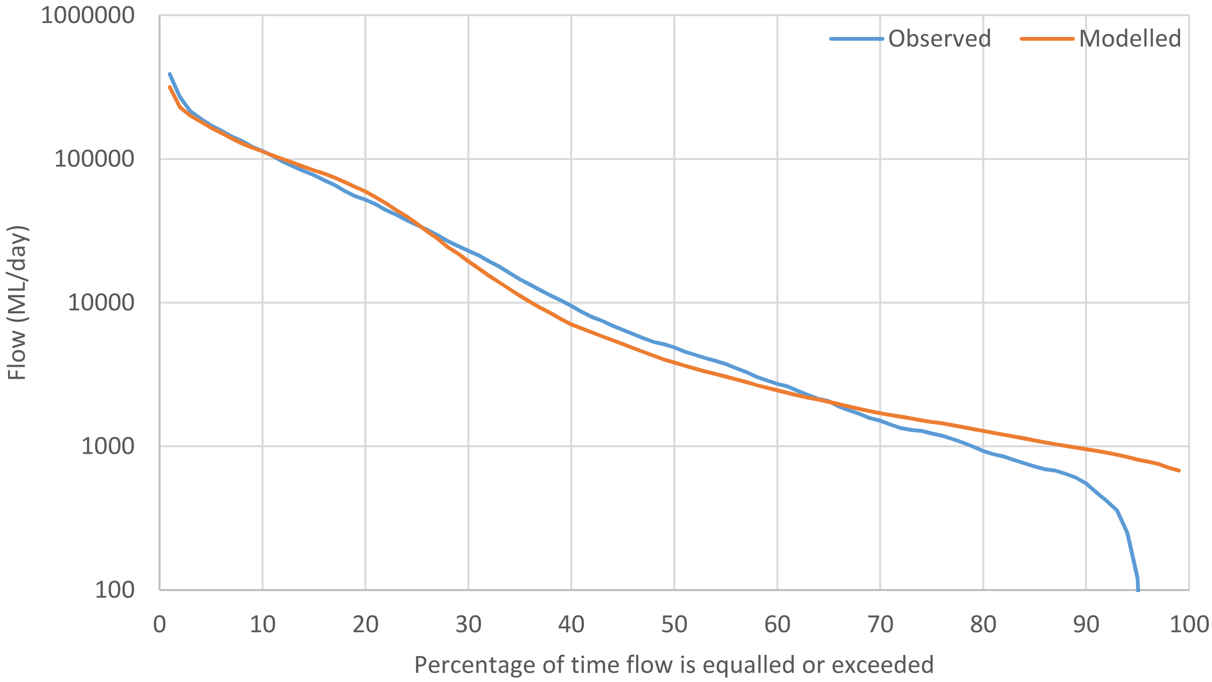

Figure 31 River system model: modelled (red) and gauged (blue) flow duration curves (Rengali)

Table 51 Assessment of river system model performance (Rengali)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE		NSE	Volume bias (%)
Calibration (daily)	Fair	Good	Average	Poor	Average	Average
Validation (daily)	Fair	Average	Fair	Fair	Fair	Average
Calibration (monthly)	Good	Good	Good	Poor	Excellent	Average
Validation (monthly)	Good	Average	Good	Fair	Excellent	Average
Whole period (daily)	Fair	Good	Fair	Good	Average	Excellent
Whole period (monthly)	Good	Good	Good	Good	Excellent	Excellent

B.6 Talcher section

Results from the baseline river system model validation and calibration are presented in Table 52 and Figure 32. The key difference between the model set up between the rainfall-runoff model and the river system model in this section is that the Rengali Dam has been included in the river system model along with the demand for irrigation being simulated by crop models. The irrigation demands from downstream control the operation of the storage (as opposed to observed releases in the rainfall-runoff model).

Overall the river system model for this catchment is considered average on a daily basis and fair on a monthly basis (Table 53).

Table 52 River system model statistics (Talcher section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Validation (daily)	0.75	0.47	12.45	0.72	0.38	-27.98	0.80	0.58	-2.61
Calibration (monthly)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Validation (monthly)	0.91	0.70	15.82	0.74	0.33	-22.55	0.94	0.81	-2.67
Whole period (daily)	0.75	0.47	12.45	0.72	0.38	-27.98	0.80	0.58	-2.61
Whole period (monthly)	0.91	0.70	15.82	0.74	0.33	-22.55	0.94	0.81	-2.67

