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Government of India

Ministry of Water Resources, River Development and Ganga Rejuvenation

National Water Mission

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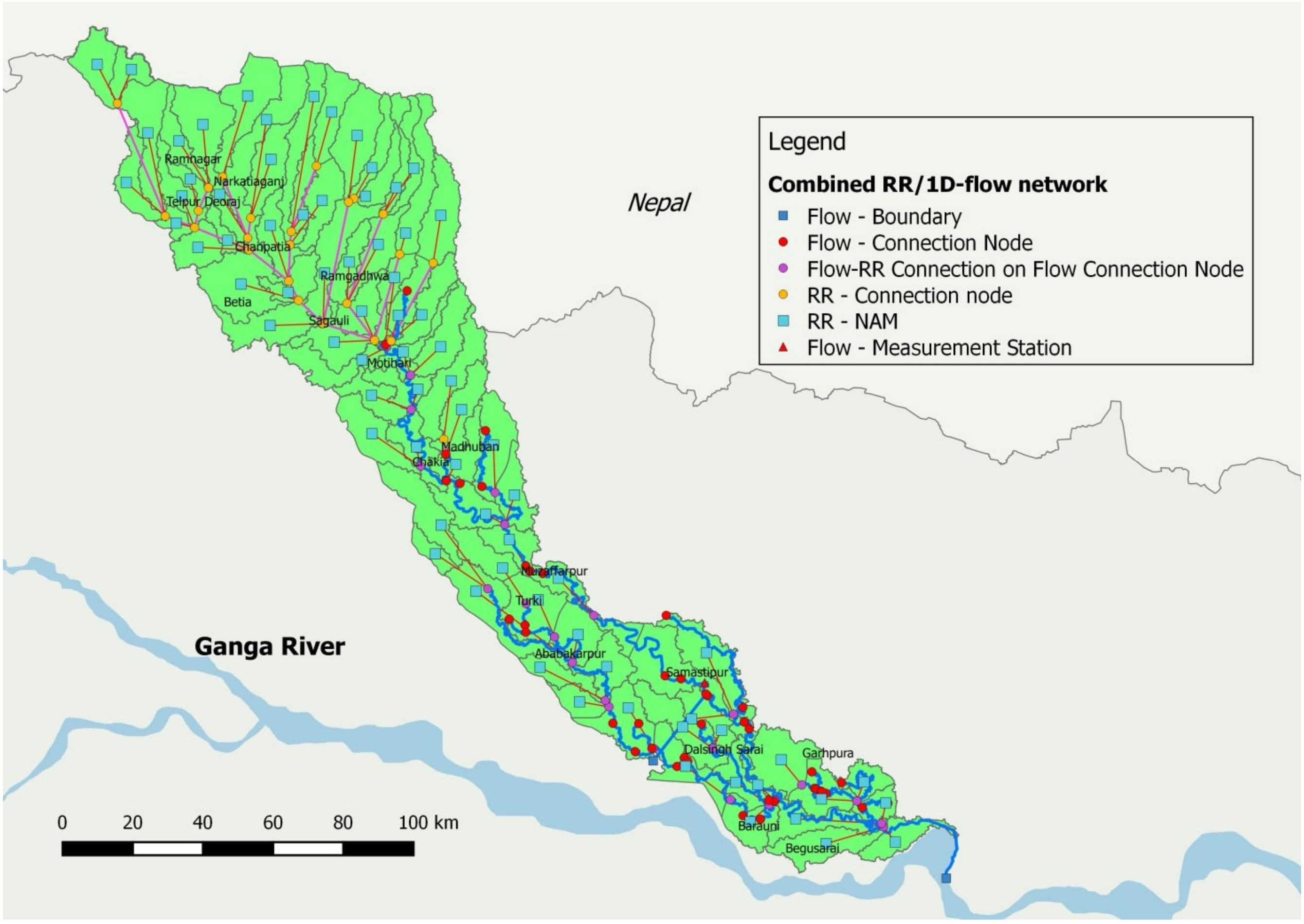
ADB

Policy and Advisory Technical Assistance 8089 IND Phase II

Operational Research to Support Mainstreaming of Integrated Flood Management under Climate Change



Volume 5a Modelling Report Burhi-Gandak, Bihar

Final

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Deltares in association with RMSI and JPS

RMSI

Deltares
Enabling Delta Life

Cover: SOBEK schematisation Burhi-Gandak River

CONTENTS

Abbreviations

1D	1 Dimensional
2D	2 Dimensional
ADB	Asian Development Bank
ARF	Areal Reduction Factor
BG	Burhi-Gandak River basin in Bihar
CC	Climate Change
CORINE	Coordination of Information on the Environment (EU programme)
CWC	Central Water Commission
DC	Delta Change (method)
DEM	Digital Elevation Model
DFID	Department for International Development
ESRI	Environmental Systems Research Institute
FMIS	Flood Management Information System
GCM	Global Climate Model
GFCC	Ganga Flood Control Commission
GHG	Greenhouse Gas
GIS	Geographic Information System
GoB	Government of Bihar
GoF	Goodness of Fit
GoI	Government of India
HFL	High Flood Level
IFM	Integrated Flood Management
IFRM	Integrated Flood Risk Management
IMD	India Meteorological Department
IWRM	Integrated Water resources Management
LBG	Lalbegiaghat
MoWR, RD&GR	Ministry of Water Resources, River Development and Ganga Rejuvenation
NAM	Nedbor Afstromnings Model
NDMA	National Disaster Management Authority
NGO	Non- Government Organisation
NRSC	National Remote Sensing Centre
NSE	Nash-Sutcliffe Efficiency
OSM	Open Street Map
PATA	Policy Advisory Technical Assistance
PMF	Probable Maximum Flood
RBO	River Basin Organisation
RCP	Representative Concentration Pathway
RP	Return Period
RR	Rainfall Runoff
Rs	Rupees
SLR	Sea Level Rise
SRTM	Shuttle Radar Topography Mission
TA	Technical Assistance
WL	Water level
WMO	World Meteorological Organisation
WRD	Water Resources Department

Units

MWh	Mega Watt hour – unit of Energy
m	Metre – unit of Length
cm	Centimetre – unit of Length
mm	Millimetre – unit of Length
Cumec	Cubic meters per second – unit of Flow
km	Kilometre – unit of Length
Sq.Km	Square Kilometres – unit of Area

Chapter 1 Introduction

1.1 Flood Risk Modelling and Mapping

This report describes the implementation of the hydrodynamic model for the Burhi-Gandak basin that constitutes the principal activity of Component I 'Flood Risk Modeling and Mapping. The report describes principal architectural choices which were made during the design phase of the model, including their technical justification. The report describes in detail how particular hydraulic situations have been represented in the model, and how the model was tailored to meet specific requirements of the study. The report also includes a technical description of the SOBEK 1D model and the NAM hydrological model.

1.2 The role of the consortium

The implementation of the hydrodynamic simulation model constitutes a fundamental component of the 'Operational Research to Support Mainstreaming of Integrated Flood Management under Climate Change'-project which is part of the Policy and Advisory Technical Assistance (TA8089 IND). The model is the core simulation tool to be used for carrying out scenario simulations, to operate a decision support system to address water resources management questions of the lower Burhi-Gandak basin, and to develop potential basin plans.

The setup of the combined hydrological/hydro-dynamical/1D-flow/2D-overland simulation model, the preparation, the running and analysis of the model simulations has been carried out by the modeling team which consisted of:

- Mr. Manoj Kumar, modeler, Central Water Commission (CWC), Delhi, India;
- Mr. Vasanthakumar Venkatesan, modeler, Central Water Commission (CWC), Delhi, India;
- Mr. Ruben Dahm, hydrology and flood modeling advisor, Deltares, Delft, The Netherlands; and,
- Mr. Chris Sprengers, flood modeling advisor, Deltares, Delft, The Netherlands.

Preparation and processing of GIS-data was done by:

- Mr. Ujjwal Sur, Remote sensing and GIS advisor, RMSI, Noida, India; and,
- Mr. Rupesh Kumar Sinha, Remote sensing and GIS advisor, RMSI, Noida, India.

Preparation and processing of Climate Change-data was done by:

- Dr. Uttam Singh, Agronomist, RMSI, Noida, India.

The team members were inspired and supported by:

- Dr. Marcel Marchand, Team leader, Deltares, Delft, The Netherlands; and,
- Mr. S. Sethurathinam, Deputy Team leader, Private Consultant, Delhi, India.

1.3 The purpose of probabilistic analysis

For a quantitative flood risk and hazard assessment, probabilities of flood extents in the project area are required. Ideally, these probabilities are derived directly from available observations. However this is generally not possible because:

a) the record of observation is too short to have a witnessed all potential flood events; and

b) records are only available for a limited number of locations in the project area.

The best alternative is to execute a probabilistic analysis in which potential flood events are identified and probabilities and hazards of these events are quantified. Due to the limited resources it was not possible to carry out a proper probabilistic analysis within the scope of the current project.

1.4 Outline

This report describes the several aspects of Component I: Flood Risk Modelling and Mapping.

Chapter 2 describes the Burhi-Gandak basin in Bihar. The topographical data is described in chapter 3. In chapter 4 the setup, calibration and validation of the hydrological models for the basin are described.

Chapter 5 discusses the setup of the hydrodynamic SOBEK model. Besides a 1D-open channel flow component, this model also comprises a reservoir control model of the Rengali dam and an 2D-overland flow component to enable flood calculations and flood risk mapping. The chapter also discussed the calibration and validation of the model. In chapter 6 the forcing statistics and the boundary conditions are described for the 2040 and 2080 future situations.

Chapter 7 discusses the framework of analysis together with the simulation results.

The main conclusions and recommendations are reported in Chapter 8.

Chapter 2 Basin description: Burhi-Gandak

2.1 Burhi-Gandak river basin

The Burhi-Gandak river flows from its upper Nepal catchment through an almost entirely embanked river channel towards it confluence with the Ganga River (Figure 2.1). The river is thus characterized by slope changes and high sediment load ("silt") causing meandering and instability but generally do not appear to possess flash flood characteristics. The floodplain is cultivated between the flood embankments. There is a ribbon of settlements all along the outside of the embankments on both sides of the river (Phase 1 Final Report).

The River originates in the Someshwar range of hills at 300 m above mean sea level near Bishambharpur in the West Champaran district in Bihar (Figure 2.2). The main River course lies entirely in Bihar in Indian Territory. However, some left bank tributaries of the Sub-basin flow through Nepalese Territory. The total catchment of the Sub-basin is 12,500 km^2, out of which 2,350 km^2 lies in Nepal. The Sub-basin is surrounded in the North by the Bagmathi River system, on the Western side by the Gandak-Ganga River system, on the Southern side by the Ganga River and on the Eastern side by the Bagmathi-Kosi River system. The total length of the main river system is 320 km. The important right bank tributaries are Kunhra, Dhanauti and None Blan; and such important left bank tributaries are Masan, Belor, Pandai, Sikta, Uria, Tilawe and Teur. The River Burhi-Gandak outfalls in to Ganga near Khagharia Railway station (GFCC, 1992).

The upper portion of the catchment in Nepal and in the West Champaran district is hilly and associated with fairly dense forest. The rest of the catchment is highly fertile alluvial plain. The agriculture area is 754 thousand hectares (as per base year 1992-GFCC), and is predominantly being used for paddy, wheat and maize. More details can be found in Chapter 7.

The area is well connected by rail and road ways. Also, good communication network exists. There are no major industries in the Sub-basin. There is a small aerodrome in Muzaffarpur in the Sub-basin in India.

Figure 2.1 Map of the Burhi-Gandak basin (Indian part)
(Source: Deltares&RMSI)

Table 2.1 Characteristics of the Burhi-Gandak river

Sl.No.	Item	Quantity (FMIS, Binar)
1	Total Drainage Area	12021 Sq.Km
2	Drainage Area in Bihar	9601 Sq.Km
3	Population in Bihar	83.01 Lakh
4	Water resources	4040 MCM
5	Average annual rainfall	1283 mm
6	Total length of main river	320 Km
7	Cropped area in Bihar	7600 Sq.Km

Source: FMIS, Bihar.

The Burhi-Gandak is a so-called “plains-fed” river, which has different morphological, hydrological and sediment transport characteristics compared to other rivers in Northern Bihar, such as the Kosi and Gandak (“mountain-fed”) and Baghmati (“foothills-fed”). It implies that the ratio between upland and plains is almost zero, i.e. hardly any catchment area above the so called mountain front. The Burhi-Gandak is a typical single-channel river with a high sinuosity (meandering) (Sinha & Jain, 1998). The meandering pattern is more pronounced in the lower reaches. Gradual building of point bars on the inner side of a bend and consequent lateral erosion of concave embankments is a common feature of the river. There are several erosion points spread over the reach downstream of Muzaffarpur.

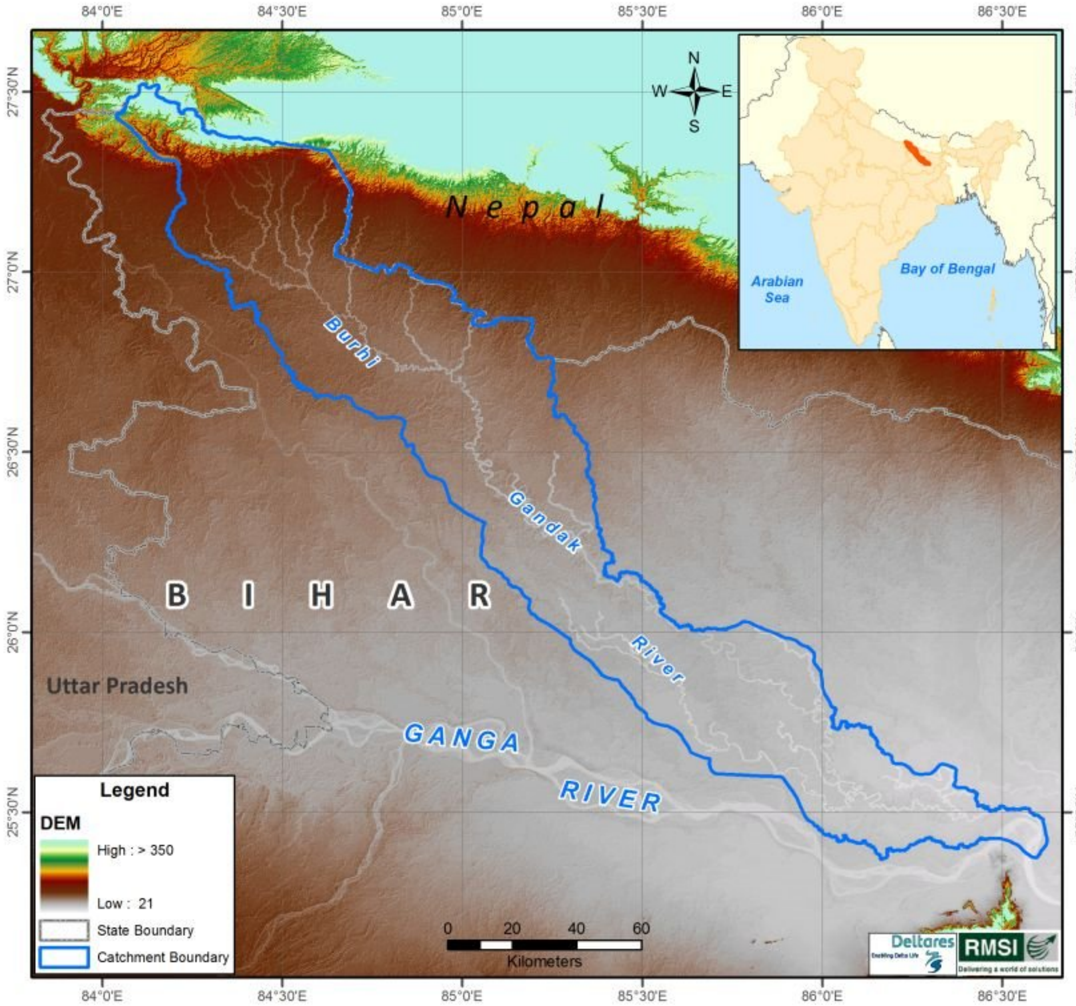


Figure 2.2 Elevation map of the Burhi-Gandak basin

Seeing the terrain and the hydraulic characteristics, the river may be divided in to 3 reaches as (i) from origin at Bishanbharpur to Champatia; (ii) Champatia to Motihari and (iii) Motihari to Khagaria. The elevation of the countryside through which the river flows drops to about 50 meters over a distance of about 580 Km from the elevation of 300 m at the origin.

2.2 Hydrology

The average annual rainfall in the sub-basin is 1,283 mm, out of which the monsoon months (June to October) receive 1,155 mm, which is about 91 % of the above annual average rainfall. In general, the upper part of the catchment receives higher rainfall than the lower part. The South-West monsoon generally sets in the first or second week of June and withdraws in the second week of October. The high concentration occurs in the period from July to September. Storms of 1 to 3 days durations are common. One day storm at 50-year return period may vary between 280 to 400 mm from the lower to upper reaches. Similarly, the 100-year return periods one day rainfall increases from 320 to 440 mm from the lower to upper reaches. About 20 Hydrological stations were operating in the sub- basin in the past. Out of these only 4 gauge-discharge stations and three gauge stations are maintained by CWC. The gauge-discharge stations are

Champatia, Lalbegiaghat, Sikanderpur and Rosera; the gauge stations of CWC are at Ahirwalia, Samastipur and Kagharia. The Hydro-meteorological network in the catchment is more or less satisfactory as per WMO stipulations. The Hydrological features of the four gauge-discharge stations are as below Table . For comparison, also the discharges according to another source (Sinha & Jain, 1998) are presented in Table .

Table 2.2 Discharges for specific return periods (according to GFCC, 1992)

Station	Data base	Catchment area Km ^{2}	Maximum observed discharge (m^3/sec)	25-year Return Period Discharge	50-year return period Discharge	100-year return period Discharge
Champatia	1960-90	1,464	1,469	1,941	2,300	2,690
Lalbagiaghat	1974-90	6,900	2,295	3,241	3,814	4,211
Sikanderpur	1961-90	8,510	3,787	4,040	4,646	4,927
Rosera	1960-90	9,580	2,890	2,735	3,102	3,489

Table 2.3 Discharges for specific return periods (according to Sinha & Jain, 1998)

Station	Observed * Maximum Discharge (m^3/s)	Discharge for specific recurrence interval (T) (m^3/s)		
		T = 50 Yr	T = 100 Yr	T = 1000 Yr.
Chanpatia	2810 (1986)	652.86	3017.53	4306.02
Sikanderpur	3787 (1975)	1905.94	5653.88	7696.40
Rosera	2234 (1975)	1308.59	2978.82	3889.05

* Period of observation is from 1975 to 1989 (Source: Sinha & Jain, 1998)

As can be observed from the two tables, maximum discharges and discharges for specific recurrence intervals differ considerably between the two sources (GFCC, 1992 and Sinha & Jain, 1998). In our project we will prepare our own distribution, using longer time series which increases confidence.

The midstream station (Sikanderpur) shows higher values of peak discharge than upstream (Chanpatia) or downstream (Rosera). The increase in peak discharge between Chanpatia and Sikanderpur can be explained due to tributary influence. No major tributary seems to be joining the Burhi-Gandak between Sikanderpur and Rosera and therefore, flood peak is being attenuated (Sinha & Jain, 1998).

The sediment flow measurement is being done at Sikanderpur and Rosera. The River does not carry coarse sediment during the non-monsoon period and carries medium sediment during the period from March to May. About 90 % of the annual sediment load is transported in the monsoon months. The average annual sediment load at Sikanderpur and Rosera are 5.38 million tons and 14.45 million tons. The fine sediment concentration is 0.247 mg/litre and 0.835 mg/litre respectively.

This area is highly vulnerable to flood inundation not because of the floods of Burhi-Gandak alone. The Ganga River, which receives the floods of its tributaries in the upstream along with its own catchment generated floods, is in high stages in the monsoon in general and definitely during flood events. As such the backwaters push the Burhi-Gandak brought flood volume in to its upstream channel. Thus the inundated waters spread up to even about 20 to 25 km upstream into Burhi-Gandak channel (Figure 2.3). As such the boundary conditions for modelling and mapping are foreseen to be a challenge, which we will have to address in an apt manner.

Table 2.4 Tributaries of Burhi Gandak

Sl. No.	Name of tributaries	Origin of the tributary	Outfall point	Catchment area (km^2)	Length of the tributary (km)	Discharge in Cumecs	Distance of river from origin to meeting point of tributaries (km)	Remarks
1	3	4	5	6	7	8	9	
Left Bank tributaries								
1.	Masan	Someshwar range of hills	Basantpur	480	85	383.6	18	0.85 m/km
2.	Belor	Someshwar range of hills	Baghlochana	608	63	331	30	1 m/ km
3.	Pandai	Someshwar range of hills	Tularamghat	875	80	63	54	1.80 m/km
4.	Sikta	Someshwar hills near Nepal border	Murgiatola	847	-	-	75	
5.	Tilawe	Churia range of hills in Nepal	Agarwa north of Loknathpur	1330	98	153.4	132	
6.	Tiur	Foot hills of Himalaya in Nepal	Gularia	530	64	109.4	140	
Right Bank Tributaries								
7.	Kunhra	Bettiah town	Bairatpur	282	64	-	87	
8.	Dhanauti	Spill Channel of the Gandak	Bardaha west of Pakridayal	870	192	-	176	
9.	None Balan	Kamtaul	Near Dihapur	2283	-	-	492	

Table 2.5 District wise distribution of catchment area

Sl. No.	Name of the district	area of the district lying in the catchment (sq. km)	% of the district area lying in the catchment	% of the catchment in the district.
1	2	3	4	5
1.	West Champaran	2880	55.2	28.4
2.	East Champaran	2428	61.1	23.9
3.	Muzaffarpur	1577	49.7	15.5
4.	Vaishali	311	15.3	3.1
5.	Samastipur	1745	60.1	17.2
6.	Begusarai	1045	54.5	10.3
7.	Khagaria	158	10.3	1.7
	Total	10.144		100%

2.3 River morphology and behaviour

The effectiveness of any flood control scheme inter-alia depends on the river morphology. The erratic behaviour of the river causes frequent changes in its course, lateral migration, heavy over bank spilling due to inadequate channel capacity, frequent carving of new or secondary channels, rise in river beds as well as frequent attacks on the river banks and flood embankments.

In the course of the Burhi-Gandak River there is minor shift in the river course as most of the river length is embanked. However, spilling occurs during floods in the reach upstream of Motihari town where embankment constructions are not completed. The embanked portions of the river reaches remain under constant threat of breach because of the improper alignments of the embankments in many places. Channel characteristics of the river at Champatia, Lalbiaghat, Sikandarpur and Rosera were studied as part of the Comprehensive Plan of Flood Control for the Ganga Basin (GFCC, 1992). The findings described below will be updated during our study:

- The study at Champatia shows that the bottom level of the river or the depth of flow has a negligible change during the period from 1987 to 1991. However, there is considerable progressive erosion in the river banks over the years.
- At Lalbiaghat, the river cross section is more or less stable. The study reveals that the river cross section (bed only) has aggraded towards obtaining an "U" shape since 1989. Both the banks have remained stable.
- At Sikanderpur, there is some variation in the cross section in the bed level and river sides, but the depth has remained more or less stable, except in the year 1991, in which the cross section shows aggradation.
- At Rosera there is no change in the bank-full width at this site except in the year 1989, but there has been slight fluctuation in almost all the years in the bank-full depth. The study of bed form with reference to the flow characteristics at these four sites almost confirms the trends of characteristics of beds as per available superimposed cross sections of these sites. The study of plan form and channel migration indicates that the river is highly meandering, especially in the lower reaches, and is un-braided throughout its course.

Due to the high silt load and recurrent flooding, the floodplain is gradually accreting. At one point in the Burhi-Gandak floodplain Sinha & Jain (1998) found evidence of 1.4 m vertical accretion over a time period of 15 years.

2.3.1 Flood characteristics

Before the embankments were constructed from near Motihari up to the confluence with Ganga, the river used to spill more or less throughout its length. But even now, when embankments have been constructed over most of the length, the area remains highly vulnerable to flood inundation not because of the floods of Burhi-Gandak alone. The Ganga River, which receives the floods of its tributaries in the upstream along with its own catchment generated floods, is in high stages in the monsoon in general and definitely during flood events. As such the backwaters push the Burhi-Gandak flood volume to its upstream channel. To add to the problem, the Koshi River, known for its flood fury and damages, running in the left side (East) of Burhi-Gandak, is also affected by the high stages of Ganga and is not able to drain into Ganga. As such, the Koshi river pushes its floods into the Burhi-Gandak channel. Thus the inundated waters spread up to even about 20 to 25 km upstream of the Burhi-Gandak river. Both Koshi and Burhi-Gandak look like a single channel in these plains (Figure 2.3). As such the boundary conditions for modelling and mapping are foreseen to be a challenge, which we will have to address in an apt manner.

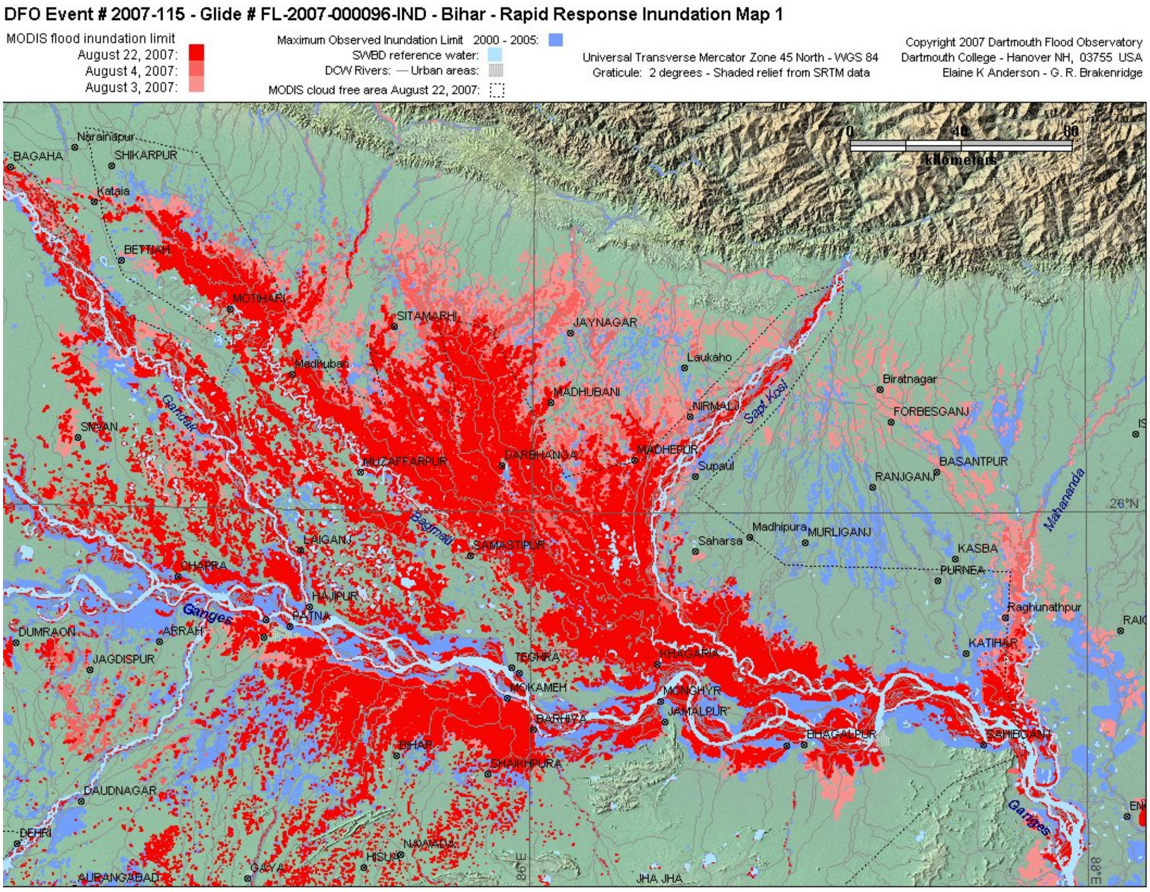


Figure 2.3. Flood extent in northern Bihar on August 2007 (Source: Dartmouth Flood Observatory)

The flooding characteristics can be summarised as follows:

- A lot of flooding is due to water logging and impeded drainage, and not river flooding.
- Flooding also occurs through breaching of embankments, which is said to be often man-made.
- Downstream inundation is partly also coming from backwater effect of Ganges and overflowing water from other rivers (Koshi, Kareh).
- Bank erosion problems in the reach below Muzaffarpur
- Inundation due to spilling of the River in the upstream reaches
- Drainage congestion due to in-adequate waterway provided in the rail/road bridges, especially in the East Champaran district.

2.3.2 Recent floods and their impact

The plains of north Bihar have experienced extensive and frequent loss of life and property over the last several decades (Sinha & Jain, 1998). Based on the years 1968 to 1990 the GFCC estimated the average annual flood damages to crops, houses and public utilities as Rs 1,141 lakhs, 168 lakhs and 233 lakhs, respectively. The annual loss of human life was 11 and that of cattle was 62. The average annual area affected was 2.13 lakh hectares. From 1991 till 2012 the damages and fatalities are given in Table for the districts of West Champaran, East Champaran, Muzaffarpur , Samastipur, Begusarai and Khagaria (based on the Disaster Management Department of Bihar). Although it is tricky to compare these figures because of possible differences in data collection, they suggest a significant increase in damages in the last two decades.

Table 2.5 Damages and fatalities for Burhi-Gandak over the period 1991-2012.

year	Number of people affected (lac)	Affected land (lac ha)	Estimated Crop Damage (Lac INR)	Estimated House Damage (Lac INR)	Estimated public property damage (Lac INR)	Number of fatalities
1991	6.88	1.88	642.4	193.91	27.7	16
1992	0.34	0.09	2	9	0	0
1993	18.88	3.12	7293.8	1982.59	72.76	21
1994	15.33	1.93	2567.32	290.57	2046.05	20
1995	7.35	1.26	738.82	160.85	58.01	28
1996	17.67	2.39	3062.98	202.09	16.5	50
1997	0	0	0	129	1.45	25
1998	35.66	8.9	12267.14	1859.35	1090.43	60
1999	15.01	2.14	9409.34	190.94	91	46
2000	11.44	1.95	1488.13	79.87	129.56	41
2001	31.09	3.31	10139.12	2117.22	1784.94	80
2002	35.98	4.37	16306.16	4054.22	9116.63	185
2003	21.88	5.44	4372.01	1296.41	247.07	97
2004	60.67	7.46	24616.4	23614.78	35821.12	316
2005-2006	9.2	2.96	370.98	60.43	16	20
2006-2007	3.78	177.152	818.28	1480.76	7456.17	14
2008	3.6	0.1402	336.94	799.85	80.03	18
2009	4.88	0.64	1151.55	21	55	22
2010	4.47	0.7	115.5	152.85	100	5
2011	2.84	15.25	435.51	50.92	0	42
2012	1.2	0.27	135.8	0.6	141	9
average	15	11	4,584	1,845	2,779	53

2.4 Current flood mitigation strategies

2.4.1 Embankments

No major flood management scheme has been taken up till the middle of fifties, though the river witnessed many severe floods after the great earthquake of 1934 in Bihar. The successive floods of 1952, 1953, 1954, coming in a row, crystalized the idea of protecting the affected areas by making continuous embankments along both the banks of the River. Accordingly, constructions of embankments were taken up in 1955 and practically completed in 1957 in all the reaches starting from downstream of Motihari town to the end (GFCC, 1992).

Still, the embankments at both sides of Burhi-Gandak have gaps and the upper reach has yet to be embanked. The existing embankments should be maintained adequately as at places the top and slopes have faced deterioration. Also various anti-erosion measures should be continued to safeguard the embankments from bank erosion. Besides, many rail bridges have inadequate water way. GFCC Patna had asked for comprehensive proposals for raising and strengthening of existing embankments along Burhi-Gandak and construction of new embankments along Sikrahna river (as a short term flood control measures of Burhi-Gandak river system) vide its letter no. G.F.C.C./P/Tech/338/2007/2614 dated-11/4/2008 to Water Resources Department.

Opinion in Bihar was against construction of embankments in the twenties and thirties of the past century. And according to Sinha & Jain (1998) the flood control efforts through embankments have largely failed in North Bihar as the geological and geomorphological considerations have not been taken into account. Artificial embankments have merely transferred the trouble from one place to another and have given a false security to the people living in the area. Moreover, these embankments interfere with natural fluvial processes of rivers. Also waterlogging and salinity problems have developed (Sinha & Jain 1998).

2.4.2 Flood warning

There are seven flood forecasting sites (Ahirwalia, Champatia, Lalbegia Ghat, Sikanderpur, Samastipur, Rosera and Khagharia) in the Sub-basin. All of them are maintained by CWC (Middle Ganga Division-IV Patna). These stations are well connected to the base stations, Divisional and Sub-divisional headquarters of CWC. The CWC uses these stations for providing flood forecast bulletins to district administrations via the Flood Control Cell of the WRD.

2.4.3 Preparedness

Before the onset of the flood period, WRD creates different zones for flood fighting. For every zone a Senior Retired Chief Engineer is notified to head as Chairman of the Flood Fighting Force. The force is manned with one serving Executive Engineer and one Asst. Engineer to help the chairman in suggesting, supervision and monitoring the flood fighting works being executed. The Burhi-Gandak river flood fighting works in recent past has been covered by Flood Fighting Force stationed at Muzaffarpur up to Samastipur District Border near Mohamda (Pusa) and downstream of this is supervised and monitored by a Flood Fighting Force stationed at Khagaria.

After the end of each monsoon period the Chairman of the Flood Fighting Force (who has supervised flood fighting works on the river from 15 June to 15 October) and the Chairman of the Anti-erosion Committee visit the river sites which had faced onslaught of heavy floods, erosion points, where flood fighting took place to save public, property and agriculture crops. The joint committee identifies vulnerable sites and proposes anti-erosion schemes. On the basis of the committee report, field Executive Engineers measure the damages and frame a scheme with required design. Through a number of administrative steps the scheme is sent to the State Flood Control Board, headed by State Chief Minister. This board has to finally approve the agenda and makes funds available for the anti-erosion scheme.

2.5 Suggested improvements / measures

Improvements that would lead to Integrated Flood Management in the Burhi-Gandak basin should encompass reductions of hazards as well as current flood vulnerability.

2.5.1 Hazard reduction

Reduction of hazards can be achieved by:

Upgrading embankments. The height of the existing embankments has reduced at various places and therefore the embankments need raising and strengthening. The embankments have been aligned close to the river banks, thereby infringing the required minimum distance of one Lacey's width between the two embankments. Possibly this is causing constant threat of breaches in the embankments and consequently excessive expenditure is being incurred on anti-erosion works and improving the embankments. As such, model studies of the entire reach of the river have been suggested so that a view regarding properly aligning the embankments as also other flood management measures suitable for the un-embanked upper reaches may be taken, so that overall expenditure on the flood protection works could be reduced (GFCC, 1998).

Retaining rainfall through storage , increasing infiltration as well as diverting the runoff to natural retention basins such as wet lands and depressions would lead to a reduction in runoff during extreme weather events and subsequent reduction of flooding in downstream areas.

Storage reservoirs: presently there is no dam or barrage across any tributary or main river. However, there are favourable reservoir sites in the Masan, a tributary of the Burhi Gandak: the scheme is known as "Masan Dam project". Already CWC has cleared the scheme, but is (perhaps) pending for clearance by Forest or R.R. Constructing a dam on the Masan river, which contributes about 30% discharge (having 480 sq. km catchment with 383.6 cumecs discharge) to Sikrahna river, can reduce flood hazards. The proposed Masan Dam can irrigate 27,062 ha. of land benefitting 115 villages.

Diversion structures such as a barrage in lower reaches of Burhi -Gandak river. Presently a DPR for a barrage on the Burhi Gandak river 19 km downstream of Samastipur which has been prepared and submitted by NWDA to WRD-Bihar, is under examination. It is proposed for 1.0 lakh hectares irrigation as well as for passing floods (discharge from Baghmati old spill channel by 40 km link channel to river Baya), and which will finally go to the Ganga river. Similarly, water logging can be reduced by provision of adequate waterway in anti-flood sluices and bridges of railways and roads.

Check dams: the run-off of different tributaries of the basin and district wise area can be delayed using small dams/reservoirs which could mitigate flooding downstream. Such check dams can also be used for irrigation.

2.5.2 Vulnerability reduction

Reduction of consequences (vulnerability) can be reached by:

Land use management: planning of households and infrastructure buildings above H.F.L (not inside of embankments), water parks and landscaping, using water logged area for fish production, growing Makhana, singhara fruits etc. which are rich in nutrition. Growing crops which can withstand water logging and short duration of submergence.

Providing flood proofing measures: This includes construction of raised platforms above Embankments Formation level and few metres back in country side and also away from vulnerable points with sufficient space for sheltering the population likely to be affected. The platform should have proper shed, food for needed, hand pumps for water, toilet facility, solar/ electric lighting, emergency aids equipment such as ropes, life jackets, boats, search lights, medical kits, medicines. Further, the platform should have sufficient fodder for animals of concerned villages. The planning and fixation of top levels of raised platform for Burhi Gandak should be done using design H.F.L. on minimum 25 years return period which are as follows: Chanpatia Railway Bridge: 76.11m; Lalbagia Ghat: 67.10m; Akhara Road Bridge: 54.05m; Samastipur: 49.28m; Rosera: 45.60m; Khagaria: 38.86m.

Flood warning: siren and public address system should be in place to warn people in advance. Evacuation to high and safe area during emergency should be prepared in advance and villagers should be trained before onset of monsoon for any eventuality.

An emergency action plan should be prepared. A committee consisting of district/block/ panchayat administration, police, medical, and disaster management people should be constituted to provide service in the period of distress. Sufficient numbers of (motor) boats, should be kept near vulnerable sites.

Increase coping capacity of people: Increase the ability of people and their assets and crops to withstand flood, increase capacity to cope with flood and recover from negative effects of floods. Reduction of vulnerability can be achieved by improving infrastructure, living environment, well-being, occupational opportunity, by facilitating equal participation opportunity, and imparting awareness, providing skills and social support system and by motivation: building awareness and facilitating self-organization.

Chapter 3 Topographical data

3.1 General

This chapter describes the topographical data used for the flood risk modelling, including:

- River network in the hydrodynamic model;
- Digital Elevation Model (DEM) used for both hydrological and hydrodynamic model developments;
- The Land use map for estimation of runoff characteristics in the hydrological model and hydrodynamic roughness conditions in the flood plains (2D modelling);
- Inventory of river cross-sections and their sources, and
- Inventory of structures as weirs, gates and bridges affecting the flow in the rivers.

3.1.1 River Network

The river network data was provided by several Indian national and state agencies. Comparing these shapefiles with Google Earth images of the river network showed that the overall fit could be improved. This was done by deriving the outline of the main river network using OpenStreetMap, (see www.openstreetmap.org). According to www.geofabrik.de the OpenStreetMap (OSM) project is aimed at creating a free, world-wide geographic data set. The focus is mainly on transport infrastructure (e.g. streets, railways, and rivers). OSM relies mostly on data collected by project members using their GPS and data importing of third parties. The Indian set was downloaded on October 15, 2014 and was used to improve the river network (see http://download.geofabrik.de/asia/india.html).

3.1.2 Digital Elevation Model

The Digital Elevation Model (DEM) is one of the key inputs for hydrological /hydraulic model development, and flood hazard mapping. This section presents the details of DEM available from free sources, the limitations and enhancement/ use of these DEMs, as well as the choice of appropriate DEM for flood modelling in the present study.

There are two important sources identified by the team from where free DEM data can be acquired and used in the present study considering certain aspects of the basin after necessary enhancement. The first source is the National Remote Sensing Centre (NRSC) Bhuvan portal that provides free downloadable Cartosat DEM with a spatial resolution of 30m and vertical accuracy of about 8m. The other source is the DEM generated from Shuttle Radar Topography Mission (SRTM) having a spatial resolution of 90m and vertical accuracy of ± 16m. Although, the Cartosat DEM from Bhuvan was initially thought to be a good source for flood analysis, however this DEM failed to meet the required criteria after detailed analysis. The SRTM 90m DEM is most commonly practiced for flood modelling across the globe, however, the coarser resolution of this data would require a thorough need-assessment analysis from the perspective of its use in the present flood model.

As mentioned above, looking at the specific requirement of DEM for detailed flood hazard and risk analysis, the team initially considered purchase of higher resolution Cartosat DEM having a horizontal resolution of 10m and vertical accuracy of about 4m available with NRSC. However, it was observed that the cost of this high resolution Cartosat DEM data (vertical accuracy of 1m) would require around 511,500 US$ that exceeds the budget available under the survey and data component in the present study. Therefore, the team considered the possibility of using the freely available Bhuvan DEM and SRTM DEM in the present flood model. The following section presents the pros and cons associated with the Bhuvan and SRTM DEM data.

3.1.3 Bhuvan Cartosat 30m DEM

The team downloaded the Bhuvan Cartosat 30m DEM tiles from Bhuvan web-portal and mosaiced them to generate seamless DEM data for the Burhi-Gandak river basin. It was observed that the mosaiced DEM has certain types of errors present for the study area. These include problems like line stripping, missing values near tile edges, arbitrary values in no data cells etc. In addition, it was observed that few raw tiles had inconsistent values present with respect to the surrounding areas (patches). The issues observed in Bhuvan DEM are presented below.

Observations in the Burhi-Gandak basin

In the DEM enhancement process, the team worked on the Cartosat 30m DEM and removed errors of line stripping, no data, negative values and sinks. Even after this enhancement, the following prominent errors were observed in the data (Figure to Figure).

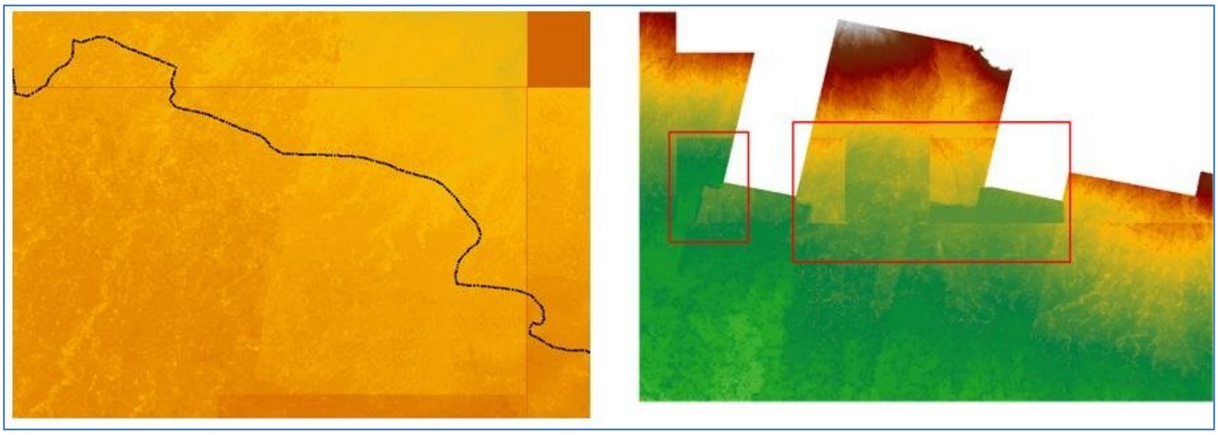


Figure 3.1 Line stripping error in BG basin (left), Patch error (right)

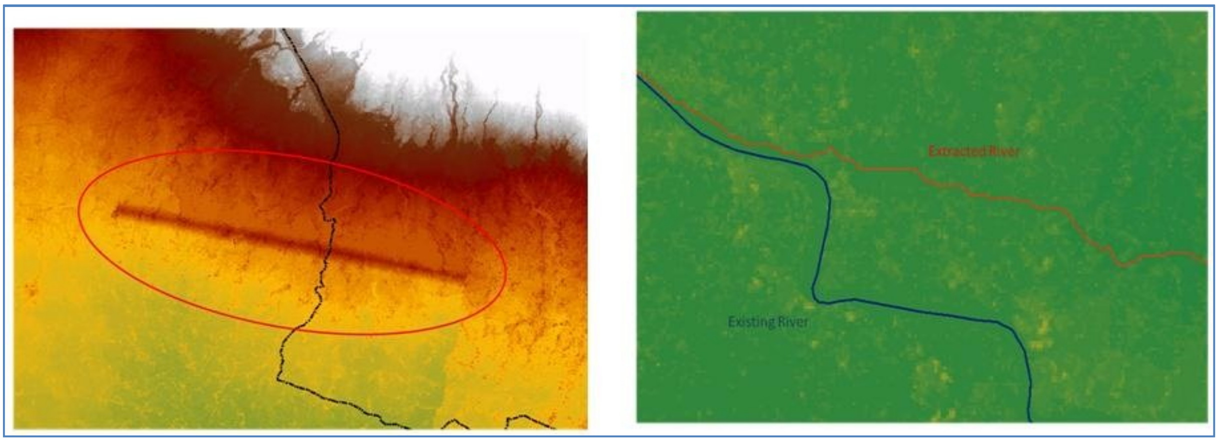


Figure 3.2 Arbitrary values error in BG basin (left), River spill-out as less value is present outside river course (right)

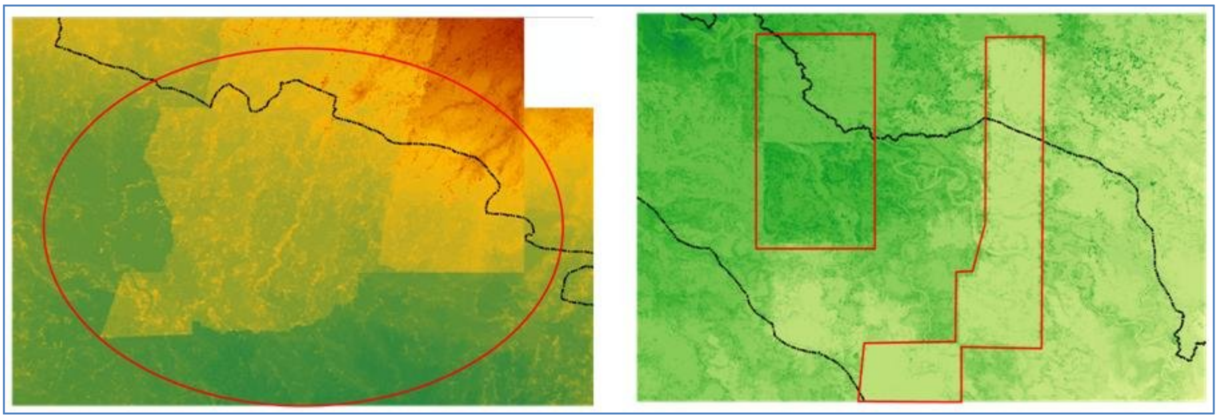


Figure 3.3 Patch error in BG basin (left), Sudden change of elevation values (right)

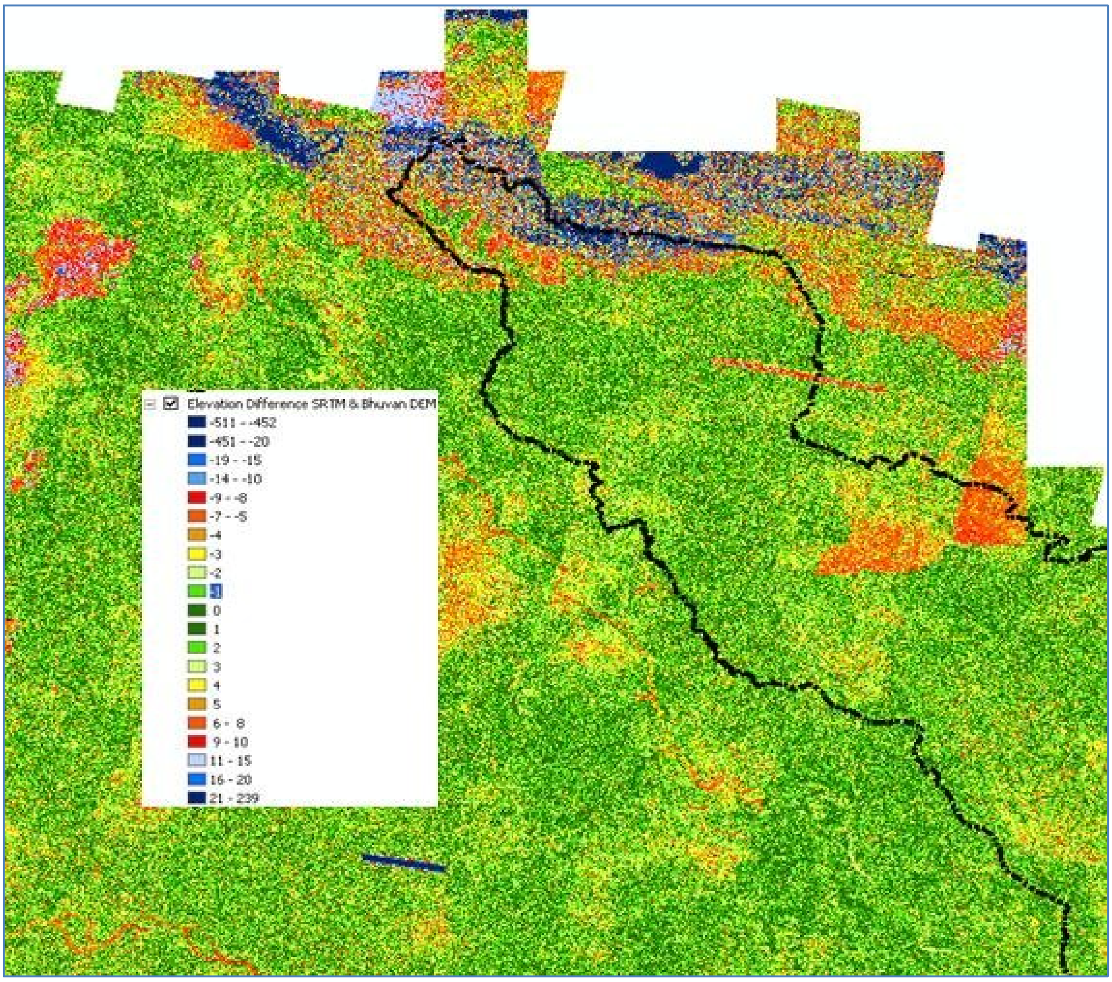


Figure 3.4 Elevation Difference between two DEM (Cartosat 30m & SRTM 90m)

Suggested Actions

Looking at the overall quality of Cartosat 30m DEM data after applying appropriate enhancement techniques, the team concludes that it may be difficult to use this data for modelling purpose in the present study. As an alternate, the team suggested the use of available SRTM 90m data that can be replaced with subsequent higher resolution DEMs at later stage. Indeed, by the end of April 2015 the higher resolution SRTM 30m data became available.

3.1.4 SRTM DEM

From the 1 second SRTM data, various data products are provides including: the Digital Surface Model (DSM); the Digital Elevation Model (DEM), the Smoothed Digital Elevation Model (DEM–S) and the hierologically enforced (DEM–H) products. The 1 second DSM, DEM, DEM-S and DEM-H are elevation data products, where a DEM represents a regular grid of ground surface topography and, where possible, excludes other features such as vegetation and man-made structures. To verify the statement if the available SRTM is a DSM or DEM, the team has compared the elevation values at different part adjacent to Delhi where there are open spaces and buildings / built up areas available for checking. In this sample, the building size/built up cluster selected are often more than 100 m in size and there was not much difference in elevation values (at times it's +- 1m only). Some of the buildings include covered stadium and other large buildings. Hence, this also supports that the available STRM data is a DEM (subset of DTM).