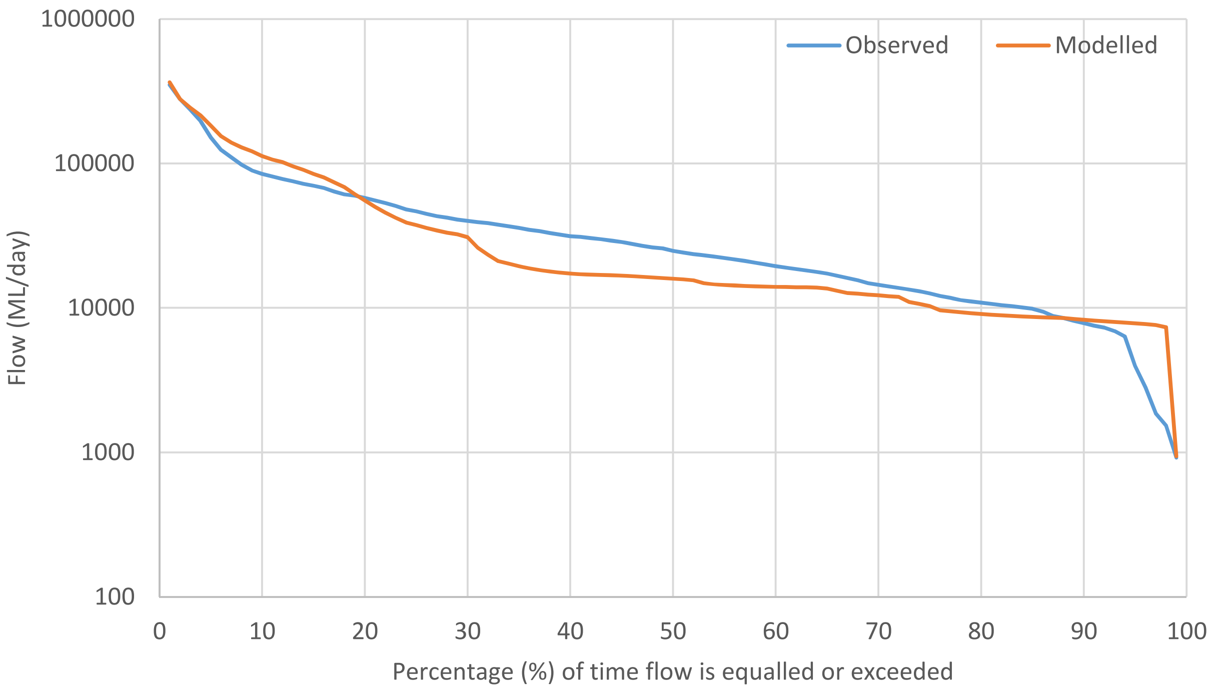

Figure 32 River system model: modelled (red) and gauged (blue) flow duration curves (Talcher)

Table 53 Assessment of river system model performance (Talcher)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE		NSE	Volume bias (%)
Calibration (daily)	NA	NA	NA	NA	NA	NA
Validation (daily)	Poor	Fair	Poor	Poor	Fair	Good
Calibration (monthly)	NA	NA	NA	NA	NA	NA
Validation (monthly)	Fair	Fair	Poor	Poor	Average	Good
Whole period (daily)	Poor	Fair	Poor	Poor	Fair	Good
Whole period (monthly)	Fair	Fair	Poor	Poor	Average	Good

B.7 Jenapur section

Results from the baseline river system model validation and calibration are presented in Table 54 and Figure 33. Modelled upstream flows have been used as inputs to this section. The river system model performance is fair on both a daily and monthly time step for this gauge (Table 55).

Table 54 River system model statistics (Jenapur section)

Period	Monsoon			Non-monsoon			Overall		
	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)	R	NSE	Volume bias (%)
Calibration (daily)	0.82	0.53	22.66	0.84	0.63	8.31	0.86	0.63	18.39
Validation (daily)	0.78	0.46	18.97	0.85	0.69	-8.74	0.85	0.61	9.94
Calibration (monthly)	0.91	0.64	22.69	0.91	0.72	8.24	0.94	0.77	18.38
Validation (monthly)	0.94	0.64	19.03	0.90	0.75	-8.95	0.96	0.80	9.89
Whole period (daily)	0.81	0.50	20.79	0.84	0.67	-0.88	0.85	0.62	14.02
Whole period (monthly)	0.92	0.64	20.84	0.90	0.74	-1.04	0.95	0.78	14.00