The team has downloaded the SRTM DEM tiles with spatial resolution of 1 second from the https://lta.cr.usgs.gov/SRTM1Arc website. The original DEM tiles were then mosaicked for the basin. The DEM was then processed to fill the voids/ no data cells before the delineation of river basins and sub-catchments for both the basins. The outcome of this process was comparatively satisfactory for the basin. The SRTM DEM has been enhanced using the spot heights present in Survey of India (SOI) toposheets. These toposheets are mostly available at 1:50,000 scale with a few at 1:25,000 scale. The enhancement process includes overlay of SOI spot height over SRTM DEM pixel values and then systematic correlation between these two datasets have been studied. This gives the relationship between error and increasing elevation in the study area (Sanyal et al. 2013). Using the SOI median error value at different parts of the basin, the vertical accuracy of SRTM can be enhanced and used for hydrodynamic modelling, subsequently.

3.2 Geography

The geographical shape of the Burhi-Gandak basin is relatively small with respect to the total length of the basin. It is situated from the North-West to the South-East along the south Nepalese border, as shown in figure 2.1. The SRTM data show an upstream part covering the more hilly and mountainous areas and the downstream part, covering the lower areas towards Ganga River. Figure 3.5 shows the DEM as derived from the SRTM 30 m DEM dataset.

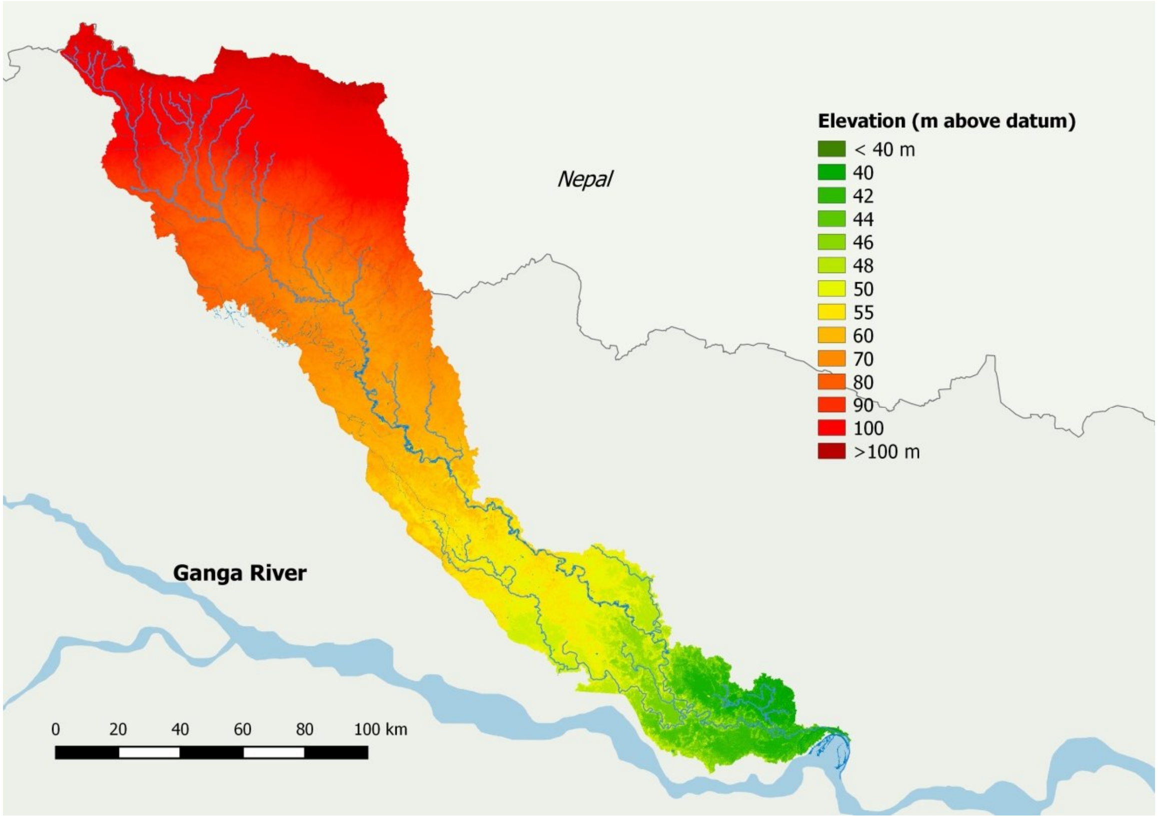


Figure 15 Elevations in the Burhi-Gandak basin.

Figure 3.5 shows the elevations in the lower part of the basin, between 0 and 25 m. The blue and greyish areas represent the rivers and water bodies as derived from the land use dataset which is shown in figure 3.6 in the next paragraph. Especially the green shaded areas are vulnerable for flooding from the Ganga river (backwater effect) but also from the rivers. The orange and red shaded areas are vulnerable for flooding from the rivers. But for the whole area flooding because of excessive rainfall leading to waterlogging is also of a major importance.

3.3 Land use

The land use map with gridded fat has been sourced from the Government of Bihar. The land use map comprises 22 land use types, see table 3.1.

Table 3.1 Land use types in the land use map

Value	Description
1	Urban
2	Rural
3	Mining
4	Crop land
5	Plantation
6	Fallow
7	Current Shifting cultivation
9	Deciduous
10	Forest Plantation

Value	Description
11	Scrub Forest
12	Swamp / Mangroves
13	Grass/ Grazing
15	Gullied / Ravinous Land
16	Scrub land
17	Sandy area
18	Barren rocky
20	Inland Wetland
21	Coastal Wetland
22	River / Stream / canals
23	Water bodies

A graphical display of the land use map is shown in figure 3.6.

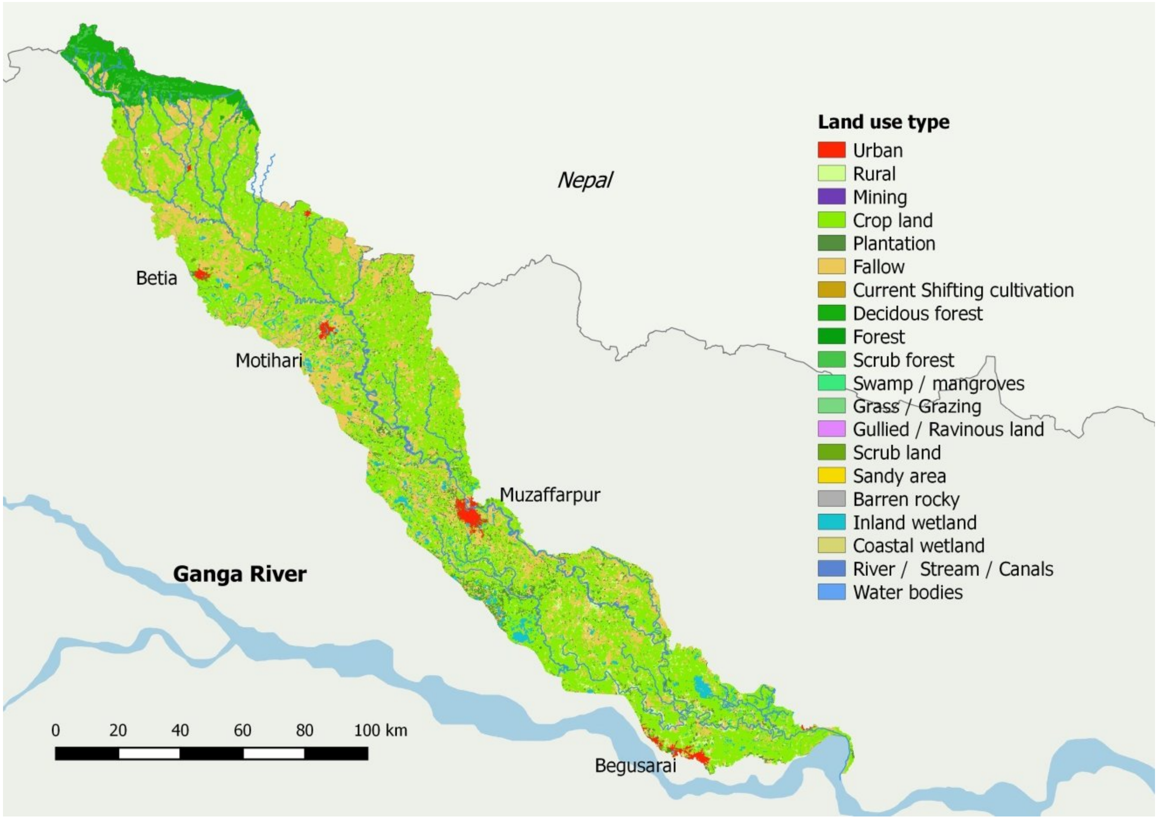


Figure 26 Land use of the lower part of the Burhi-Gandak basin.

Figure 3.6 shows that the most upstream part comprises forest land. Clearly we see the red shaded urbanized areas Betia, Motihari, Muzaffarpur and Begusarai. For the whole basin the land use values are used to derive the roughness coefficients for the 1D/2D model.

3.4 Inventory of cross sections

The applied hydrodynamic model for Burhi-Gandak consists of a 1D channel flow combined with a lumped hydrological model. The 1D model includes the rivers and larger channel system of the Burhi-Gandak basin.

The implementation of the hydrodynamic 1D model requires the insertion of the cross section profiles of these river branches at regular spatial intervals. This cross sectional data has been drawn up by combining several data sources. Firstly, a selected number of cross sections has been surveyed in the downstream part of the basin. Secondly, already available cross section information has been combined with assumed cross sections based on the width of the river and general width-depth relationships. A typical trapezoidal profile is used for the assumed cross sections. The use of these profiles is an expedient solution, but allows the application of the 1D model in absence of the real cross-section profiles where no additional information is available.

In the Burhi-Gandak basin a total number of 60 cross sections have been surveyed. The surveying activities have been carried out during the period March-May 2015 in 3 batches of 20 cross sections each. The location of the surveyed cross sections is shown in figure 3.7.

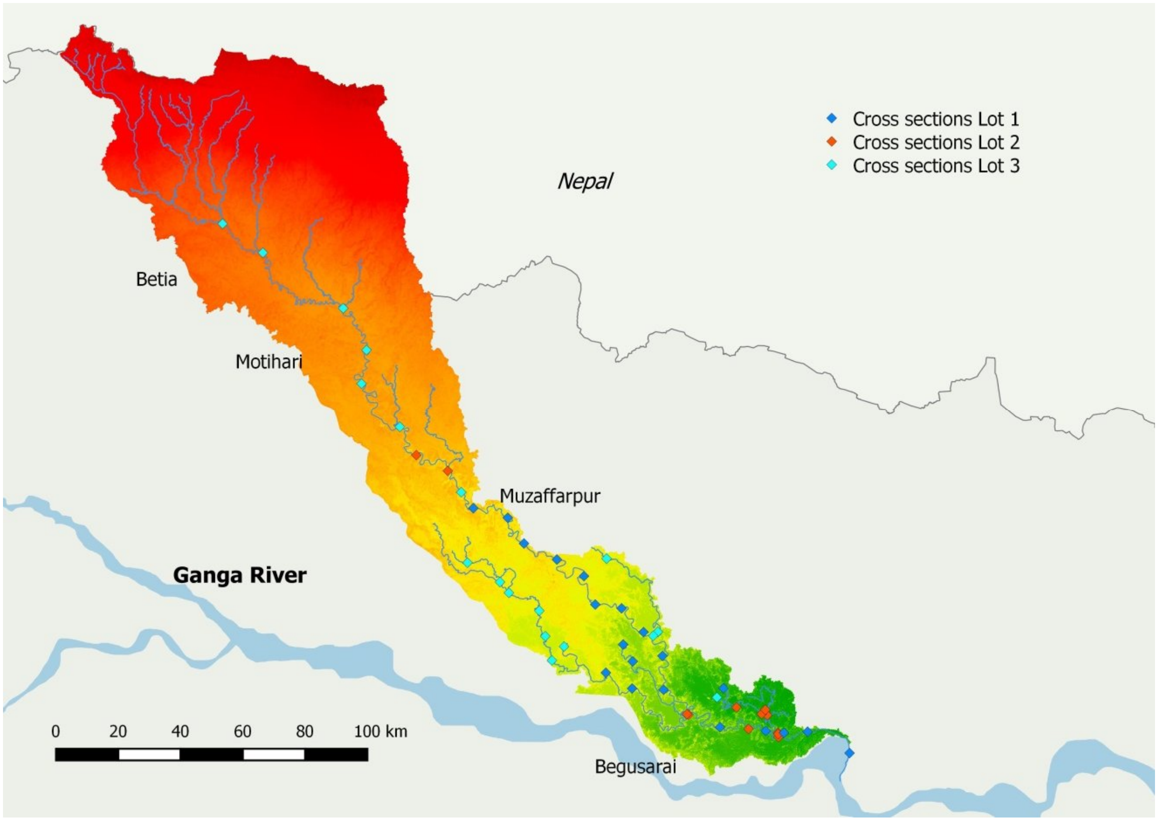


Figure 37 Location of surveyed cross sections in the Burhi-Gandak basin

The information as comprised in the surveyed cross sections has been used to check with the data in the Digital Elevation Model (DEM). This will be elaborated more in chapter 5 of this report.

3.5 Inventory of modelled structures

For the hydrodynamic model no structures have been identified to be implemented into the model. Regarding projects to be planned and used in our strategies, some hydraulic structures will be added to the model. This will be elaborated further in Chapter 7.

3.6 Inventory of civil line elements

3.6.1 Embankments

The delineation of the embankments has used for the Burhi-Gandak basin has been sourced from the State of Bihar. The data has been supplied as an ESRI-shape file of which the actual delineation has been checked by the states Flood Management Officer.

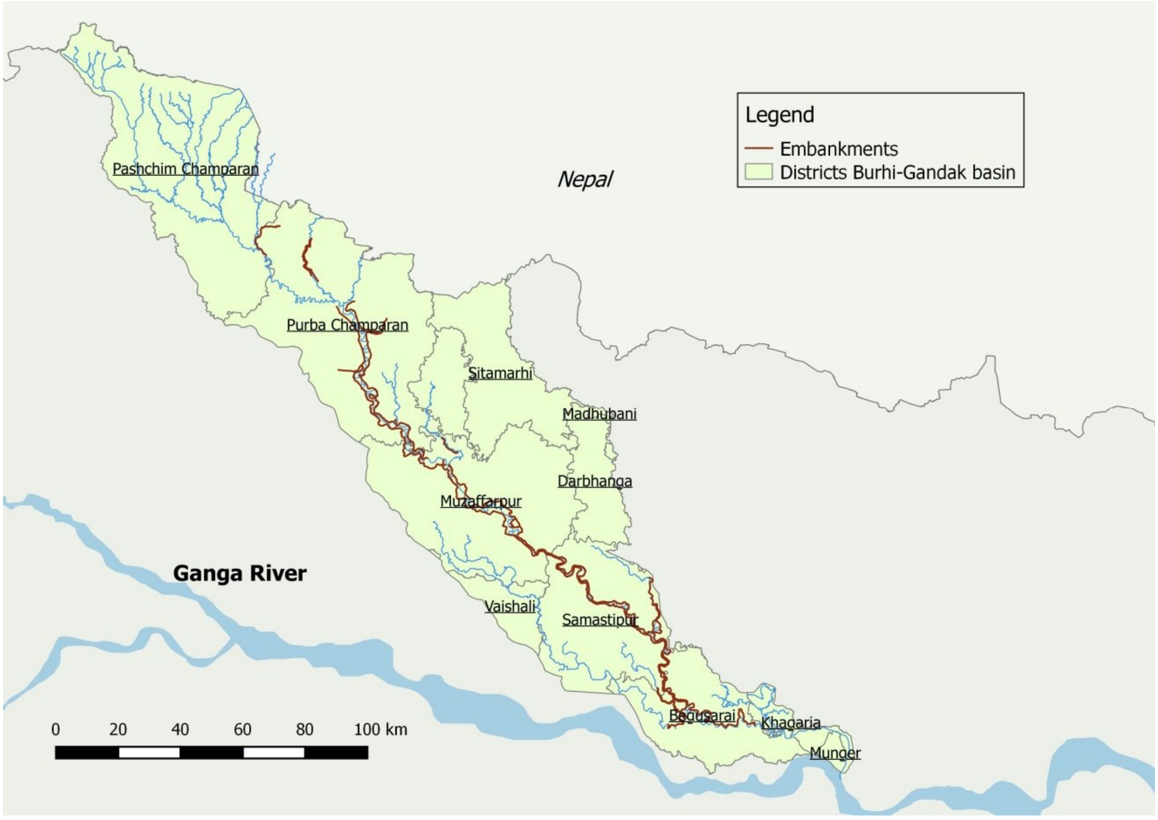


Figure 48 Delineation of embankments in the Burhi-Gandak basin

Actual embankment elevations were not available. How this was handled with the modelling will be discussed in chapter 5.

3.6.2 Roads

The road data has been supplied as an ESRI-shape file and is sourced from WRD, Bihar. In the attribute a distinction is made between Highways, type 1, and Major roads, type 2. Figure 3.9 shows the highways and major roads in the Burhi-Gandak basin. The delineation of the roads is used in the 1D/2D flood modelling which will be discussed in chapter 5.

Figure 59 Delineation of the roads in the Burhi-Gandak basin

Chapter 4 Hydrological model

4.1 General

For the modelling of the Burhi-Gandak basin we use a combination of a hydrological and a hydro-dynamical model. In this chapter we will discuss the hydrological model for the Burhi-Gandak basin. We also describe the approach which we used to set up the model. In general rainfall is the most important forcing parameter for a hydrological model. The hydrological model of the Burhi-Gandak basin is an integral part of the combined NAM/1D/2D-model and its calibration and validation and will be described in chapter 5.

4.2 The Nedbor Afstromnings Model (NAM) concept

In general rainfall is the most important forcing parameter for a hydrological model. The model processes the rainfall data into runoff data which can be input to a 1D-flow or a 2D-overland flow model. So, rainfall-runoff models provide discharge inputs to the hydrodynamic modules, additional to the discharges imposed on the hydrodynamic model at the model boundaries. The transformation of rainfall towards runoff in the model is schematized by using the NAM model concept.

NAM is an abbreviation of the Danish “Nedbor-Afstromnings-Model”. It is a rainfall-runoff concept developed by the Technical University of Denmark. NAM describes in a simplified manner the behavior of the land phase of the hydrological cycle. NAM accounts continuously for the moisture content in four different and mutually interrelated storages, which represent physical elements of the catchments. As NAM is in essence a conceptual model, some parameters might be evaluated from physical catchment characteristics. However, normally parameter estimation is performed during calibration.

4.3 Drainage area definition

4.3.1 Catchment delineation

For a proper application of the NAM model it is necessary to define the catchment delineation of the area to be schematized for the Burhi-Gandak basin. The delineation of the basin has been done applying stream flow direction maps and the DEM using GIS. For this process it is necessary to define the necessary level of detail as an input. The same process is used to define the sub-catchments within the catchments, see the next paragraph.

4.3.2 Sub-catchment delineation

For the catchment we have derived the sub-catchments as are used as input areas for the hydrological model. A total number of 78 sub-catchments has been delineated, see figure 4.1.

Figure 6 Delineation of sub catchments in the Burhi-Gandak basin

Each of the 78 sub-catchments is represented by a run-off node in the hydrological model. The run-off nodes are connected to connection nodes, which are inter-connected as well. In this way a network schematization is formed representing the hydrological model. For each of the 78 sub-catchments input data for NAM-model has been derived, which is shown in table A.1 in Appendix A. Depending on the type of the connections additional routing data is needed. This will be discussed in the next paragraph.

4.3.3 Muskingum routing

To route the computed discharge output through the stream and river system in the hydrological model the Muskingum routing technique is used. It translates and attenuates the discharget output by means of two parameters K and x, where K stands for the channel lag time and x determines the degree of attenuation. The latter can assume values between 0.0 and 0.5, where x = 0.0 refers to maximum damping and x = 0.5 to pure translation. Generally, values of about 0.3 apply. The channel lag time is the product of flood wave celerity and channel length. The celerity is 5/3 times the flow velocity for in-bank flow. When the flow goes over-bank, the celerity has to be multiplied by the ratio of river width / total width (= river + flood plain width) (assuming that flood plain velocities << main stream velocities). Hence, for over-bank flow a different set of K, x parameters apply. Such a layered approach is not used in our model since flood plains play an insignificant role in the hydrological models for the Burhi-Gandak. The more important flood plain are modelled in the 1D/2D-model.

The run-off discharge which is computed at every of the run-off nodes of the hydrological model can directly be transferred by a RR-link or can be routed through a RR-routing link to a connection node. Which of the two types is needed depends on the location of both the outflow point of the sub catchment and the connection node. The latter representing the downstream confluence of the river branches.

Figure 4.2 shows an overview of the nodes and links of the hydrological model for the upper part of the Burhi-Gandak basin.

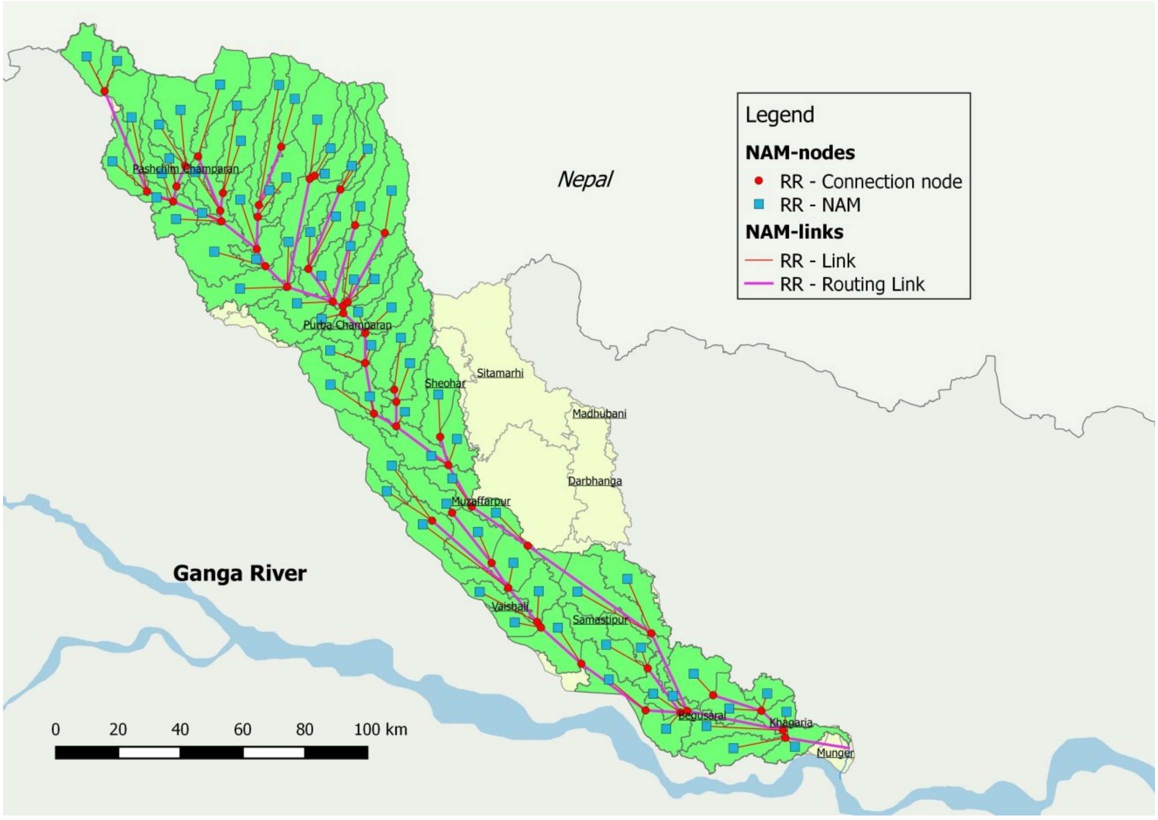


Figure 72 Nodes and links of the hydrological model the Burhi-Gandak basin

The red-colored lines represent the connections between the nodes without routing parameters. The purple colored lines represent the routing links between the nodes with routing properties. These routing links represent the streams and river branches in the system, which are important for simulating the proper hydrograph at the outflow points of the model. In table a.2 of appendix A an overview is given of the x- and k-values which are used at the routing links in the hydrological model of the upper part of the Burhi-Gandak basin.

4.4 Calibration approach

4.4.1 General

The main objective of our modelling activities is to set up models which are tuned for simulation of high flow periods in order to simulate (future) flood events in a satisfactory way. The applied approach for the calibration and validation of the models therefore is to select a suitable period for the calibration as well as for the validation. And suitable means that we use a representative situation where flooding occurs and, most importantly, where simultaneous forcing data and measurements are available. This means in case of model simulation of 1D/2D flooding that besides water level and discharge measurements, also raster data of the actual flood extents, e.g. based on satellite data, should be available. The latter seemed rather difficult at times.

For calibration and validation we compare the model outputs with the observations, while looking at certain key values. These key values may be different for the different model components, such as:

Table 4.1 Model outputs for comparison at calibration and validation

Model component	Location/Station	Comparison
RR/1D-flow	Khagaria, Samastipur, Muzzafarpur, Rosera	H-max, T-peak, GoF
RR/1D/2D-flow	Khagaria, Samastipur, Muzzafarpur, Rosera	H-max, T-peak, GoF
RR/1D/2D-flow	Flood extent	Flood map, Total area

The GoF expression in table 4.1 refers to the Goodness of Fit indicators, which may give insight in the overall difference between the model simulation outputs and the observations. Indicator T-peak refers to the time of occurrence of the maximum water level or discharge.

4.4.2 Selection of calibration periods

For the simulation of the hydrological model of the Burhi-Gandak basin we have selected consecutive years for the period 2007. For the calibration as well for the validation we looked at different flood periods of 2007.

4.4.3 Meteorological forcing

The hydrological model of the Burhi-Gandak basin uses precipitation and evaporation as forcing parameters. The precipitation is used from 7 rain gauging stations maintained by CWC and one station in Nepal. The stations are listed in table 4.2.

Table 4.2 List of rain gauging stations as used for the hydrological modelling in the Burhi-Gandak basin

Station	Area (km^2)
Chanpatiya	3269.5
Khagaria	717.0
Muzafarpur	1103.0
Simara (Nepal)	2180.0
Samastipur	1519.0
Ahirwalia	1455.0
Rosera	1229.0
Lalbegiaghat	2174.0

In table 4.2 also the areas are given resulting from the Thiessen calculation in GIS. In our model we use the precipitation on a daily basis.

Regarding the evaporation we have sourced a time series of Muzzafarpurr station from CWC for the period of January 2004 – March 2014.

4.4.4 Goodness of Fit criteria

The evaluation of hydrologic model behaviour and performance is commonly made and reported through comparisons of simulated and observed variables. Frequently, comparisons are made between simulated and measured stream flow at the catchment outlet. In distributed hydrological modelling approaches, additional comparisons of simulated and observed measurements for multi-response validation may be integrated into the evaluation procedure to assess overall modelling performance. In both approaches, single and multi-response, efficiency criteria are commonly used by hydrologists to provide an objective assessment of the Goodness of Fit (GoF) of the simulated behaviour to the observed measurements. While there are a few efficiency criteria such as the Nash-Sutcliffe efficiency, coefficient of determination, and index of agreement that are frequently used in hydrologic modelling studies and reported in the literature, there are a large number of other efficiency criteria to choose from. The selection and use of specific efficiency criteria and the interpretation of the results can be a challenge for even the most experienced hydrologist since each criterion may place different emphasis on different types of simulated and observed behaviours. Kraus et.al. (2005) investigated nine different efficiency measures for the evaluation of model performance with three different examples. They found that none of the efficiency criteria described and tested performed ideally. Each of the criteria has specific pros and cons which have to be taken into account during model calibration and evaluation. They concluded that the selection of the best efficiency measures should reflect the intended use of the model and should concern model quantities which are deemed relevant for the study at hand. For scientific sound model calibration and validation a combination of different efficiency criteria complemented by the assessment of the absolute or relative volume error is recommended. In our study we focus on high flows and consider the correct simulation of low flows as less relevant. Kraus et.al. found that the Nash-Sutcliff efficiency is sensitive to peak flows so it is suitable for application in our study.

The efficiency E proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. It is calculated as:

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2}$$

Where:

O_i = observation at time step i

P_i = prediction at time step i

$\bar{O}$ = average of observations

For the calibration and validation of the hydrological model in the upper part of the Burhi-Gandak basin we use the Nash-Sutcliffe efficiency together with the assessment of the volume errors. For the combined RR/1D/2D-flow model in the lower part of the Burhi-Gandak basin we use the Nash-Sutcliffe efficiency as well as the other indicators as shown in table 4.1.

4.5 Initial parameter settings

4.5.1 Model input

As already explained in paragraph 4.4.3, we use the observed rainfall at the CWC rain gauging stations on a daily basis and the evaporation from station Muzzafarpur as the meteorological forcing for hydrological model. The hydrological model for the Burhi-Gandak basin has been run stand alone to perform a first estimation of the NAM-parameters by verifying the discharge downstream in Burhi-Gandak river. We applied different settings for the NAM-parameters. The final set of NAM-parameters is given in tables 4.3a, 4.3b and 4.3c.

Table 4.3a Settings for each Initial parameter definition for the Burhi-Gandak basin model

Parameter	Description	Unit	Parameter definition
			test_initial
unul	Initial waterdepth in surface storage	mm	0.75
lnul	Initial waterdepth in lower zone storage	mm	10
qif1	Initial waterdepth in first interflow storage	mm	0
qif2	Initial waterdepth in second interflow storage	mm	0
of	Initial waterdepth in overland flow storage	mm	0
bf	Initial waterdepth in groundwater storage	mm	400

Table 4.3b Settings for each capacity parameter definition for the Burhi-Gandak basin model

Parameter	Description	Unit	Parameter definition		
			Cap_chanpatiya	cap_LBG	Test_cap
umax	Maximum water depth in surface storage	mm	20	20	10
lmax	Maximum water depth in lower zone storage	mm	80	80	150
tof	Threshold used for overland flow	-	0.9	0.85	0.7
tif	Threshold used for interflow		0.45	0.45	0.5
tg	Threshold used for groundwater recharge		0.6	0.6	0.7

Table 4.3c Settings for each runoff parameter definition for the Burhi-Gandak basin model

Parameter	Description	Unit	Parameter definition		
			Test_runoff	runoff_chanpatiya	runoff_LBG
cqof	Overland flow runoff coefficient	-	0.45	0.8	0.8
ckif	Time constant for interflow	days	592.1	150	150
ck12	Time constant for routing interflow and overland flow	1/hr	0.0147	0.05	0.02
ofmin	Upper limit determining overland flow runoff coefficient	mm	10	10	10
beta	Exponent determining overland flow runoff coefficient	-	0.4	0.48	0.48
ckbf	Time constant for base flow	days	1945	500	500

The setting of the parameters is based on expert judgement. At the time of setting up the model schematization, the actual soil maps and characteristics were not available. The routing parameter settings of the connecting routing links have been derived using expert judgement and the slopes in the terrain as can be extracted from the DEM. Since no discharge measurements were available within the area which is covered by the hydrological model, we decided to calibrate and validate the hydrological model in combination with the 1D-flow/2D-overland flow simulation modules.

The parameter definitions as shown in table 4.3 are connected to each one of the NAM-runoff nodes in the hydrological model. In Appendix A, table A.1 an overview of the nodes is given including the assigned parameter definitions.

Chapter 5 1D/2D Hydrodynamic model

5.1 Introduction

A hydrodynamic model of the Burhi-Gandak basin is complex due to the multiple facets of the natural flow system to be physically described. The Burhi-Gandak constitutes an inland delta on the confluence of multiple rivers in an area with a low topographic gradient. The situation is further complicated by the fact that the lower part of the main river in the system, the Burhi-Gandak, is highly dominated by the water levels in the Ganga River.

A representation of the hydrodynamics of the area by a simulation model requires the combined use of a 1D hydraulic model, representing the principal river network, and a selected group of these smaller channels, and with a 2D inundation model for an area of interest. Given the large extent of the basin the generation of runoff and evaporation loss within the area itself needs to be taken into account by a water balance model, in order to ensure a solid closure of the water balance. Without doing so, the net runoff (precipitation minus evapo-transpiration) would not be correctly accounted for, leading to underestimation of flow exiting the area at the lower boundary node and underestimating water levels and flows within the area. Therefore, also a hydrological model is included.

5.1.1 Integrated 1D/2D modelling

The model proposed for the hydrodynamic modelling of the basin is the DELTARES model SOBEK 1D/2D (www.deltaressystems.com/hydro/product/108282/sobek-suite). The SOBEK model is based on the solution of the Saint-Venant equations for channel flow and the solution of the shallow water equations for 2D flow. In both cases a coupled system of mass and momentum conservation equations is solved after applying appropriate initial and boundary conditions.

The Saint-Venant equations constitute the 1D model, while the shallow water equations are solved within the 2D version. The two models are mutually inter-connected in such a way, that the 1D Saint-Venant equations are solved if the water is flowing unidirectional within the channel network. As soon as the water level reaches a critical level and overtopping or levee collapses occur, water floods the areas surrounding the channel network, leading to a situation in which the 2D shallow water equation solver is activated.

5.1.2 Rationale for model selection

In flood modelling, there are numerous practical examples where flows are best described by combinations of 1D and 2D schematizations. An obvious example is the flooding of deltaic areas, often characterized by a flat topography with complex networks of natural levees, polder dikes, drainage channels, elevated roads a possible variety of hydraulic structures. This is the case in the Burhi-Gandak basin.

Flow over flat terrains is best described by the 2D equations, whereas channel flow and the role of hydraulic structures are satisfactorily described in 1D. Flow over higher elevated line elements, such as roads and embankments can be modelled reasonably well in 2D by raising the bottom of computational cells to embankment level. Higher accuracy of the numerical description can be achieved by applying adapted formulations, such as energy conservation upstream of overtopped embankments.

Floods often propagate in meandering rivers, with shortcuts via the flood plain when overbank flow occurs. In large scale models, the flow between the river banks is satisfactorily described by the Saint Venant equations solved with 1D grid steps several times the width of the channel. An equivalent accuracy of description of flow between the river banks in 2D would require a large number of grid cells, with step sizes being a fraction of the channel width. However, flow in the flood plain may be better described in 2D and may allow for 2D grid steps often exceeding the width of the river.

For this reason, SOBEK has been developed for the application of hybrid 1D and 2D schematizations. Basically there was a choice to be made between two approaches during the implementation decision process: one with interfaces defined between 1D and 2D along vertical planes and the other approach with schematization interfaces in almost horizontal planes.

Coupling along vertical planes, gives a full separation in the horizontal space of the 1D and 2D modelled domains. In the 1D domain the flow is modelled with the Saint Venant equations applied over the full water depth. The direction of flow in the 1D domain is assumed to follow the channel x-axis and in the model it carries its momentum in this direction, also above bank level. Physically this is incorrect.

In a model coupled along an almost horizontal plane, 2D grid cells are placed above the 1D domain, as shown in Figure 5.1. In this schematization, the 1D Saint Venant equations are applied only up to bank level. Above this level, the flow description in the 2D cell takes over. For relatively small channel widths compared to the 2D cell size, errors in neglecting the effect of momentum transfer at the interface are minor. For wider channels, resolved by several 2D grid cells, the hydraulic radius in the 2D cells that overlie a 1D channel should be corrected for the local depth in the 1D model part. This can be done be specifying a separate GIS-layer containing the difference between true and modelled 2D bathymetry. In turn, the hydraulic radius in the 1D part is corrected for the thickness of the 2D water layer if this 2D layer carries flow. In this way, both the 1D and 2D part use a consistent hydraulic radius.

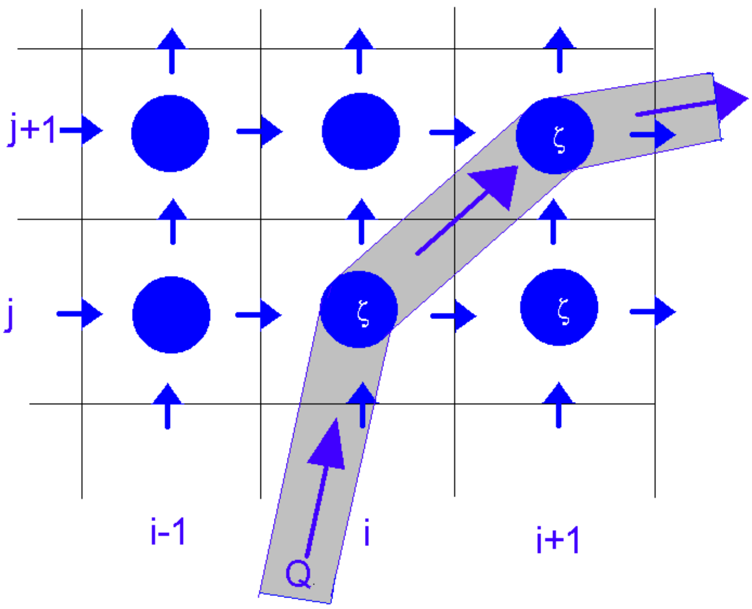


Figure 5.1 Coupling of 1D and 2D domains in SOBEK

This last approach has been implemented in SOBEK and guarantees the most realistic schematization of the integrated 1D and 2D flow processes. This approach also has the advantage that larger grid cells can be used in the integrated 1D2D models as compared with models which use the coupling via vertical interfaces. In SOBEK the coupling between 1D and 2D is generated automatically, reducing the amount of work required for model construction and reducing the possibility of introducing errors in the coupling.

5.2 Setup of the 1D/2D hydrodynamic model

The proposed hydrodynamic model for Burhi-Gandak consists of a 1D channel flow combined with a lumped hydrological model. The 1D model includes the rivers and larger channel system of the Burhi-Gandak basin up to the boundary at the confluence with the Ganga River. Furthermore, the 1D/2D model has been coupled with the hydrological model, which has been schematized as discussed in paragraphs 4.3.2 and 4.3.3 of chapter 4. The calibration of the combined model will include all model components: NAM, 1D-flow and 2D-overland flow.

5.2.1 The schematised river system

The 1D hydrodynamic model is schematized with a number of nodes and branches as is shown in figure 5.2.

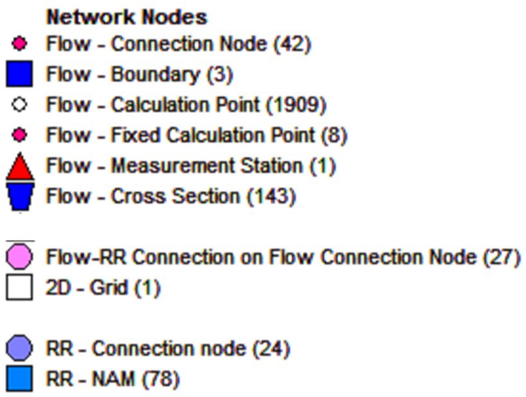


Figure 5.2 Nodes as used in the SOBEK schematization for the Burhi-Gandak basin

An overview of the model schematization is shown in figure 5.3.

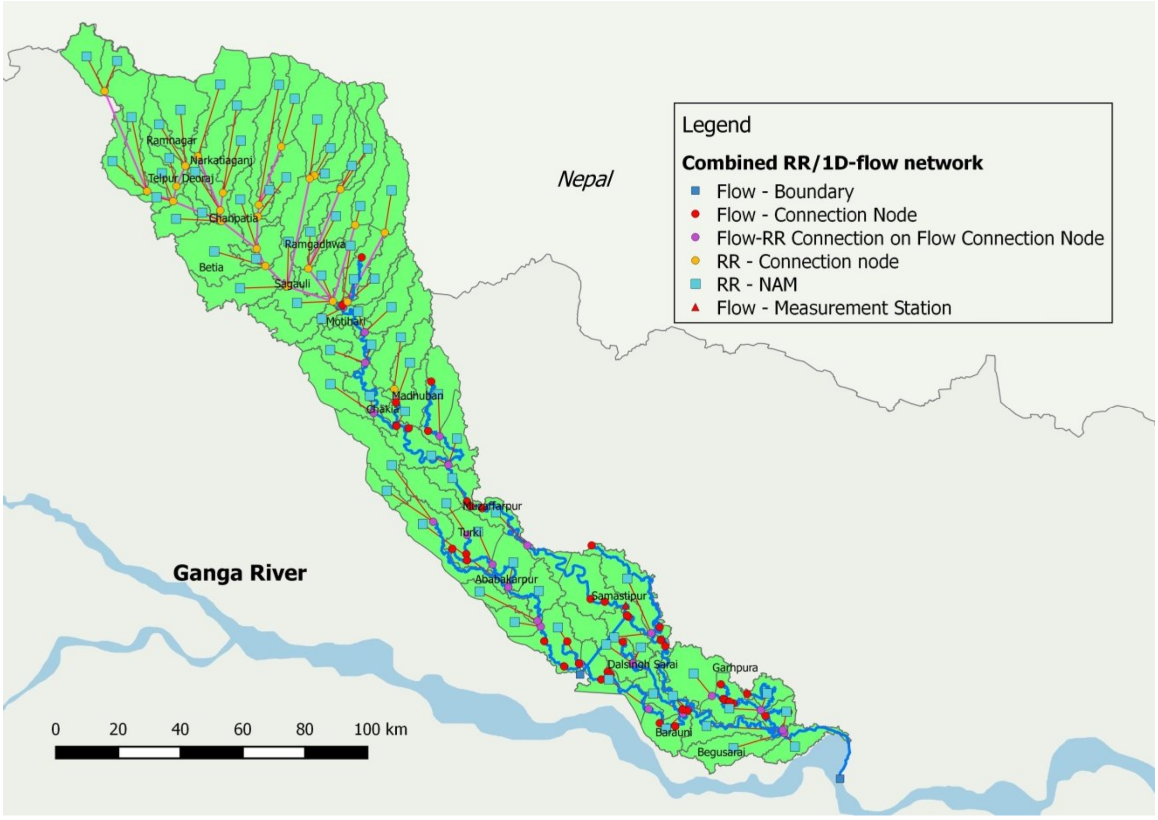


Figure 5.3 Overview of the SOBEK schematization for the Burhi-Gandak basin

The delineation of the 1D-flow network has been based on the river network data (ESRI-shape-files), which was provided by several Indian national and state agencies. By comparing these shape files with Google Earth images of the river network the overall fit has been improved. This was done by deriving the outline of the main river network using OpenStreetMap, (see www.openstreetmap.org). The Indian set was downloaded on October 15, 2014 and was used to improve the river network (see http://download.geofabrik.de/asia/india.html).

5.2.2 Cross-sections

The 1D-flow model comprises a total number of 143 cross sections which are spread across the 1D-channel flow network. At the first setup of the model there were only a few number of surveyed cross sections available. For the greater part of the schematization a trapezium profile has been assumed. The width and height of the latter have been based on expert judgement and information from Google Earth. During this project field activities have been carried out to survey a total number of 60 cross sections in the lower Burhi-Gandak basin. Appendix A, table A.3 comprises the list of surveyed cross sections.

5.2.3 Structures

The hydrodynamic model in its basic setup does not comprise hydraulic structures. These will be added when the planned projects will be implemented.

5.2.4 Overland flow

5.2.4.1 Digital Elevation Model (DEM) preparation

For the overland flow module in the combined RR/1D/2D simulation model, the SRTM 30 m DEM has been processed for use in the model. Therefore a number of steps have been carried out.

Firstly, the actual terrain levels in the DEM have been compared with the terrain levels from the topo sheets which were sourced from the State of Bihar. Figure 5.4 shows the comparison of the topo sheet values and the SRTM 30 m DEM values.

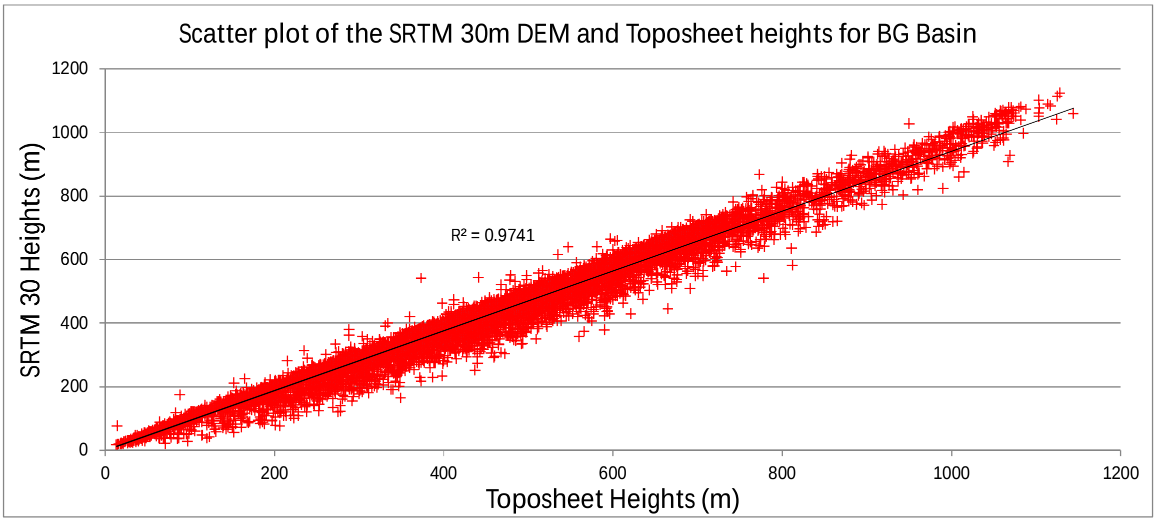


Figure 5.4 Comparison of terrain levels from the topo sheets and the 30m SRTM DEM for the Burhi-Gandak basin.

Secondly, the actual terrain levels in the DEM have been compared with the terrain levels from the surveyed cross sections. This comparison showed that the SRTM 30 m DEM values were on average close to the recorded values for the surveyed cross sections. Based on this we concluded that it was not necessary to apply a vertical shift on the DEM values.

Thirdly, the SRTM DEM 30 m has been smoothened by applying low-pass filtering. Fourthly, a resampled DEM has been derived with 500 m cell size for Burhi-Gandak basin. The latter is used as the input for the overland flow module of the combined RR/1D/2D simulation model. Figure 5.5 shows the DEM as used in the 2D-overland flow module of the simulation model.

5.2.4.2 Line elements

Line elements can be of importance for interaction with overland flow. The most important line elements are (rail) roads and dikes. For the roads we have used available information which consists of a shape file where in the attribute data a distinction is made between Highways, type 1, and Major roads, type 2, see also paragraph 3.6. The latter paragraph also discusses the embankments, for which elevation data became not available from the State of Bihar. No rail road data was available, thus this has not been taken into account. The interaction with the overland flow can generally be seen as an obstruction to the overland flow by higher elevated roads and dikes. Discussions with the team resulted in assumed elevations of road elements. The embankment sections as given in table 5.3

Table 5.3 Relative elevations of line elements

Line element	elevation w.r.t. terrain level
High ways	1.5 m
Major roads	1.0 m

The line elements with the relative elevations from table 5.3 have been converted to raster data with a 500 m resolution using GIS. After the conversion this raster data has been superposed on the 500 m resolution DEM as discussed in the previous paragraph. Figure 5.5 shows the resulting DEM as used in the 2D-overland flow module of the simulation mode.

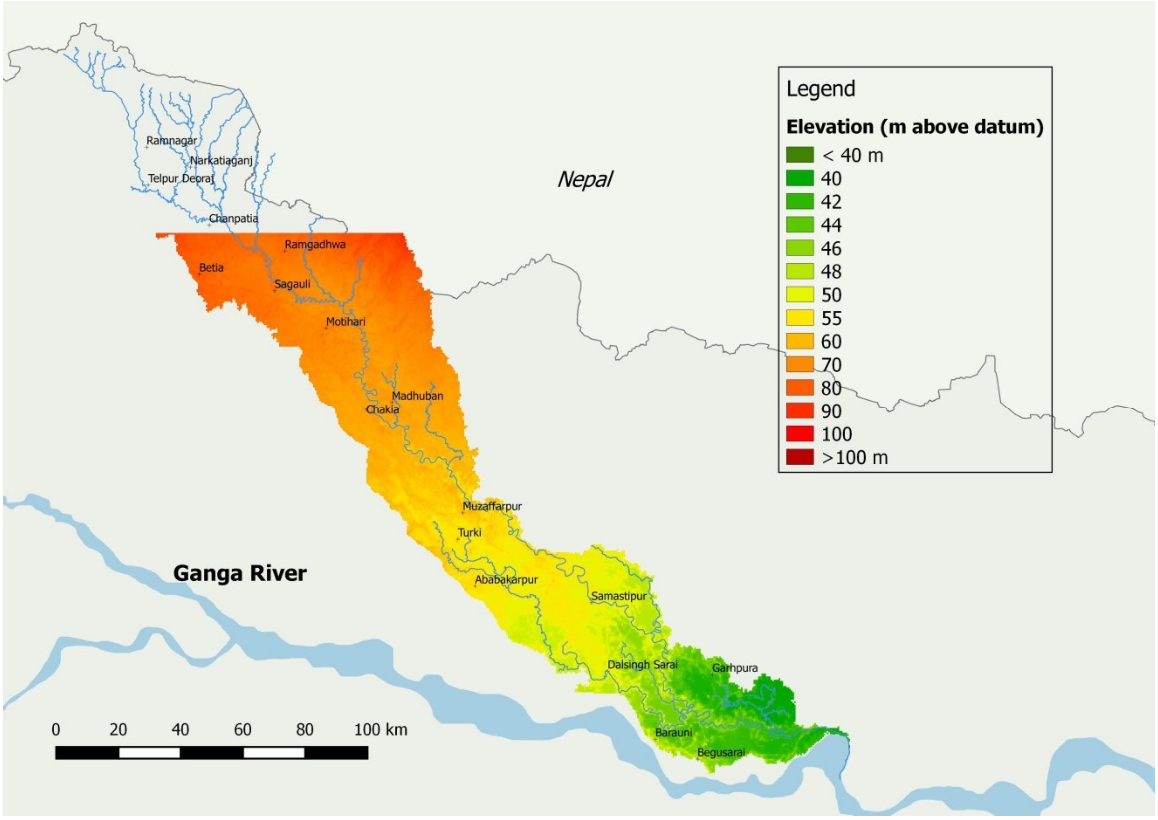


Figure 5.5 DEM with 500 m resolution as used in overland flow module of the simulation model

If flooding in the model is simulated then it will occur in the green, yellow and orange shaded areas of the DEM and in the areas close to the river branches in the red shaded areas. For application in the combined RR/1D-flow/2D-overland flow model, the DEM has been cut at the upstream boundaries of the 1D-flow model. This is done because overland flow only can occur where also 1D-channels are modelled in case of a combined 1D/2D-flow setup. In the 2D-modelled area, the elevations range roughly between 40 m above datum at the confluence with the Ganga river and 80 m above datum at the upstream part near Ramgadhwa. This means an elevation gradient of about 40m at a distance a roughly 250 km, or 0.00016, which for river systems is very flat. This also means that when inundation starts to occur, the extent of the flooding can spread easily when no elevated obstructions like dikes and roads are present.