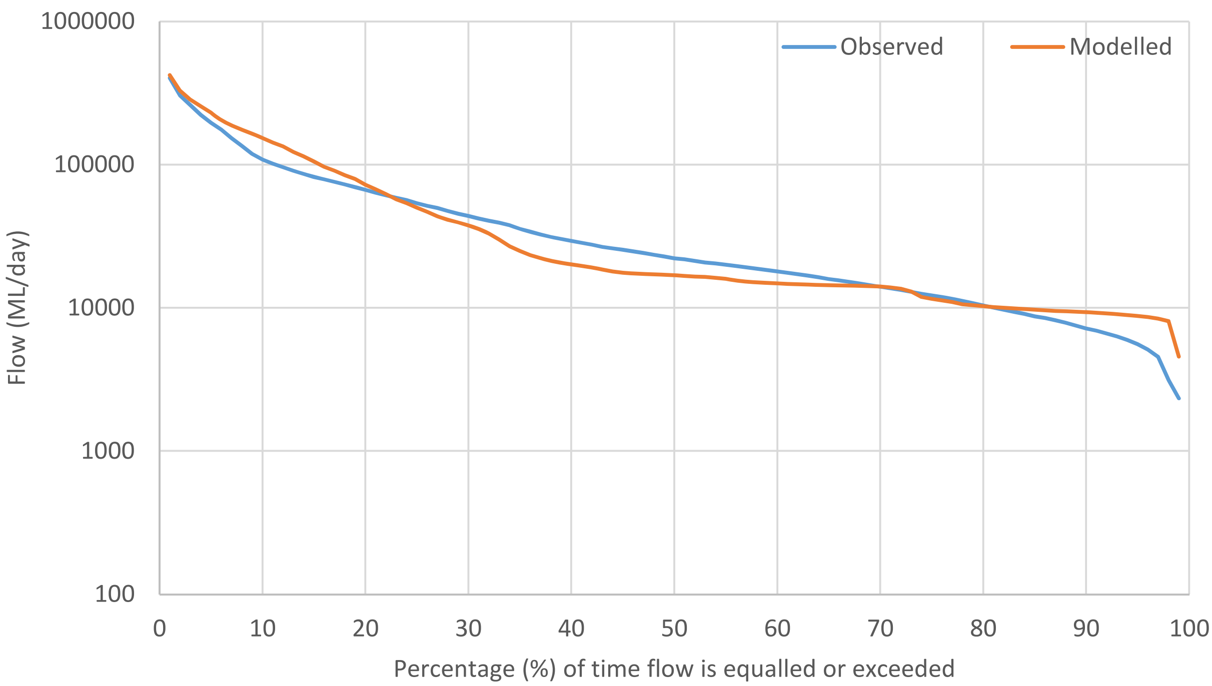

Figure 33 River system model: modelled (red) and gauged (blue) flow duration curves (Jenapur)

Table 55 Assessment of river system model performance (Jenapur)

	Monsoon		Non-monsoon		Overall	
	NSE	Volume bias (%)	NSE	Volume bias (%)	NSE	Volume bias (%)
Calibration (daily)	Fair	Poor	Fair	Average	Fair	Fair
Validation (daily)	Poor	Fair	Fair	Average	Fair	Average
Calibration (monthly)	Fair	Poor	Fair	Average	Fair	Fair
Validation (monthly)	Fair	Fair	Fair	Average	Fair	Average
Whole period (daily)	Fair	Poor	Fair	Excellent	Fair	Fair
Whole period (monthly)	Fair	Poor	Fair	Good	Fair	Fair

Appendix C Scenarios and input sets

Scenarios have been created using base sets with modifiers for supply efficiency, extent of crop areas, crop pattern/mixes, and climate change. The order of calling the base sets is critical and is set out in Table 56.

Table 56 Mapping of Source input sets to scenarios

ID	
Baseline	"Baseline Crop Area and Efficiency"
WOD	"Baseline Crop Area and Efficiency", then "Without_Development"
S1	"Baseline Crop Area and Efficiency" then "Crop Mix at Command Area"
S1-80	"Baseline Crop Area and Efficiency" then "Crop Mix at Command Area" then "Supply Escape Efficiency 20%"
S1-80-DT	"Baseline Crop Area and Efficiency" then "Crop Mix All Double_Trip at Command Area" then "Supply Escape Efficiency 20%"
S2	"Baseline Crop Area and Efficiency" then "New Dams and Command Areas and Hydropower"
S2-80	"Baseline Crop Area and Efficiency" then "New Dams and Command Areas and Hydropower" then "Supply Escape Efficiency 20%"
S2-80-OR	"Baseline Crop Area and Efficiency" then "New Dams and Command Areas and Hydropower" then "Supply Escape Efficiency 20%" then "Flood Operation All Dams"
S2-80-OR-E	"Baseline Crop Area and Efficiency" then "New Dams and Command Areas and Hydropower" then "Supply Escape Efficiency 20%" then "Flood Operation All Dams" then "Environmental FLows Releases On New Dams"
S3-80-DT	"Baseline Crop Area and Efficiency" then "Crop Mix All Double_Trip at Command Area" then "New Dams and Command Areas and Hydropower" then "Supply Escape Efficiency 20%"
S3-80-DT-OR	"Baseline Crop Area and Efficiency" then "Crop Mix All Double_Trip at Command Area" then "New Dams and Command Areas and Hydropower" then "Supply Escape Efficiency 20%" then "Flood Operation All Dams"
S3-80-DT-OR-E	"Baseline Crop Area and Efficiency" then "Crop Mix All Double_Trip at Command Area" then "New Dams and Command Areas and Hydropower" then "Supply Escape Efficiency 20%" then "Flood Operation All Dams" then "Environmental Flows Releases On New Dams"

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