5.2.4.3 Friction

For simulation of overland flow we need also friction data. To derive the friction data we have used the land use data which is sourced from the Government of Bihar, see also paragraph 3.3 from Chapter 3. The land use type can be converted to friction data using similar land use types as in the CORINE land cover map for which Arcement (1989) derived Manning friction coefficients. The Manning coefficients for each land use type are shown in table 5.4.

Table 5.4 Manning coefficients for each land use type in the Burhi-Gandak basin.

Land use type	Name in CORINE database	Manning
Urban	Continuous urban fabric	0.048
Rural	Natural grasslands	0.040
Mining	Mineral extraction sites	0.068
Crop land	Land principally occupied by agriculture, with significant areas	0.041
Plantation	Fruit trees and berry plantations	0.054
Fallow	Pastures	0.035
Current Shifting cultivation	Complex cultivation patterns	0.043
Deciduous	Mixed forest	0.090
Forest Plantation	Broad-leaved forest	0.100
Scrub Forest	Transitional woodland-shrub	0.060
Swamp / Mangroves	Inland marshes	0.050
Grass/ Grazing	Natural grasslands	0.040
Gullied / Ravenous Land	Sparsely vegetated areas	0.039
Scrub land	Natural grasslands	0.040
Sandy area	Beaches, dunes, sands	0.038
Barren rocky	Bare rocks	0.061
Inland Wetland	Inland marshes	0.050
Coastal Wetland	Coastal lagoons	0.030
River / Stream / canals	Water courses	0.030
Water bodies	Water bodies	0.030

The land use raster data, cell size 66 m, has been resampled to 500 m applying the 90 percentile values of the source data. From the land use raster map a 500 m friction raster data set has been derived using the values from table 5.4. The Manning coefficient raster data set is shown in figure 5.6.

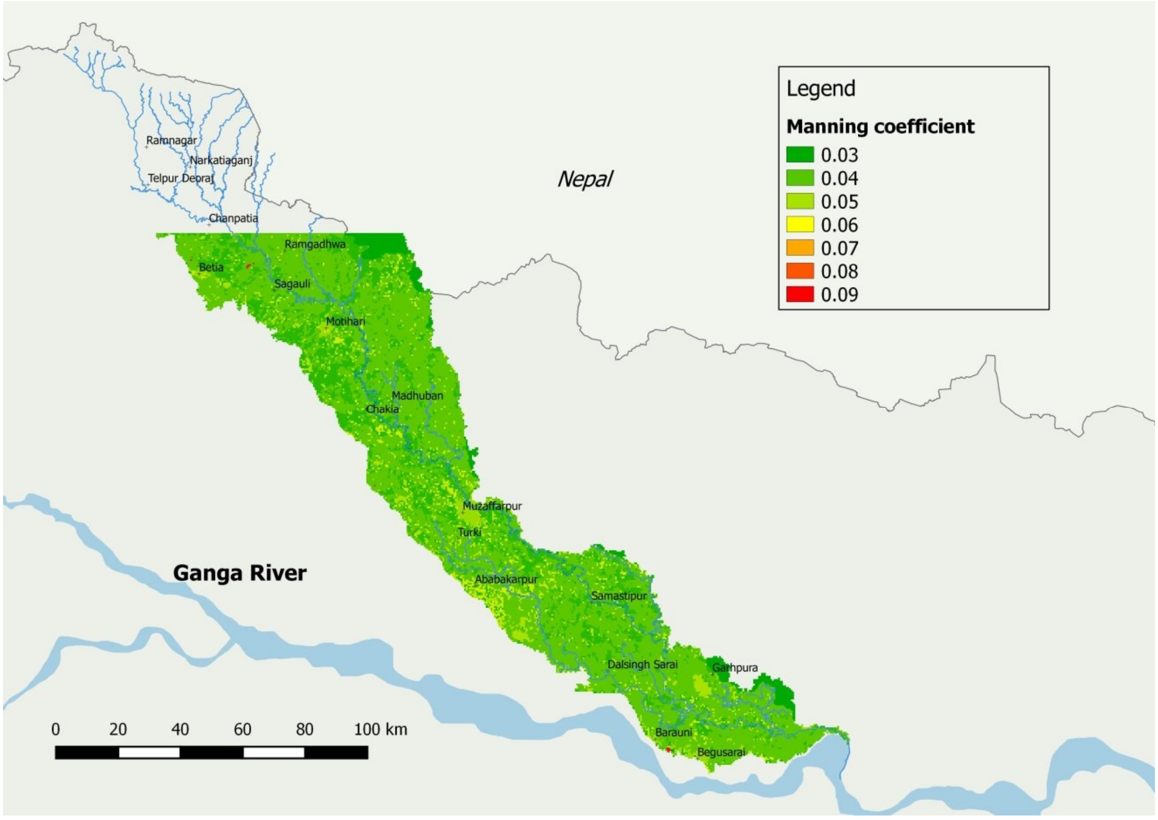


Figure 5.6 Manning coefficients as used in the overland flow module of the Burhi-Gandak simulation model.

5.2.5 Boundary conditions

The combined model of the lower Burhi-Gandak basin uses a number of boundary conditions to operate properly. The boundary conditions for the hydrological component we use the rainfall and evaporation forcing of 10 stations sourced from the CWC, see table 5.5.

Table 5.5 Rainfall stations as used for the hydrological model of the lower Burhi-Gandak basin

Station	Station	Forcing
1	Chanpatiya	Rainfall
2	Lalbegiaghat	Rainfall
3	Ahirwalia	Rainfall
4	Muzafarpur	Rainfall
5	Samastipur	Rainfall
6	Rosera	Rainfall
7	Khagaria	Rainfall

The boundary conditions as used for the 1D component are sourced from the CWC and listed in table 5.6.

Table 5.6 Locations with boundary conditions for the simulation model of the lower Burhi-Gandak basin

Location	Boudary condition type	Unit
Ganga River water level	time series	m above datum

We did not implement boundary conditions for the 2D-overland flow component of the simulation model. When the 1D-flow component overtops the top levels of the cross sections, the overtopping water is flowing into the 2D-overland flow component, which in fact functions as an internal boundary condition.

5.2.6 Ganga water level boundary

For the water level boundary conditions we sourced the times series of measurements at stations Hathidah and Munger from the SoI on which we performed a linear interpolation. We used these time series as the water level boundary at the confluence of the Burhi-Gandak river with the Ganga River. Figure 5.8 shows the time series for the period June 15th, 2003 till October 15th, 2014.

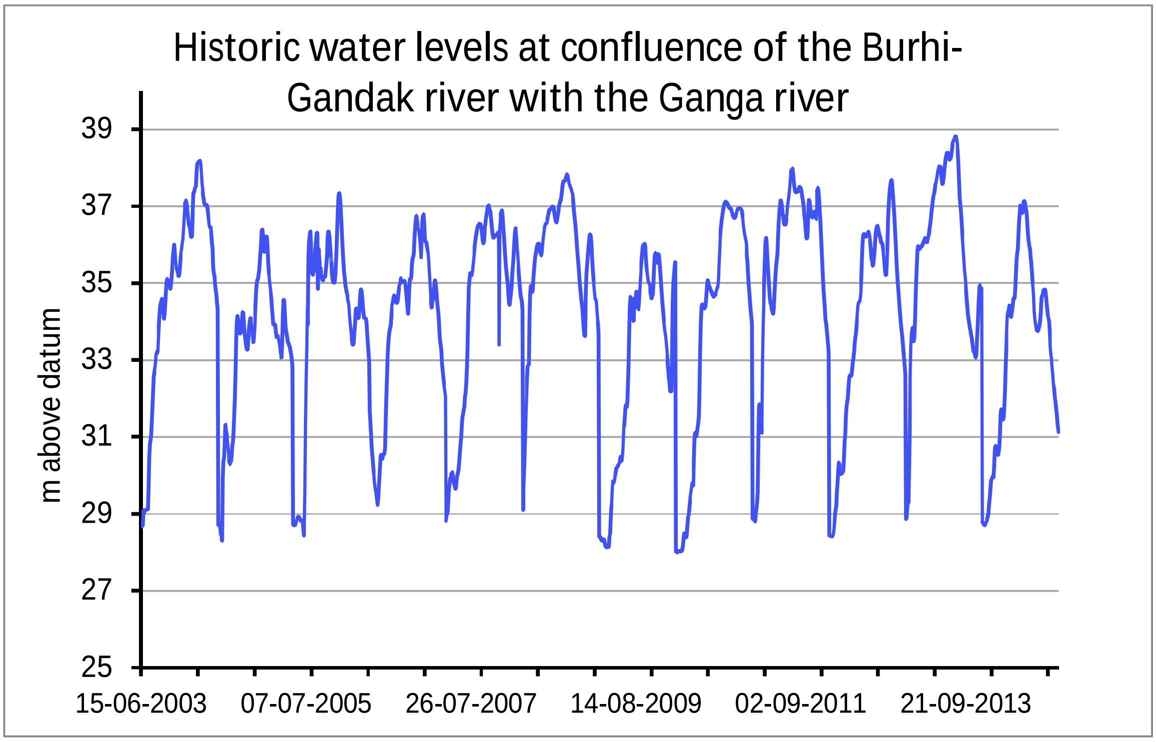


Figure 5.8 Water level time series at the confluence of the Burhi-Gandak river with the Gang River

The time series as shown in figure 5.8 are not continuous, but hold only the data for the monsoon period, June-October for every year. Table 5.7 shows the distribution of the maximum water levels in each of the months.

Table 5.7 Distribution of the maximum water levels in the monsoon season for the period 2003-2014 for the confluence of the Burhi-Gandak and Ganga rivers. Values in m above datum.

Year	6	7	8	9	10
2003	31.05	35.11	37.17	38.19	36.53
2004	31.32	34.25	36.40	36.21	33.91
2005	28.93	36.35	37.35	36.46	34.85
2006	31.67	34.75	36.76	36.80	34.61
2007	30.09	35.94	37.03	36.90	36.42
2008	34.93	36.93	37.84	37.43	36.27

Year	6	7	8	9	10
2009	28.40	32.36	36.03	35.79	35.55
2010	28.49	34.46	37.01	37.13	36.51
2011	31.86	37.16	37.99	37.49	36.89
2012	30.34	34.38	36.50	37.69	35.62
2013	33.94	37.43	38.70	38.83	34.96
2014	29.94	34.42	37.14	35.54	33.75

The colours in table 5.7 indicate high maximums (red shaded) and lower maximums (green shaded). Overall is shown that during August and September the maximum water levels are recorded. We see also that the year 2013 shows high water levels for July – September and has the highest values for this set of years. Figure 5.9 shows the frequency distribution of the maximum water levels at the same location for the same period.

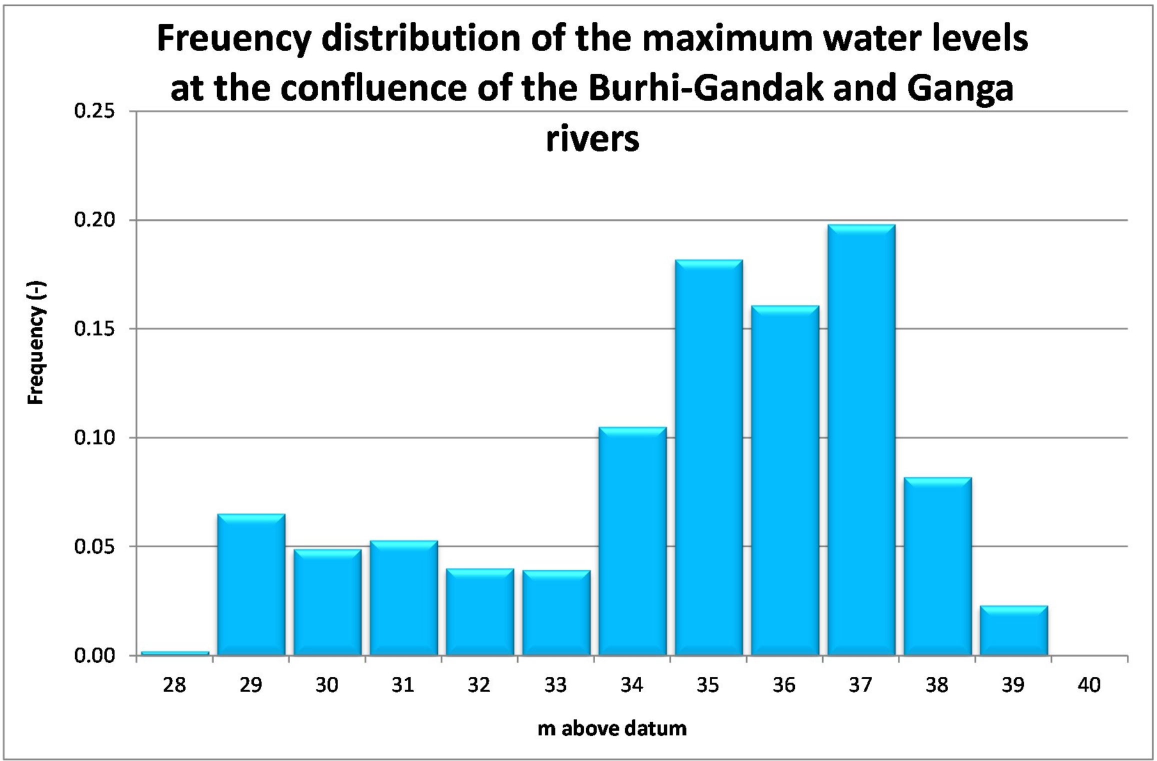


Figure 5.9 Water level time series at the confluence of the Burhi-Gandak river with the Gang River

Figure 5.9 shows that in total more than 50 % of the maximum water levels are in the range of 35-37 m. About 10 % of the values are higher than 37 m above datum.

5.2.7 Initial conditions

For starting a simulation for the first time, we have selected a water depth of 2 m in all the 1D-flow sections of the simulation model. At the completion of the calculation we write the settings of the flow channel to a so-called restart file. This restart file comprises the last values of all parameters at every calculation point in the model. These values can then be used as initial values for the next simulation runs.

The same holds for the hydrological model for which the initial settings are already discussed in paragraph 4.5 of Chapter 4. The restart file which is produced after the initial run, is used as initial file for the next runs.

For the 2D-overland flow module there are no additional initial conditions other than to start every simulation run with a total dry 2D-model.

5.2.8 Simulation settings

The BG-model uses a simulation time step of 1 hour. This time step is determined by combining: i) simulation results of assessing the sensitivity of the water level on changes in the time step; and ii) a model with limited simulation time. When changes in simulation conditions do vary significantly in a short time period, the model automatically cuts down the simulation time step, so numerical instabilities will be avoided. This happens when overland flow stars to occur changing from dry land state to wetted state. Independent of this, model results will be produced at one hour time step intervals as values computed at those moments in time.

5.3 Calibration and validation of the RR/1D/2D-model

5.3.1 General approach

The main objective of our modelling activities is to setup models which are tuned for simulation of high flow periods in order to simulate (future) flood events in a satisfactory way. The applied approach for the calibration and validation of the models therefore is to select a suitable period for the calibration as well as for the validation. And suitable means that we use a representative situation where flooding occurs and, most importantly, where simultaneous forcing data and measurements are available. This means in case of model simulation of 1D/2D flooding that besides water level and discharge measurements, also raster data of the actual flood extents, e.g. based on satellite data, should be available. The latter seemed rather difficult at times.

For calibration and validation we compare the model outputs with the observations, while looking at certain key values. These key values may be different for the different model components, such as already listed in table 4.1 of Chapter 4. For convenience we list the key values as used for the combined RR/1D/2D-model in the table 5.8 again.

Table 5.8 Model outputs for comparison at calibration and validation

Step	Model component	Location/Station	Comparison
1	RR	Lalbegiaghat (LBL)	H-max, T-peak, GoF
2	RR/1D-flow	Sikandarpur, Samastipur	H-max, T-peak, GoF
3	RR/1D/2D-flow	Sikandarpur, Samastipur	H-max, T-peak, GoF
4	RR/1D/2D-flow	Flood extent	Flood map, Total area

From the table it can be derived that we look at the discharges in Lalbegiaghat (LBL) at the water levels in stations Sikandarpur and Samastipur. We have used a multi-step approach to go through the calibration and validation process. This is done to make the process more transparent by looking at the parameters of each model component separately. As the first step, we adjusted the parameters of the hydrological model roughly based on expert judgement to get an initial setting of the model parameters. Due to the fact that in the coverage of the hydrological model (NAM-model) only station LBL was available to be used for calibration, we calibrated the upstream part of the RR-model using the data of station LBL. From this step we derived a first estimation of the parameters for the RR-model. Furthermore, we calibrated and validated the NAM-model in combination with the 1D-flow model. With this last step we arrived at a second setting of the model parameters. It was expected that the absence of overland flow in the RR/1D-model would lead to overestimation of the water levels at some points. By calibrating and validating the combined RR/1D/2D-model including the simulation of overtopping of the dikes and of overland flow, the setting of the model parameters has been adapted again, where applicable. The results are discussed later on in this paragraph.

5.3.2 Selection of calibration periods

For the combined model of the Burhi-Gandak basin we have selected 30/06/2007-14/8/2007 as the calibration period and 15/8/2007-30/9/2007 as the validation period. We selected the year 2007 because the significance of the flooding in this year. For the upstream part of the RR-model we selected the monsoon period of 2005 as calibration period and the monsoon period of 2007 as validation period.

5.3.3 Meteorological forcing

The hydrological models of the Burhi-Gandak basin use precipitation and evaporation as forcing parameters. The precipitation is used from 7 rain gauging stations maintained by CWC and 1 station in Nepal. The stations are listed in table 5.9.

Table 5.9 List of rain gauging stations as used for the hydrological model of the Burhi-Gandak basin

#	RF -Station	Area (km^2)
1	Chanpatiya	3269.5
2	Lalbegiaghat	2174.0
3	Ahirwalia	1455.0
4	Muzafarpur	1103.0
5	Samastipur	1519.0
6	Rosera	1229.0
7	Khagaria	717.0
8	Simara (Nepal)	2180.0

In table 5.9 also the areas are given resulting from the Thiessen calculation in GIS. In our models we use the precipitation on a daily basis.

Regarding the evaporation we have sourced a time series of Jenapur station from CWC for the period of January 2004 – March 2014.

5.3.4 Goodness of Fit criteria

For the combined RR/1D/2D-flow model of the Burhi-Gandak basin as well as the upstream part of the RR-model we use the Nash-Sutcliffe efficiency as well as the other indicators as shown in table 5.8.

5.4 Calibration

5.4.1 Model input

As already explained in paragraph 4.4.3, we use the observed rainfall at the CWC rain gauging stations on a daily basis and the evaporation as the meteorological forcing for hydrological model. The hydrological model for the Burhi-Gandak basin has been run in combination with the 1D-flow model to perform the calibration and validation simulations. For the calibration of the model we applied the initial settings for the NAM-parameters as already discussed in paragraph 4.5.1 from Chapter 4. The final set of NAM-parameters is given in tables 4.3a, 4.3b and 4.3c.

For the 1D-flow model component the friction settings of the 1D-flow channels are of importance for calibrating the water levels. Table A.4 in Appendix A shows the settings for each of the 1D-flow channels (reaches). Also the vertical position w.r.t the datum is an important input value for referencing the water level. In practice it may occur that the datum of cross sectional data has been vertically shifted due to natural or manmade events. For the distribution and routing of the flows through the !D-channel network are besides the roughness values also the cross sectional areas of importance.

5.4.2 Calibration results

For the calibration of the RR-model upstream of Lalbegiaghat (LBG) we look at the discharges at station LBG. The results are shown in figure 5.15.

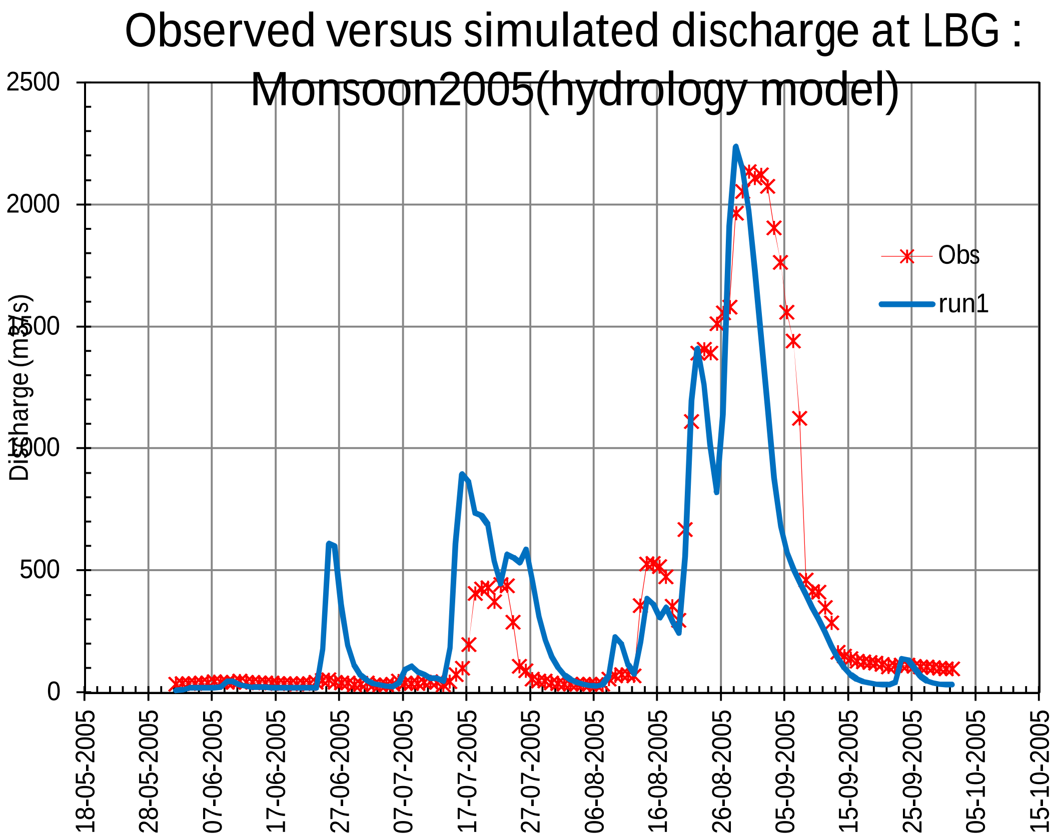


Figure 8 Observed and simulated water level at LBG for the monsoon period of 2005

For the calibration of the simulation model for the Burhi-Gandak basin we look at the water levels for stations Sikandarpur and Samastipur. The results for Sikandarpur are shown in figure 5.16.

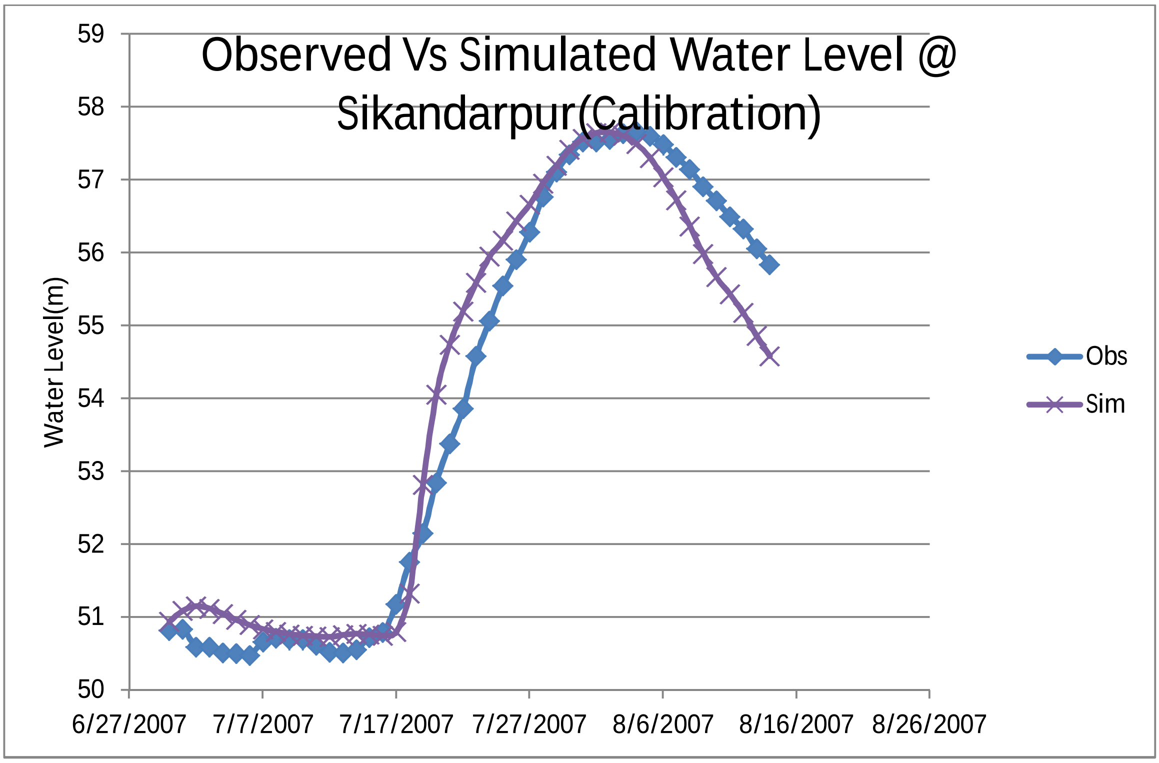


Figure 9 Observed and simulated water level at Sikandarpur for the period 30/6/2007-4/8/2007

The results for station Samastipur are shown in figure 5.17.

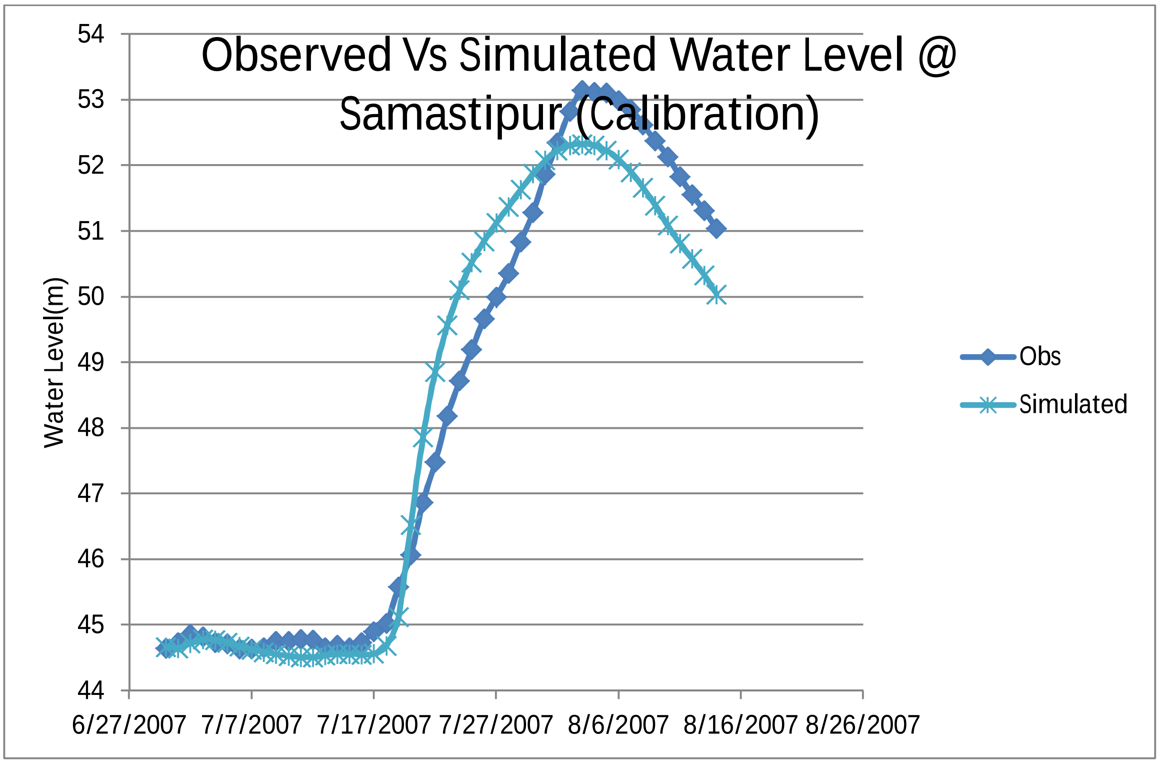


Figure 107 Observed and simulated water level at Samastipur for the period 30/6/2007-4/8/2007

5.4.3 Evaluation of GoF criteria

The evaluation criteria are given in table 5.10.

Table 5.10 GoF criteria for the calibration at stations LBL, Sikandarpur and Samastipur

Station	Criteria	Observed	Simulated	Difference	NSE
LBL	Peak discharge (m^3/s)	2135.0	2238.2	103.2 (4.8 %)	
	T-peak (date)	30-08-2005	28-08-2005	2 days	
	Nash-Sutcliffe Efficiency(-)				0.74
Sikandarpur	Peak level (m)	57.7	57.7	0.01	
	T-peak (date)	04-08-2007	02-08-2007	2 days	
	Nash-Sutcliffe Efficiency(-)				0.95
Samastipur	Peak level (m)	53.2	523	-0.90	
	T-peak (date)	03-08-2007	03-08-2007	0 days	
	Nash-Sutcliffe Efficiency(-)				0.95

5.5 Validation

5.5.1 Validation results

For the validation of the RR-model upstream of Lalbegiaghat (LBL) we look at the discharges at station LBL. The results are shown in figure figure 5.18.

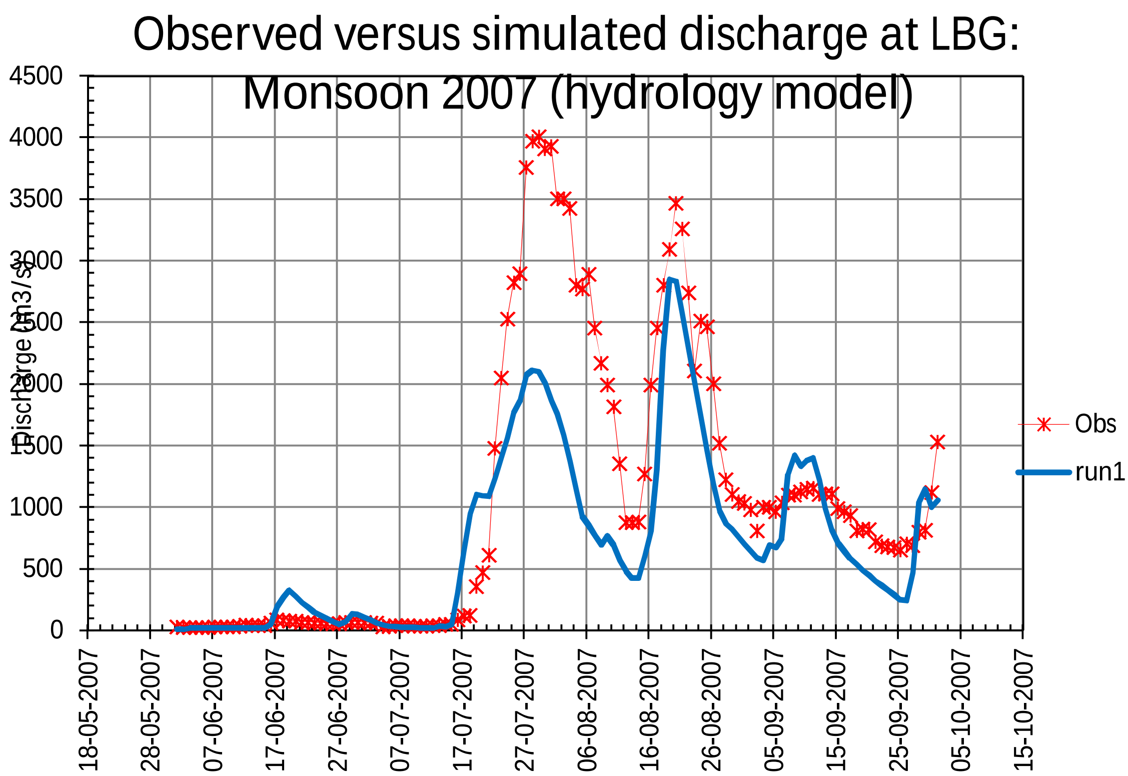


Figure 11 Observed and simulated water level at LBL for the monsoon period of 2007

For the validation of the simulation model for the Burhi-Gandak basin we look at the water levels for stations Sikandarpur and Samastipur. The results for Sikandarpur are shown in figure 5.19.

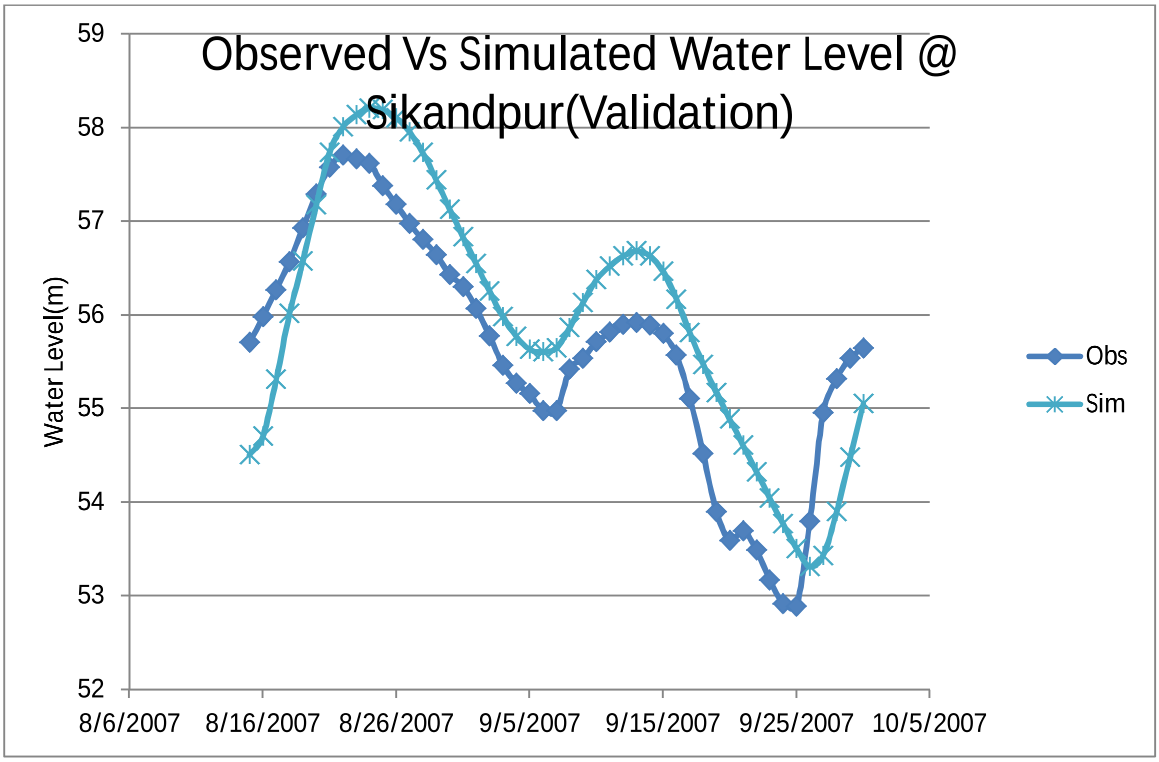


Figure 129 Observed and simulated water level at Sikandarpur for the period 15/8/2007-30/9/2007

The results for station Samastipur are shown in figure 5.20.

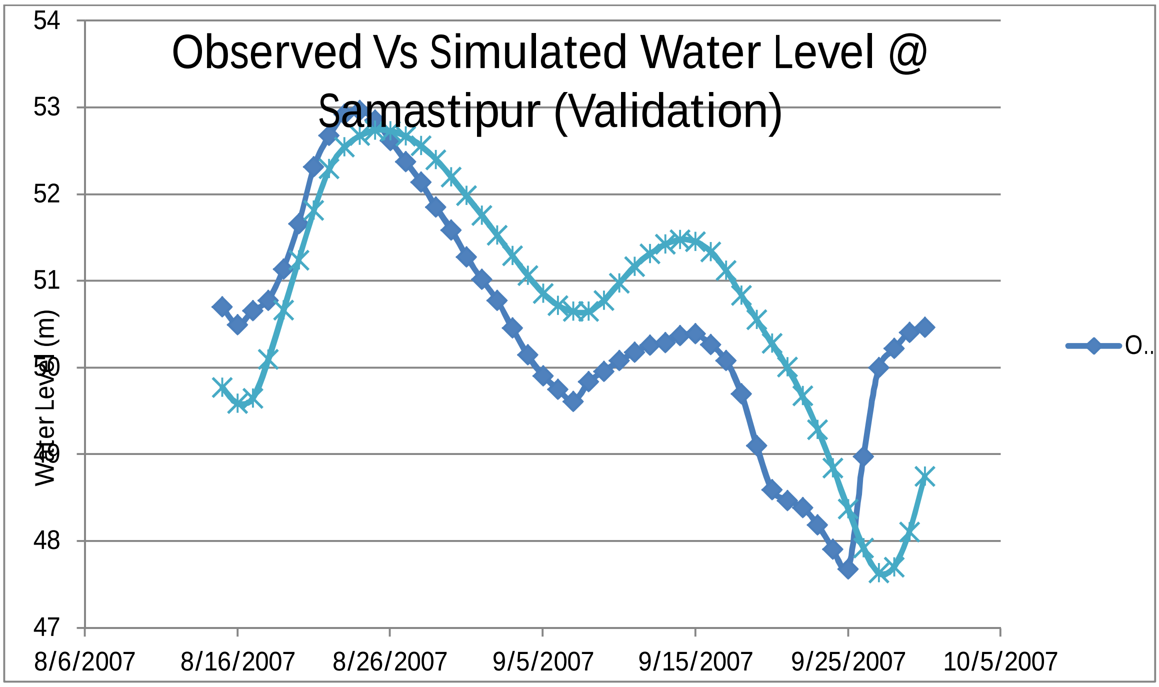


Figure 1320 Observed and simulated water level at Samastipur for the period 15/8/2007-30/9/2007

5.5.2 Evaluation of GoF criteria

The evaluation criteria are given in table 5.11.

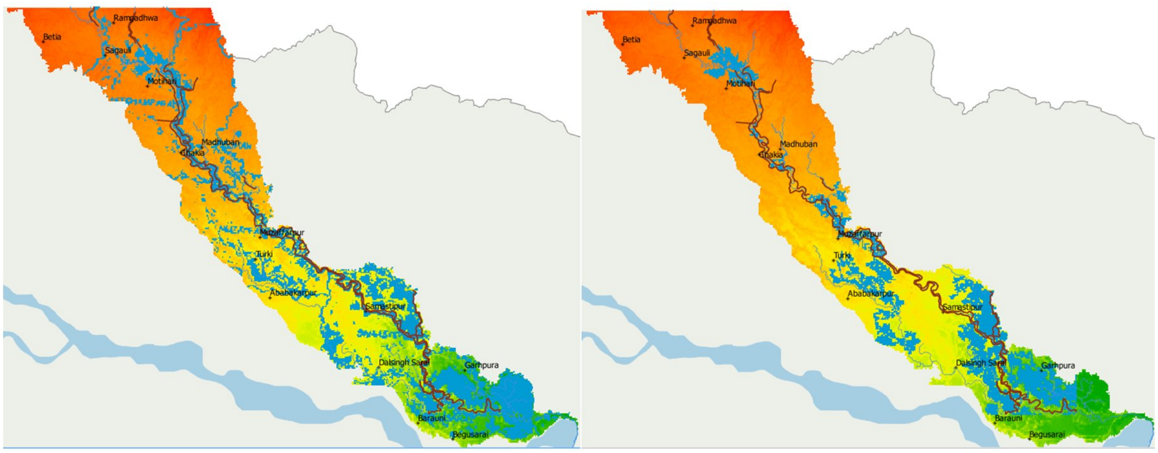
Table 5.11 GoF criteria for the validation at stations LBL, Sikandarpur and Samastipur

Station	Criteria	Observed	Simulated	Difference	NSE
LBL	Peak discharge (m^3/s)	3472.0	2848.8	-623.2 (-17.9 %)	
	T-peak (date)	20-08-2007	19-08-2007	1 day	
	Nash-Sutcliffe Efficiency(-)				0.60
Sikandarpur	Peak level (m)	57.7	58.2	0.50	
	T-peak (date)	22-08-2007	24-08-2007	2 days	
	Nash-Sutcliffe Efficiency(-)				0.61
Samastipur	Peak level (m)	53.0	52.8	-0.20	
	T-peak (date)	24-08-2007	25-08-2007	1 day	
	Nash-Sutcliffe Efficiency(-)				0.33

5.5.3 Flood extent

For the selected periods of calibration and validation only raster data with the flood extent for October 10th, 2007 were available. In figure 5.21 the flood extent is shown based on the analysis of Radarsat SAR data of 10/10/2007 and sourced from the Flood Management Information System of the State of Bihar.

Observed and simulated flood extent for October 10th, 2007



Observed Simulated

Figure 1420 Observed and simulated flood extent in the Burhi-Gandak basin for October 10th, 2007

As can be seen some differences in spatial distribution between simulated and observed flood extent occur. We see spots of inundation are observed where the model does not predict inundation. The reason may well be that the combined RR/1D-flow/2D-overland flow simulation model does not account for the smaller drainage systems in the rural areas. Rainfall on the area covered by the 2D-overland flow raster is processed by the hydrological model which routes the water to the 1D-flow module. Flooding and overland flow in the model only occur when the dikes of the 1D-flow channels are overtopped. Simulation of the hydrological process in this way may underestimate the water logging in the rural areas by excessive rainfall directly on the land.

It is also known that the sources of flooding in the Burhi-Gandak basin can lie outside the basin. These sources (overland flow from other river basins) are not included in the RR/1D-flow/2D-verland flow model of the Burhi-Gandak.

The calculated the total areas of both flood extents are given in table 5.12.

Table 5.12 Calculated flood extent areas for observed and simulated flooding of the lower part of the Burhi-Gandak basin for October 10th, 2007.

Flood extent	Observed	Simulated	Difference
Area (km^2)	1348.7	1229.0	-8.9%

It is shown that the difference between the simulated and the observed areas is less than 10 %, which indicates a good performance of the model. However, precautions are to be made due to the underestimation of waterlogging as discussed above. Underestimation can also occur when gaps in the embankments are present in reality, which the simulation model does not take into account.

5.6 Conclusions on calibration and validation

We have calibrated and validated the combined RR/1D/2D-simulation model for the Burhi-Gandak basin. Only a part of the hydrological model has been calibrated separately. The main part of the hydrologixal model has not been calibrated separately because gauging stations with observed data were not available in the area which is covered by the remaining part of the model. For the combined model of the Burhi-Gandak basin we have selected 30/06/2007-14/8/2007 as the calibration period and 15/8/2007-30/9/2007 as the validation period. For the upstream part of the RR-model we selected the monsoon period of 2005 as calibration period and the monsoon period of 2007 as validation period. The calibration and validation results have been examined for the following criteria:

- Time series graph;
- Peak level(s);
- Time of occurrence of the peak level (date);
- Nash-Sutcliffe Efficiency (-); and,
- Flood extent.

Time series graph: The simulation results show that the overall shape of the simulated time series graph resembles the observed series. The calibration run shows the best results for the three stations: discharges at LBG and water levels at Samastipur and Sikandarpur.

Peak levels: The simulation results for the calibration show that the peak level differences between simulated and observed water levels are simlulated well in Sikandarpur but are underestimated for Samastipur (-0.90 m). The peak discharges at LBL station are simulated well (+4.8 %). Regarding the validation period, the peak levels are overestimated at station Sikandarpur (+0.50 m) and underestimated at Samastipur (-0.20 m). The peak discharges at LBl station are underestimated with -17.9 %.

The time of occurrence of the peak flow: For the calibration period we see a time shift of the simulated peak water level in Sikandarpur of 2 days. The time of the simulated peak water level at station Samastipur is the same as observed. The two days shift is also seen in the peak discharge at LBL station. The simulation results for the validation period show that the peak levels for the three stations are predicted within the same simulation time step as the observed one.

The Nash-Sutcliffe efficiency (NSE): The NSE is regarded as a useful efficiency parameter in cases of simulations of high flows. The value of the NSE is regarded as poor < 0.5 and as excellent when equal to 1.0. At the stations Sikandarpur and Samastipur we found NSE values of 0.95 for the calibration period, which show a good model performance for simulating high flows. For station LBL we found a sufficient value for the NSE, 0.74.

For the validation period we found NSE values of 0.61 and 0.33 for the stations Sikandarpur and Samastipur respectively. The values show a lesser model performance for simulating high flows than for the calibration period. For station LBL we found an NSE value of 0.60 for the validation period.

Depending on the simulated monsoon period there seems to be an alternating quality of comparison between the peak flows. The resulting peak water levels values for both calibration (underestimation) and validation (underestimation) show that the difference between model simulation and observed values is not consistently underestimated or overestimated. The difference may vary between different hydrological situations. Given the limitations of datasets that were available for setting up the model and compilation of the model input data (nr. 1 modelling rule: garbage in = garbage out), we found a sufficient performance of the combined RR/1D/2D simulation model.

Flood extent: We have compared the observed and simulated flood extent for the flooding of October 10th, 2007. The comparison shows that the simulated flood extent differs within a reasonable amount (-8.9 %) from the observed flood extent. Our simulation model does not take the smaller rural drainage systems into account, possibly leading to underestimation of waterlogging in rural areas. This can be seen in the difference of the spatial distribution of the flood extended areas. Also existing gaps in river embankments may not be present in the simulation model. It is also known that the sources of flooding in the Burhi-Gandak basin can lie outside the basin. These sources (overland flow from other river basins) are not included in the RR/1D-flow/2D-verland flow model of the Burhi-Gandak

Based on the simulation results we are confident that our simulation model gives a good prediction of the flood extent and can be used for analysis of proposed flood reduction projects as well as analysis of the impacts of CC and future extreme situations.

Chapter 6 Forcing data future situations and extreme events

6.1 General

Given the calibration and validation results, we can now use our simulation models for running future situations or for simulation of extreme events. In our modelling study we look besides the current situation (baseline) also to the years 2040 and 2080. In this case we should take Climate Change (CC) into account and generate forcing data for those future situations including the effects of CC.

For simulation of extreme events we need to process the historical data with statistical methods to derive extreme values for certain return periods. When we combine the effects due to CC and the statistical analysis for the return periods we may get insight on how the extreme values for the selected return periods will change in the future.

In this chapter we will discuss how these two phenomena have been assessed and hwo we derived the forcing data for simulation of future situations and extreme events

6.2 Global Climate Models

The three state-of-the-art Global Climate Models used for CMIP5 experiments, namely, HadGEM2-ES Model (UK), GFDL-CM3 Model (USA), and MIROC-ESM Model (Japan) have been considered for down scaling the climate change scenarios in our study. These three climate models have demonstrated a reasonable degree of skill in simulating the baseline climatology over the Indian sub-continent. The Representative Concentration Pathways (RCP) GHG scenarios used in IPCC AR5 are a step evolving away from the non-mitigation SRES scenarios considered previously in IPCC AR4. They are compatible with the full range of stabilization, mitigation and baseline emission scenarios, represent consistent sets of projections of only the components of radiative forcing that serve as input for climate modelling, pattern scaling, and atmospheric chemistry modelling and span a full range of socio-economic driving forces. RCPs allow climate modellers to test different social, legislative and other policy initiatives, and see the economic effects as well as environmental; mitigation results as well as adaptation. In the current scenario of uncertainty in global agreement on mitigative actions for restricting the greenhouse gas emissions, the RCP6.0 represents the most plausible concentration pathway for the future. As policy makers and decision makers at country level and at municipal level in a developing country are not so much interested in a range of possibilities as regards the absolute local climate change but in the scale of vulnerability due to nature of future extremes and adaptive actions to be mainstreamed in their future development plan, we have opted for considering the best choice of RCP6.0 in our vulnerability assessment. Hence, in this study, RCP 6.0 representative concentration pathway was considered for the generation of the climate change projections as it follows a stabilizing CO_2 concentration close to the median range of all the four policy pathways. Projections of future climate change has been done on three time scales, namely, baseline (1961-1990), near term (2040s i.e., 2030 to 2059), and long term (2080s i.e., 2070 to 2099). Following the finalization of climate simulation models, scenarios, and time horizons, we have collected daily time series of rainfall data for all the three global climate models at selected time horizons: baseline, 2040 and 2080.

Spatial distribution patterns in maximum and minimum surface air temperatures and rainfall over Burhi-Gandak basin of Bihar state were developed using above-mentioned climate simulation models data in GIS platform (ArcGIS 9.3). These analyses provide the likely shifts in spatial changes of temperature and rainfall during 2040s (2030-2059) and 2080s (2070-2099) with respect to baseline time period (1961-1990). The results of this can be used to assess the implications of climate change on various meteorological and hydro-meteorological hazards (e.g., drought, flood, and heat wave etc.) in the selected river basin.

An examination of the change in rainfall patterns (simulated by GFDL CM3 model) suggests that the annual mean as well as monsoon season rainfall is projected to decrease by about 0.10 mm / day (a total of about 37 mm in a year) over the Burhi-Gandak basin by the middle of this century. The seasonal monsoon rainfall could increase by about 1.10 mm / day (a total of about 132 mm in the season) over the Burhi-Gandak basin by the end of this century. On annual basis, the rainfall would increase over the Burhi-Gandak basin by around 0.30 mm / day (a total of about 110 mm in a year) by the end of this century. On an average, the Burhi-Gandak basin is likely to experience increase in rainfall only in the latter part of this century whereas during mid-century rainfall is likely to decrease.

6.3 Delta Change method: 2040 and 2080

To process the effects of CC into the rainfall forcing data for use in our simulation models we have adopted the so-called Delta Change method (DC-method) (Camici et al., 2014). Using the DC-method we compared the time series with climate model outputs for 2040 and 2080 with the time series of the climate model output for the baseline. This comparison resulted in a so-called multiplier which we averaged out over the grid cells of each climate model and over the three climate models. After that we processed the data into average monthly values. Table 6.1 shows the monthly multipliers.

Table 6.1 Monthly multipliers rainfall forcing for 2040 and 2080

Month	2040	2080
1	1.27	0.81
2	1.63	1.02
3	0.88	1.05
4	1.16	0.94
5	1.24	1.03
6	1.52	1.45
7	1.05	1.17
8	1.02	1.17
9	0.97	1.19
10	1.11	1.76
11	0.79	0.96
12	0.77	0.73

Figure 6.1 shows the values in a diagram

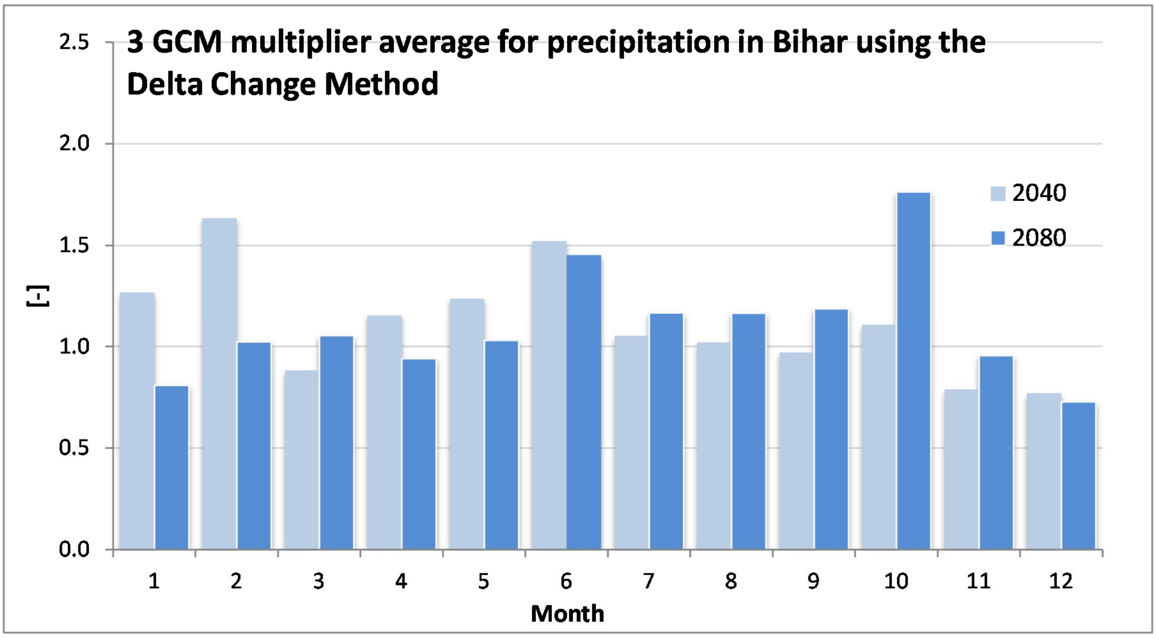


Figure 6.1 Monthly multipliers rainfall forcing for 2040 and 2080

The multipliers have been used to process the historical observed time series into future time series for 2040 and 2080 by multiplying the observed daily values with the multiplier for the proper month at the day of observation.

6.4 Rainfall

6.4.1 Return period analysis

The analysis of the return periods has been performed on the observed rainfall data series at the CWC stations as discussed in Chapter 4. We used a Gumbel Type I distribution. The return periods for which we derived the rainfall forcing data are: 1:2, 1:10, 1:25, 1:75 and 1:150. The same procedure we applied to the future rainfall forcing data for 2040 and 2080, which include the CC-impact through the applied multipliers. The result of the procedure is depth-duration-frequency curves for all reliable CWC rainfall stations. The depth-duration-curve gives for different durations of the storm (k) and return periods the corresponding total rainfall depth.

The depth-duration-curve can be calculated by extracting k-daily rainfall sum for each calendar year from the rainfall series per duration (k). Each ordered set of data has been fitted by the Gumbel-I distribution. Since the annual maximum series gives a too optimistic picture of rainfall depth at low return periods (< T = 10 years), the results are adjusted to values commensurate with annual exceedance series. For those lower return periods a Pareto distribution has been used. For higher return periods, the two methods give the same results. A clock time correction of 1.13 (Young, 2003) has been applied. In figure 6.2 an example is given of the the depth-frequency relation at station Samastipur for different time horizons.

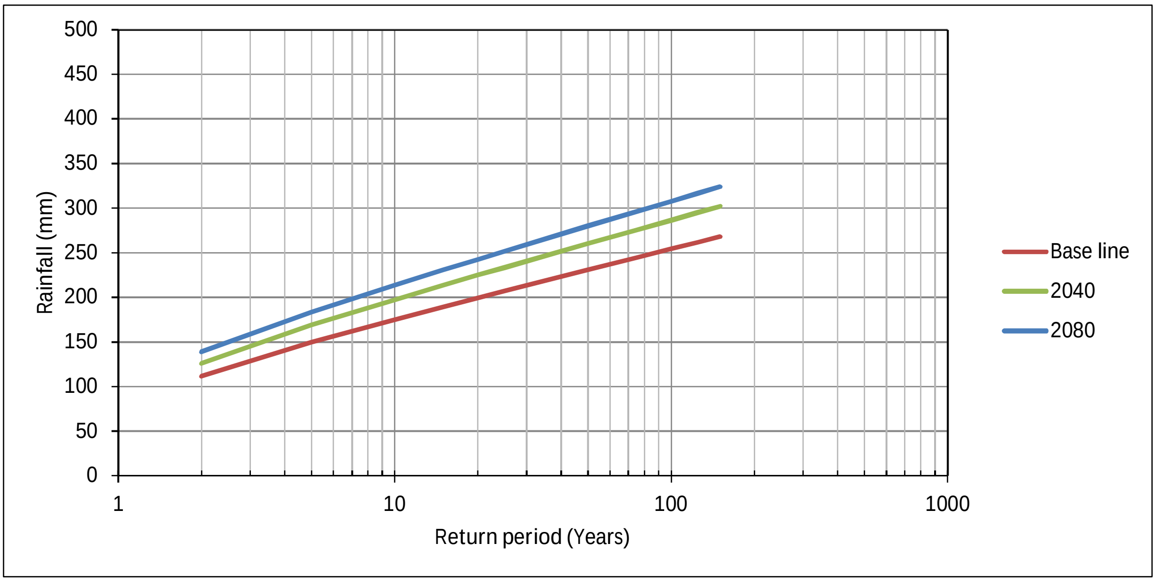


Figure 6.2 Depth-frequency relation at station Samastipur for different time horizons

The depth-duration-curves have been derived for individual-point-CWC rainfall stations.

6.4.2 Areal Reduction Factor

In order to determine the depth-duration-frequency curves for the entire upper basin of the Burhi-Gandak river and the lower basin of the Burhi-Gandak rivers, the values of the independent stations adjusted with the so-called Areal Reduction Factor (ARF). The ARF has to be applied when the point results are used for areas > 25 km^2. The point rainfall depth is to be multiplied with the ARF to arrive at the areal value. The ARF is a function of basin size and storm duration. In our model simulation we used the values as found by Kulkarni et. al., (2009). The ARF values as found on the areas of the corresponding Thiessen-polygons are shown in table 6.2.

Table 6.2 ARF values for CWC stations in the Burhi-Gandak basin.

Station	Area (km^2)	ARF
Chanpatiya	3269.5	0.75
Lalbegiaghat	2174.0	0.77
Ahirwalia	1455.0	0.81
Muzafarpur	1103.0	0.84
Samastipur	1519.0	0.81
Rosera	1229.0	0.83
Khagaria	717.0	0.89
Simara	2180.0	0.77

Applying the return period analysis, the clock time correction factor and the ARF we now have the basic information lined up to derive synthetic farinfall events for the forcing of our simulation model under future CC conditions and with various extreme events. This will be elaborated in the next paragraph.

6.4.3 Synthetic rainfall events

For the hydrological forcing of future situations one may use historical time series of certain extreme events, multiplied with a factor to indicate an increase or decrease of the forcing parameter. We have selected the method which uses design storms. A design storm is an synthetic event which relates to a certain return period with a certain rainfall depth. Design storms are par example used to design sewer systems, drainage systems or reservoirs. There are several ways to setup a design storm, from which we used the Alternating Block Method. This method works as follows:

1. Given T_d and $T_{frequency,}$ develop a hyetograph in daily time steps;
2. Using *T,* find *i* for 1 day, 2 days, 3 days,...n days using the IDF curve for the specified location;
3. Using *i* compute *P* for Dt, 2Dt, 3Dt,...nDt. This gives cumulative *P*; and,
4. Compute incremental precipitation from cumulative *P*.

T_d = duration of the storm

I = design rainfall intensity

P = rainfall

The intensity I can be derived with the formula:

$$i = \frac{KT^a}{(t+b)^n}$$

In which K, a, b and n are coefficients and t is the length of the time step in hours. In our case is that 24 hours. The value of the coefficients is sourced from Patra (2011), who derived values for several areas in India. Table 6.3 shows the values as used for the Burhi-Gandak basin.

Table 6.3 Rainfall intensity factors for the Burhi-Gandak basin

Basin	Station	K	a	B	n
BG	Gaya	7.176	0.1483	0.50	0.9459

Now after step 4, pick the highest incremental precipitation (maximum block) and place it in the middle of the hyetograph. Pick the second highest block and place it to the right of the maximum block, pick the third highest block and place it to the left of the maximum block, pick the fourth highest block and place it to the right of the maximum block (after second block), and so on until the last block.

For the design storms which we derived, we used a period of 7 days. Because the total volume generated by 1 storm event was too small compared to the average volumes as found in the Burhi-Gandak system, we added two smaller events to the design storm: a 10 years event before the maximum peak and a 2 years event after the peak. In this way a more realistic design storm event was created. Figure 6.3 shows as an example the 1/25 design storm for station Samastipur for the present situation.

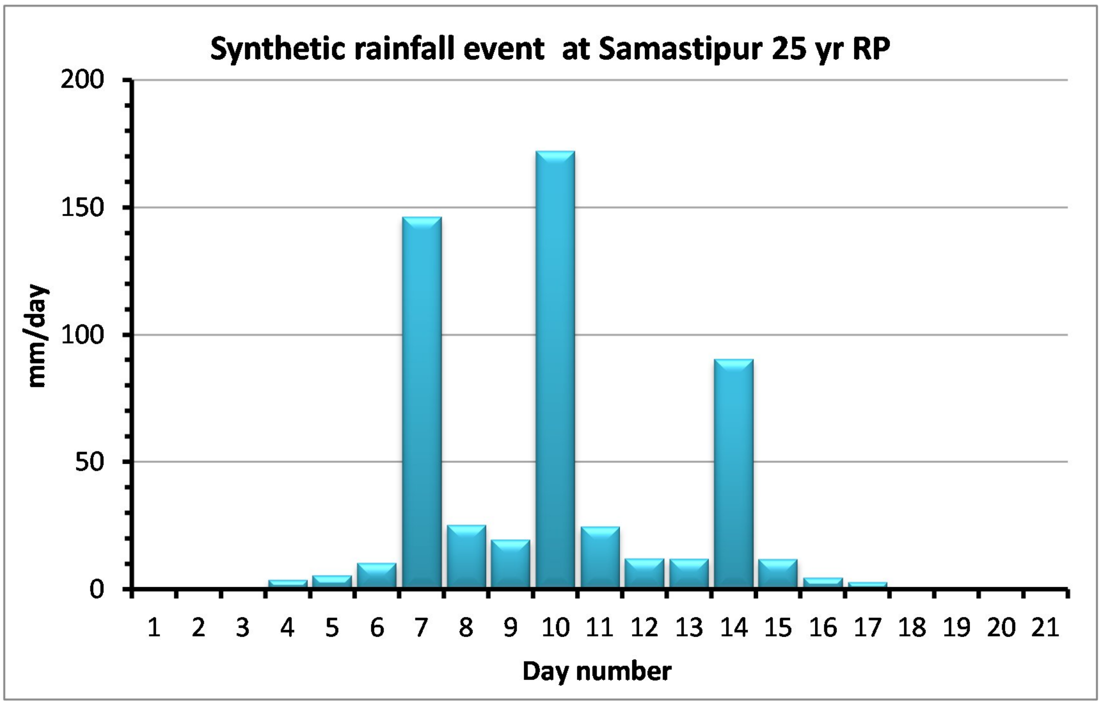


Figure 6.3 Design storm event for station Samastipur, present situation wih 25 year return period

The total volume of the discharge in the Burhi-Gandak river as generated with the rainfall event as shown in figure 6.3 fro station Samastipur is in the dame order of magnitude as the the volume of the discharge as observed in the calibration period of 2007. From the observed discharge time series at Samastipur we concluded that the flood season of 2007 shows an estimated return period between 15 and 25 years.

Based on the design storms as derived we processed the all design storms into input files for our model simulations. For proper simulation we started the events with the first values of the smaller event and after the last event we added days with zero rainfall up to a total of 21 days. For the timing of the model (the model uses real dates for the simulation) we started the events on June 1st.

6.5 Evaporation

6.5.1 Climate change

The evaporation has been taken into account in the model simulations be taking averaged daily values from station Jenapur for the design storm period. For including CC into the evaporation data for simulation of future situations we also could make use of the climate models in the same way as we have done for the rainfall. The latter is done by deriving multipliers using the Delta Change method. The climate models however do not output the values for evaporation directly. Evaporation is linearly related to temperature, which indeed is one of the outputs from the climate models. We decided that temperature is a useful proxy to derive multipliers for the evaporation. Table 6.4 shows the multipliers as applied for the evaporation input series in our simulation model.

Table 6.4 Multipliers for 2040 and 2080 as used for the evaporation in the Burhi-Gandak basin

Month	2040	2080
1	1.14	1.26
2	1.14	1.22
3	1.11	1.16
4	1.09	1.15
5	1.07	1.13
6	1.06	1.12
7	1.05	1.10
8	1.05	1.09
9	1.05	1.09
10	1.06	1.10
11	1.07	1.12
12	1.05	1.10

Figure 6.4 shows the values in a diagram.

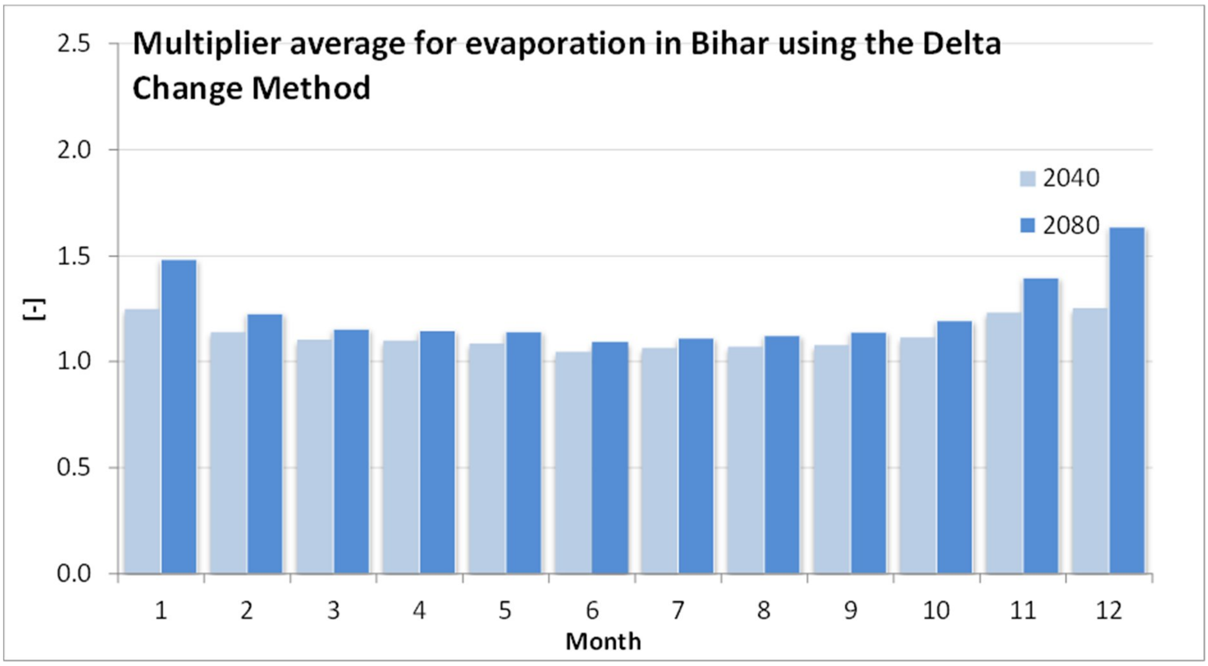


Figure 6.4 Multipliers for 2040 and 2080 as used for the evaporation in the Burhi-Gandak basin

As can be seen in figure 6.4, the multipliers for evaporation will increase slightly more in January, February, March than in the other months. During the monsoon period an increase of 5-10 % is expected for 2040 and 10-15 % for 2080.

6.6 Ganga water level boundary

6.6.1 Extreme value analysis for the Ganga boundary

Based on the observed water level time series of stations Hattidah and Munger we have derived the water level time series at the confluence of the Burhi-Gandak river and the Ganga river. For the available years the peak water levels have been normalized: the peak has been set to day ‘0’. This means that the rising limp has a negative time stamp and the falling limp has a positive time stamp. Next, we derived the average for the available years and set the maximum at 1.0. So the peak value is 1.0 and the values before and after the peak are < 1.0. We have derived a time series with multipliers ranging from 30 days before the peal level to 30 days after the peak level.

We also performed a Gumble analysis on the peak water levels and derived return periods for the maximum water level at the confluence of the Burhi-Gandak river and the Ganga river. The result is shown in figure 6.5.

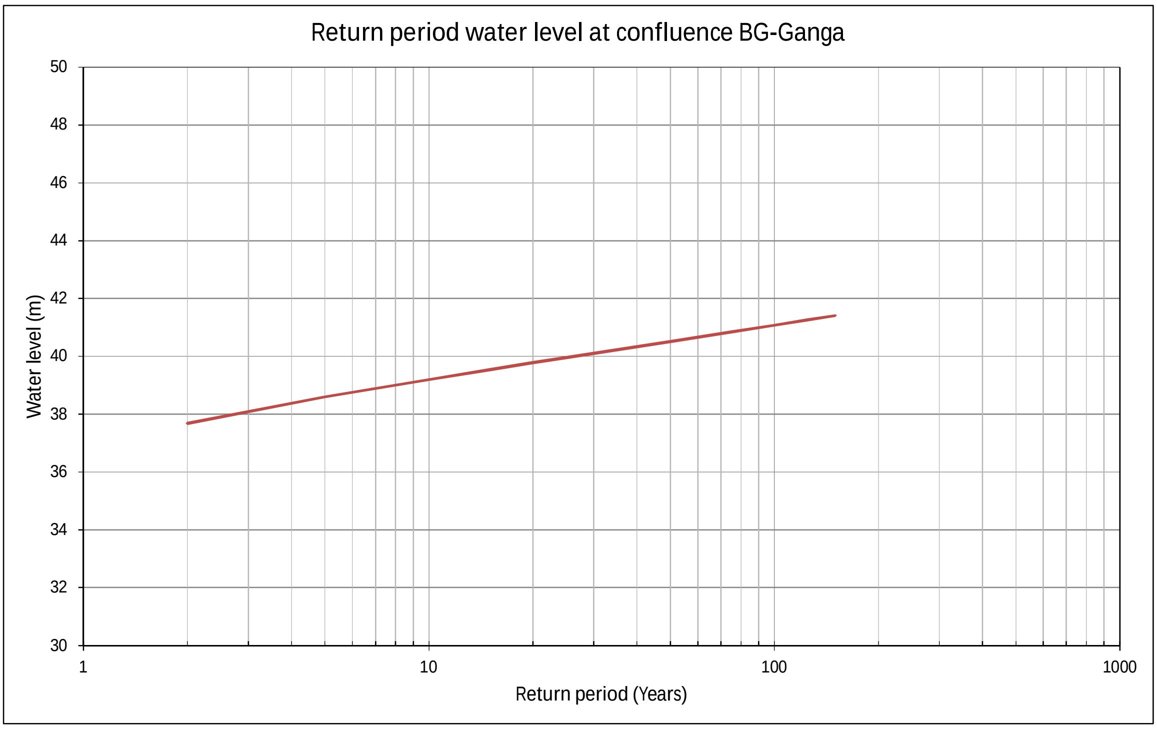


Figure 6.5 Return period for the water level at the confluence of the Burhi-Gandak river and the Ganga river.

Using the values at each relevant return period and the multipliers as described above, we generated synthetic water level time series at the confluence of the Burhi-Gandak river and the Ganga river. These are shown in figure 6.6

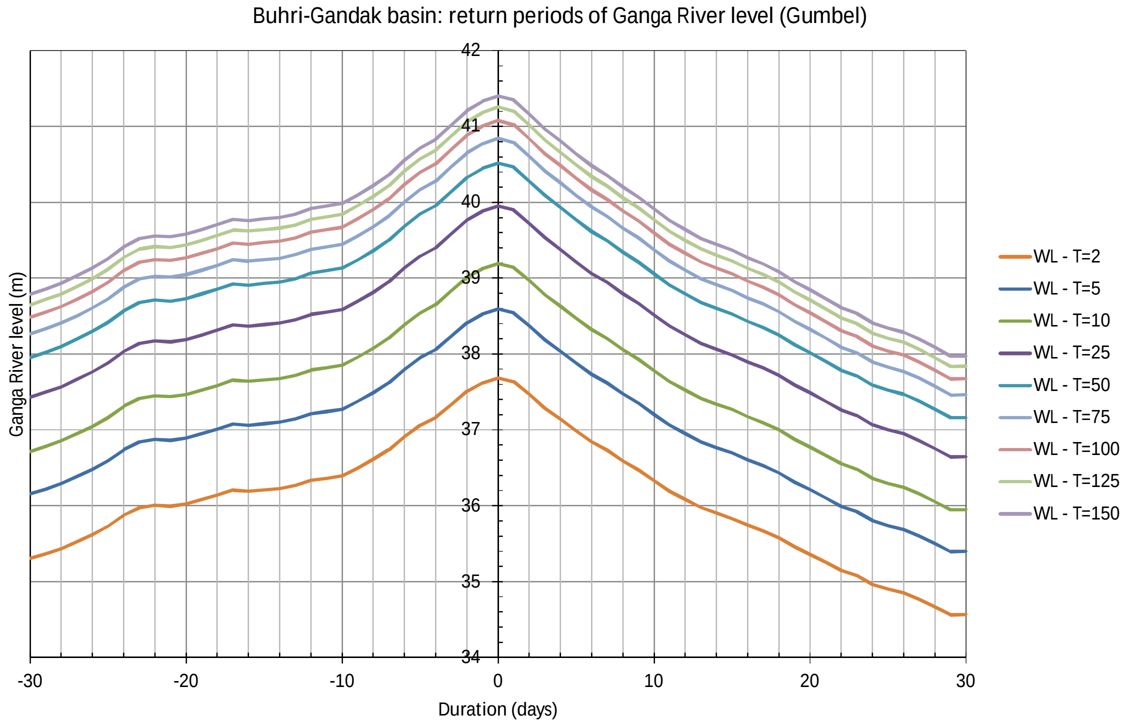


Figure 6.6 Water level time series at different return periods for the confluence of the Burhi-Gandak river and the Ganga river.

Table A.5 in Appendix A shows the multipliers as well as the values for the synthetic water level time series.

Chapter 7 Framework for analysis

7.1 General

We have set up our framework for analysis according to the events, scenarios and strategies which we have outlined. What do we mean by events, scenarios and strategies?

We regard natural influences on the model boundaries and model forcing as events. These can be rainfall, evaporation, discharges and water levels. The events are related to return periods. For the Burhi-Gandak basin we have discerned the following return periods (events): 2, 10, 25, 75, 100 and 150 years.

Autonomic developments regarding climate and society are regarded as scenarios. In our study we take only Climate Change into account as a scenario development. We have distinguished 3 levels of development: The Baseline, which is the current situation and the predicted situations in 2040 and in 2080.

A strategy is a combination of measures or planned projects for the study area in order to enforce a certain development such as: towards nature, towards industrial development, to enforce better prevention from flooding. etc.

In our framework of analysis we make combinations of events, scenarios and strategies into so-called cases. These cases are simulated with the combined RR/1D/2D-simulation model. The results of the model simulations are analysed also within the framework of analysis using a number of evaluation criteria. This will be evaluated in the next paragraphs.

7.2 Projects and measures

We have implemented 2 projects into the simulation model for the Burhi-Gandak basin. There is an old proposal of the year 1981 to build a storage dam across the Masan river. The Masan river is a tributary of the Burhi-Gandak river in its upper catchment; then there is a Detailed Project Report prepared very recently by the NWDA for inter-linking Burhi-Gandak with its western tributary Noon, then linking Noon with river Baya, a western side river which outfalls in to Ganga. As such, NWDA has termed this project as Burhi-Gandak-Noon-Baya- Ganga link.

7.2.1 Masan Dam

This is a proposal made by the State Government of Bihar as early as in 1981. This was to construct a dam across the Masan river. The Masan river is a tributary of the Burhi-Gandak river, rolling down from Nepal in the North-Western part of the upper catchment portion of Burhi-Gandak. This proposal was approved by CWC in 1981 and sanctioned; however, there are some problems with respect to the clearance from the Environment and Forest department. The location of the dam is at East Longitude 84° 13' 20'' and at North Latitude 27° 18' 30'', see figure 7.1.

Figure 7.1 Location of the Masan dam and Burhi-Gandak Noon-Baya link projects

Though a number of tributaries roll down in the upper catchment with good water resources, they do not have sites for creating storages or diversions due to unfavourable topography. As such in the upper part of the catchment of Burhi-Gandak, Masan-river only offers water resources as well as favourable topography to form a dam. The catchment area at the proposed Masan dam site is 350 km^2 near the village Behwari in the Ramnagar block of the West Champaran district; the annual water resources estimated at the site is 143.35 Mcm (at 75 % exceedance probability level), which has been considered for project planning; the proposal envisaged an earthern dam with a chute spillway arrangement; the project aims to provide irrigation benefit for an extent of 27, 062 ha with the composition of gross and cultivable commond areas of 30,062 and 21,600 ha respectively; the irrigation will be provided by two canals, one being the left irrigation canal with a discharging capacity of 11.60 m^3/sec and the other, namely right canal, with a discharging capacity of 7.93 m^3/sec; thus a constant discharge of 19.53 m^3/sec will be going out of the dam.

The cost estimate and the Benefit –cost-ratio, both assessed at 1981 year are 347.293 million rupees and 1.54:1; the gross capacity of the storage behind the dam is 178.34 Mcm. The chute spillway outflow maximum is stated to be 3851 m^3/sec, which seems to be disproportionally high for a small catchment area of 350 Km 2 (Even at Probable Maximum flood level)and this is being verified.

Perhaps the spillway outflow is based on the inflow flood corresponding to Probable Maimum flood (This needs to be confirmed). If it is designed for PMF, in other return period ranges up to even 500 year return period, the incoming flood will be absorbed in the dam; as such no release or very limited release will be coming down from the dam. This is because of the high irrigation requirement from the dam, which is more than 75% dependable flows.

However when the Model is run for different scenarios, the possible release from the dam will be assessed for that scenario and will be in put in the model at the location of the dam. Such Model runs at different scenarios will bring out the benefits or even further damages due to the Masan dam.

7.2.2 Link Burhi-Gandak-Noon-Baya-Ganga

The National Water Development Agency (NWDA), has prepared the Detailed Project Report. The structure across Burhi-Gandak is a barrage of 611 meters long; the total cost of the project has been estimated at 43,137.50 million rupees.

From the barrage, waters will be first diverted towards west to the river Noon, a tributary of Burhi-Gandak; at Noon, another regulating structure, will divert these waters to further West to Baya river, a small tributary of Ganga. The location of the Burhi-Gandak Barrage is at East Longitude 85 0 53’ 45 ‘’ and at North Latitude 25 0 49’ 15’’, near the village Muriaro (vide Figure 7.1). The objectives of the Link Project are to divert flood waters of River Burhi-Gandak to river Baya and ultimately to Ganga through the tributary of Burhi-Gandak Noon for flood moderation and irrigation to an area of 0.125 million hectares. The irrigation area is situated in the districts of Begusarai, Samastipur and Kagharia.

The catchment area of Burhi-Gandak at the proposed barrage site is 12,500 km^2.The annual mean rainfall over the catchment is 1300 mm. The maimum observed flood discharge at the barrage site is 3787 m^3/sec.The barrage design discharge however is fixed at 4920 m^3/sec, corresponding to 50-year Return period level at the site.

The Detailed Project Report has been prepared by the National Water Development Agency (NWDA), after analysing various aspects as below before fixing up the continuous diversion of 492 m^3/s, from Burhi-Gandak for irrigation in its Western track.

The Project Study has been finalyzed in the year 2013 after the approval of CWC. A continuous diversion of 492 m^3/s of water will be diverted from the River Burhi-Gandak; as such at any scenario, the flood realised at Burhi-Gandak at the Head regulator site will be reduced by this amount and only the remaining incoming flood will pass the regulator and go to to the downstream in Burji-Gandak. The cost estimate of the entire link project is 43,137.50 million rupees at year 2013 level; the irrigation benefit is for an extent of 0.125 million hectares; the benefit due to flood relief has been assessed at 1,433,1 million rupees and the irrigation benefit has been reckoned at 5,874.00 million rupees; the benefit-cost ratio has been arrived at 1.54; the internal rate of Return at 8% interest on the capital out-lay is 16 %. As such, from the present study context, with the link project in position, a definite reduction of flood peak by 492 m^3/sec is possible. The Complete Detailed Project report could be downloaded from the web site of NWDA-Burhi Gandak-Noon-Baya-Ganga link part. As such at present, the project is ready for implementation.

7.2.3 Model implementation

The projects which are elaborated in the previous paragraph have been implemented into the combined RR/1D-flow/2D-overland-flow simulation model of the Burhi-Gandak basin. For the Masan Dam project it was possible to implement the project into the RR-module of the simulation model. For the BG-NB-G link project implementation into the 1D-flow module was required. The model implementation of each of the project is elaborated more hereafter.

Masan Dam

Because no realease is to be expected from Masam dam and all rerources will be used for irrigation, the related nodes are disconneted from the Sobek RR-network. Figure 7.2 shows the model implementation of the Kanapur irrigation project.

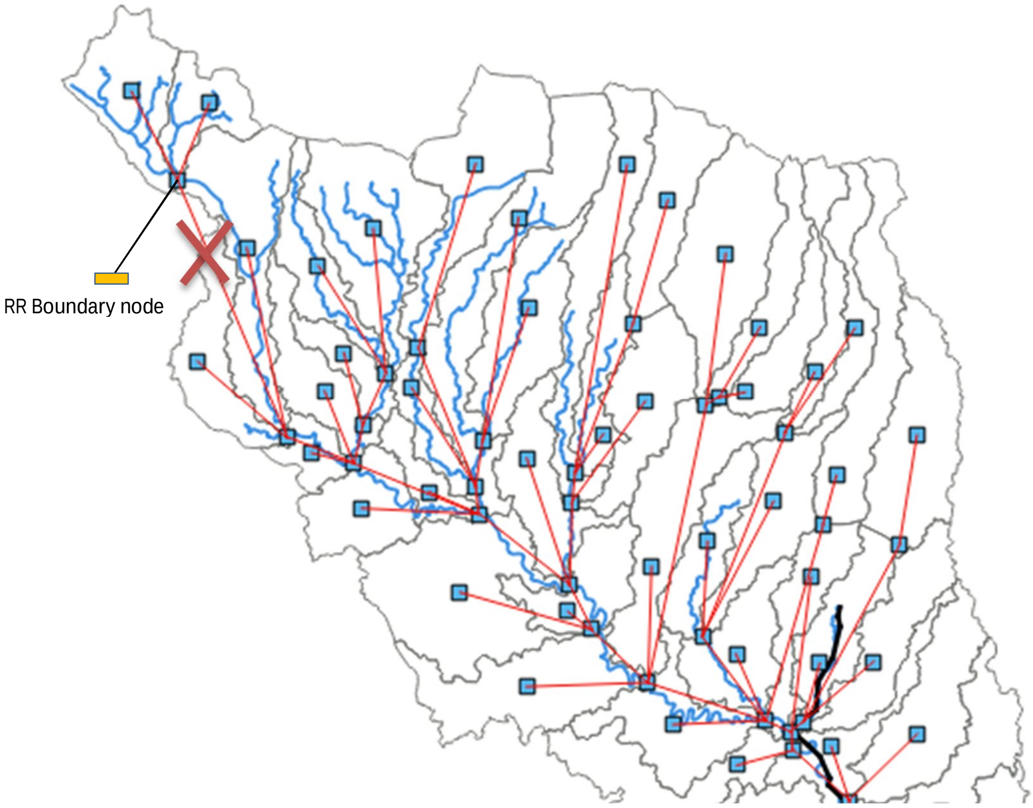


Figure 7.2 Implementation of the Masan Dam project

Burhi-Gandak-Noon-Baya-Ganga link

The Burhi-Gandak-Noon-Baya-Ganga link project has been implemented in the 1D-flow component using four types of nodes and:

Type	Function
Weir	Barrage in the Burhi-Gandak river
Connection node	Connection node
Pump	Pumping node for the BG-NB-G link flow (492 m^3/s)
Cross section node	Cross section of the BG-NB-G link (YZ-table)
Boundary node	Outlet diverted flow in the Ganga river

Based on the limited information for model implementation we assumed that the reservoir area is 1000 ha and that the water level is maintained at 118 m above datum. The open water node (reservoir) receives all the water as drained from the upstream RR-nodes (NAM-nodes). The total drainage area is 727 km^2. Figure 7.3 shows the model implementation of the Samakoi irrigation project.

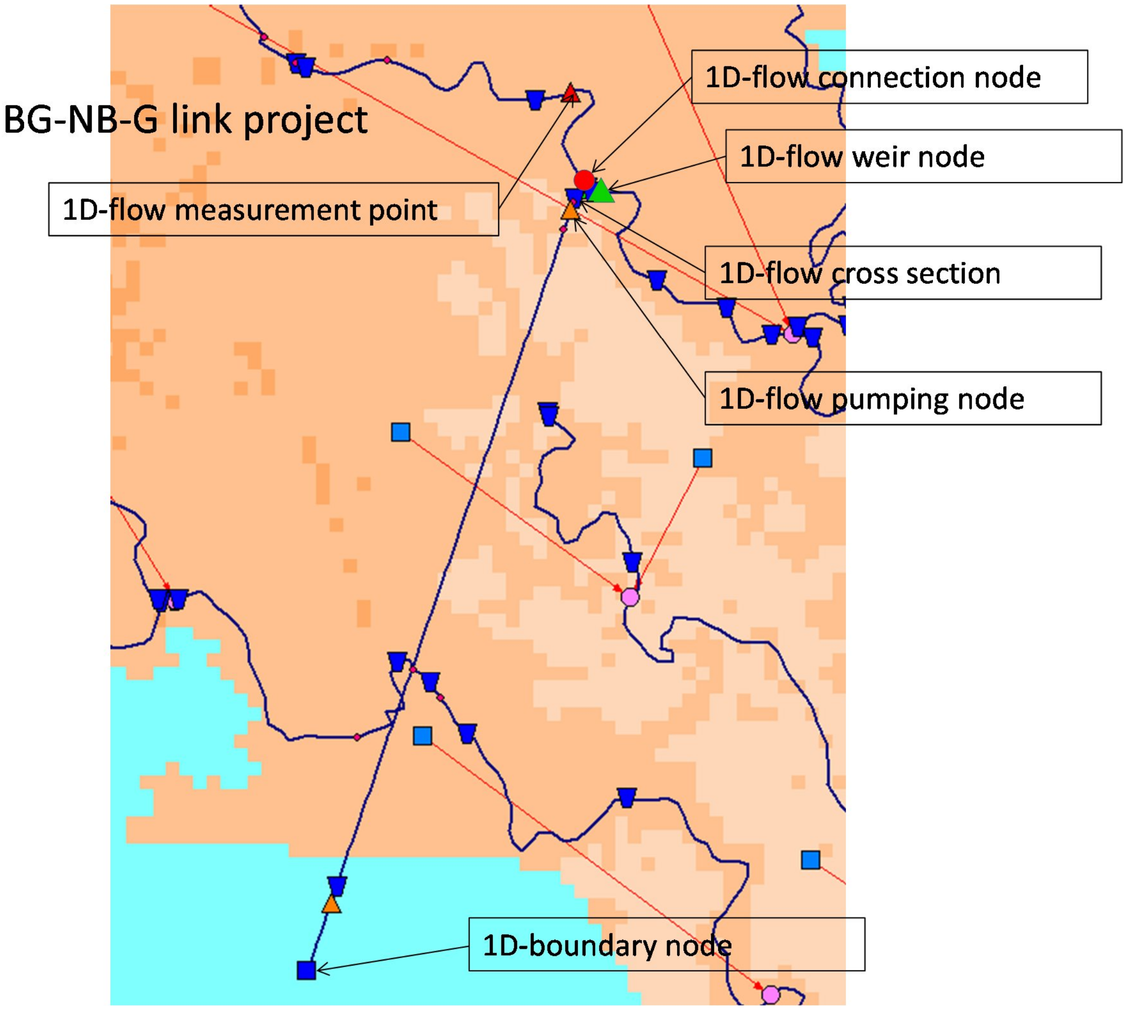


Figure 7.3 Implementation of the BG-NB-G link project

The cross section in the BG-NB-G link is of type YZ-table, because connecting branches of the Burhi-Gandak river also comprise the same cross section type. This ensures correct simulation of overland flow. Tabel 7.1 shows the dimensions of the cross section of the BG-NB-G link.

Tabel 7.1 Dimensions of the cross section of the BG-NB-G link.

Y (m)	Z (m)
0	54
10	39
190	39
200	54

The model implementation includes a discharge measurement location at the Burhi-Gandak river. The pump in the BG-NB-G link switches of when the discharge in the main river branch falls below 492 m^3/s.

7.3 Strategies

As already discussed we use strategies to indicate the implementation of 1 or more projects which may possilby lead to flood reduction. Based on the proposed projects as discussed in paragraph 7.1 we have defined a number of strategies. These are shown in table 7.1.

Table 7.1 Strategies for the model simulations

Strategy	Masan dam	BG-NB-G link	Raising embankments
A (baseline)			
B (Masan Dam)	X		
C (BG-NB-G link)		X	
D (Embankment)			X
E (Planned projects)	X	X	
F (Max. Flood control)	X	X	X

Strategy D is related to raising the embankments to reduce overtopping and inundation from the river stretch. The value with which the embankments should be raised depends on the design High Flood Level and if the design High Flood Level will change in the future.

Design High Flood Level (Design H.F.L)
Depending on observed hydrological data availability, the design H.F.L can be derived on the basis of flood frequency analysis. Embankment schemes should be prepared for a flood of 25 years frequency for the protection of predominant agricultural area. In case of embankments to be designed to protect townships, industrial areas or other places of strategic and vital importance, the design H.F.L. should generally correspond to 100 year return period.

Free board
In case of rivers carrying design discharge up to 3000 m^3/s, a minimum free board of 1.5 m over design HFL (including the backwater effect, if any) should be provided. For rivers having discharge more than 3000 m^3/s, a minimum free board of 1.8 meters over the design H.F.L. should be considered. The freeboard should also be checked for ensuring a minimum of about 1.0 meter free board over the design H.F.L corresponding to 100 year return period.

To derive a suitable value for embankment raising in the lower Burhi-Gandak basin we compare the maximum simulated water levels in the Burhi-Gandak and Burhi-Gandak rivers for the 25-year return period from the baseline with the simulated water levels of the 25-year return period from the 2080 situation. We do this at both river stretches and calculate an average value, based on the difference, for each river stretch. This value will be used as the value for raising the embankments. Strategy E comprises also the raising of embankments and will include the values for raising as applied in strategy D.

We can now make combinations of different events with scenarios and strategies. Such a combination is called a case, as we have already seen. The cases we have set up are discussed in the next paragraph.

7.4 Cases

7.4.1 Selection of cases

We have defined 5 return periods, 3 scenarios and 6 strategies. If all combinations would be run this would lead to 90 cases (model simulations). That would be too much and could not be handled within the time limitations of our project. Furthermore, it is probably not necessary to simulate every case of the 90 possible combinations. If we take a closer look at all combinations we just want to know the impact of the variation in every one of the entries. To see the impacts of the selected return period we just have to run the cases for every return period and compare the results with the current situation, which means 5 cases. Then we run each of the proposed projects separately for the current situation, which means 3 cases (see table 7.1). Then we devised 2 promising combinations of the proposed projects (strategy E, F), see also table 7.1, which means 2 more cases. To assess the results under CC conditions we run the baseline for 2040 and 2080, thus 2 cases. Then we run each of the proposed projects separately under CC-conditions for 2040, which means 3 cases Finally, we run strategies E and F under CC-conditions for 2040, which means 2 cases. So we now have a total of 17 cases.

7.4.2 Honk Kong method

For defining the impact of the selected return period at the model results, we select the proper return period and compare the outcome with the current situation, which is for statistical reasons a 2-year return period. However, in the Burhi-Gandak basin we have at least two independent forcing or stochastic variables (boundary conditions) which do not necessarily have the same return period. We regard rainfall and the water level at the Ganga river as two independent variables. To arrive at a combined return period for 2 independent forcing variables we use the so-called Hong-Kong method. This method is based on the combination of the results of two simulations: one with a certain return period for forcing #1 and one with a basic return period for forcing #2. Table 7.2 shows the possible combinations.

Table 7.2 Combinations needed to set up combined return periods using the Hong Kong method

Case	RP case	RP rainfall	RP Ganga WL
1	2 years	2 year	2years
2	25 years	25 years	2 years
		2 years	25 years
3	50 years	50 years	10 years
		10 years	50 years
4	100 years	100 years	10 years
		10 years	100 years
5	150 years	150 years	10 years
		10 years	150 years

The method as discussed above is named after the Deltares-project in which model simulations were performed for the bay of Hong Kong. The same problem arose in that project and based on a thorough statistical analysis of the results of a huge number of model simulations the Hong Kong method was derived. The results as produced after analysis of the total number of simulations proved to be consistent with the results coming from the combined model simulation results using the Hong Kong method.

7.5 Damage calculations

In this study we look at the impact of the selected combinations of events, scenarios and strategies on the average flood depth at the Taluka level. This average flood depth, or inundation depth, we use at input for the damage functions. The damage function describes the relation between inundation depth (m) and the damage fraction (may range from 0.0 to 1.0).

In 2010 Engineers Australia (EA) derived safety criteria for people during flood Hazards. EA assessed several studies on flood impacts on humans, where most studies take into account the combined effect of flood depth (D) and flood stream velocity (V), resulting in the DV-indicator. In our study, data on flood stream velocities are not available, so only flood depth (or inundation depth) is taken into account. Corresponding to the findings in the EA report, the following classes have been defined (based on a 0 - 100 scale to correspond with the other indicator values):

Table 7.3 Hazard indication as classified by Australian Engineers 2010 (column 1-4)

Classification Australian Engineers				Derived for this study	
Class	Lower boundary (m)	Upper boundary (m)	Hazard indication	Inundation depth (m)	Hazard fraction
20	0.0	0.3	Low hazard	0.00	0.0
40	0.3	0.5	Medium hazard for children/elderly, Low hazard for adults	0.40	0.3
60	0.5	1.0	High hazard for children/elderly, Medium hazard for adults	0.75	0.6
80	1.0	1.5	High hazard all groups	1.25	0.8
100	1.5	999	Extreme hazard all groups	1.50	1.0

For this study we apply the values as derived in table 7.3 as average hazard fractions for the entire population in the area under consideration. For agriculture and housing we will assess possible inundation damage to:

- Kharif (monsoon) crops: Rice, Maize and Pulses
- Houses: Pucca, Kacha and Huts

Damage functions for residential buildings (huts, kutcha and pucca) and selected crops (paddy, maize and green gram) were derived from RMSI archive database developed as part of its internal research and product development. The process followed for this includes extensive field observations to understand the building types and characteristics across the country including Bihar and Odisha and carry out analytical and statistical analysis. This is complemented with expert engineering or heuristic judgment based on local and/or international experiences. Field observations in some of the recent flood and cyclone events in the country including Mumbai flood (2005), Surat flood (2006), 2008 flood in Bihar, Thane cyclone (2011), Phailin cyclone (2013), HUDHUD cyclone (2014) were used for calibration and verification of the damage functions developed. These events were used for calibration and verification of damage functions for flood, cyclone and storm surge and for the present analysis the flood damage function thus developed is presented.

It is important to note that developing damage functions for residential structure in India is very complicated for the reason that mostly the construction of residential building do not adhere to engineering standards. This makes it difficult to develop a generalize damage function based on building typology and demands extensive field observations. The rural housing particularly is not following the building codes and is of great challenge to correlate with the structural behavior observed in lab analysis.

Structural damage functions (houses)

The residential buildings based on structural types is categorized into three – huts, kutcha and pucca and the detailed descriptions (different material combination) is provided in (Table 7.4). The damage functions were developed based on mean damage ratio as a function of flood depth to building types.

Table 7.4 Structural Types and their grouping in different categories

S.No.	Residential building categories	Structural types	Description showing combination of major wall and roof materials
1	Huts	1. Grass/ thatch/ bamboo/ wood/ plastic/ polythene etc.	Grass/ thatch/ bamboo/ wood/ plastic/ polythene etc. used in combination for wall and roof materials
2	Kutcha	2. Mud/ un-burnt brick/ stone without mortar/ light metal	Mud/un-burnt brick/stone without mortar as wall materials and grass/thatch/bamboo/ plastic/ polythene/handmade tiles/ machine-made tiles etc as roof materials/ G.I./metal/asbestos sheets as wall materials and grass/thatch/bamboo/ Plastic/ polythene/tiles/ G.I./metal/asbestos sheets as roof materials
3	Pucca	3a. Burnt brick/ stone with mortar with temporary roof	Burnt brick/ Stone packed with mortar as wall materials and temporary roof (tiles, wood, GI, slate, etc.)
		3b. Reinforced masonry buildings	Burnt brick walls and RCC roof
		3c. Reinforced Concrete Frame (RCF) with brick infill/ Reinforced Cement Concrete (RCC)	Combination of concrete and steel to build a structure

Crops:

Most crops grown in India are intolerant of flooding. However, the tolerance level of crops varies. Very susceptible crops include potatoes, pulses, and beans, which may succumb even with one day under water. Also it is critical for many crops at what growing stage they are under submergence condition.

In terms of acreage and yield, rice and maize are the major cereal crops grown in both Bihar and Odisha during monsoon season. Between the two crops, rice can survive submergence condition up to 5-7 days whereas maize can survive flooding 2-4 days. Major pulses which are grown during monsoon season are green gram, pigeon pea, and black gram. All the pulse crops are extremely sensitive to flood compared to cereal crops. Furthermore, research in flooded crop land has shown that the oxygen concentration approaches zero after about 24 hours (Weijun Z. et al., 1995[1]). Without oxygen, the plant cannot perform critical life sustaining functions, such as root respiration, nutrient and water uptake due to impaired roots. Even if flooding some time does not kill plants completely, it affects the yield. Besides, submergence also leads to accumulation of compounds like CO_2, which are toxic to plants in high concentrations (Ashipala, 2013[2]). For the present risk assessment exercise, flood damage function at different flood depths and flood durations for the three key crops (rice, maize, and green gram) have been developed using analytical approach which is a combination of field observations and crop simulation modeling techniques. This is complemented by applying national/international field experiences and observation of major flood events.

Monetary values

To derive real damages the last step is to assume unit values for houses and crops.

Table 7.5 Values used in the damage calculations

Item	Unit	Value (Rs) (Burhi Gandak)	Value (Rs) (Brahmani-Baitarani)
Huts	#	25,000	25,000
Kacha_HS	#	100,000	100,000
Pucca_HS	#	350,000	350,000
Maize*	Ha	15,458	-
Rice*	Ha	44,542	38,340
Pulses*	Ha	37,546	16,031

Unit prices for one ton of crop are as follows: Maize: 13100 Rs; Rice: 28191 Rs; Pulses: 42187 Rs
Average yield BG: Maize: 1.18 t/ha; Rice: 1.58 t/ha; Pulses: 0.89 t/ha
Average yield BB: Rice: 1.36 t/ha; Pulses: 0.38 t/ha

[1] Weijun Zhou, Linb X. 1995. Effects of waterlogging at different growth stages on physiological characteristics and seed yield of winter rape Brassica napus.

[2] Ashipala, S. N. (2013). Effect of climate variability on pearl millet (Pennisetum glaucum) productivity and the applicability of combined drought index for monitoring drought in Namibia. Department of meteorology, college of biological and physical science, University of Nairobi.

7.6 Criteria for evaluation

For the evaluation of results we have selected a number of criteria, which are:

Taluka level:

1. Average flood depth
2. Damage per crop type and house type

Basin level:

1. Maximum flooding extent
2. Maximum flooding volume
3. Max WL-LBG
4. Max WL-Ahirwalia
5. Max WL-Sikandarpur
6. Max WL-Samastipur
7. Max WL-Rosera
8. Max WL-Khagaria
9. Max Q-LBG
10. Max Q-Ahirwalia
11. Max Q-Sikandarpur
12. Max Q-Samastipur
13. Max Q-Rosera
14. Max Q-Khagaria

Values on the Taluka level can also be aggregated to the basin level. For each of the simulation cases these criteria will be calculated and assessed on impact using the framework of analysis. Table 7.6 shows the evaluation table at the basin level as can be found in the framework of analysis.

Table 7.6 Evaluation table with criteria as used at the basin level

Flooding	Unit
Maximum flooding extent	km2
Maximum flooding volume	Mm3
Max WL-LBG	m
Max WL-Ahirwalia	m
Max WL-Sikandarpur	m
Max WL-Samastipur	m
Max WL-Rosera	m
Max WL-Khagaria	m
Max Q-LBG	m3/s
Max Q-Ahirwalia	m3/s
Max Q-Sikandarpur	m3/s
Max Q-Samastipur	m3/s
Max Q-Rosera	m3/s
Max Q-Khagaria	m3/s
Impact on society	
# inhabitants affected	#

Crop damage Kharif season	
Rice	Lacs Rs
Rice and pulses	Lacs Rs
Maize and pulses	Lacs Rs
Damage to houses	
Huts	Lacs Rs
Kacha	Lacs Rs
Pucca	Lacs Rs

The flooding volume has been evaluated to get a general idea of how the total flooding volume is related to the storage capacity in existing and possible future reservoirs. Of course, the total flood volume has also sources which cannot be regulated with the upstream reservoirs like flooding from external river basins and by heavy local rainfall (waterlogging).

7.7 Simulation results at the Taluka level

As discussed in 7.6 we look for the Taluka level at average simulated flood depth, the damage per crop type and house type and the total number of affected people.

7.8 Simulation results at the basin level

For the evaluation of the simulation results we grouped the models simulation cases in different sections, as follows:

- Evaluation on return periods, 5 simulation cases;
- Evaluation on flood impact reduction projects, 3 simulation cases + 1 baseline case;
- Evaluation on strategies, 2 simulation cases + 1 baseline case;
- Evaluation on CC impact, 2 simulation cases + 1 baseline case;
- Evaluation on flood impact reduction projects at CC 2040, 3 simulation cases + 1 baseline case; and,
- Evaluation on flood control strategies with CC, 2 simulation cases + 1 baseline case 2040.

From these evaluation sections we should get a clear overview of the impact on flooding of each of the events, scenarios and strategies. The results at each of the evaluation sections are discussed in the next paragraphs.

7.8.1 Return periods

For the evaluation of the impact of different return periods we have compared 4 model simulation cases with different return periods against the current situation. An overview is given in table 7.4.

Table 7.4 Results from different return periods

Burhi-Gandak basin		Model simulation case				
		Case 1	Case 2	Case 3	Case 4	Case 5
Event						
Return period		1:2	1:25	1:75	1:100	1:150
Scenario						
Current situation		x	x	x	x	x
Strategy						
A (baseline)		x	x	x	x	x
Flooding	**Unit**					
Maximum flooding extent	km^2	674.3	1571.0	2115.2	2184.0	2289.8
Maximum flooding volume	Mm^3	983.3	2590.0	3881.6	4119.8	4460.5
Max WL-LBG	m	68.8	69.8	70.1	70.1	70.2
Max WL-Ahirwalia	m	61.3	62.3	62.6	62.7	62.7
Max WL-Sikandarpur	m	57.6	58.7	58.9	58.9	58.9
Max WL-Samastipur	m	52.2	53.3	53.4	53.4	53.4
Max WL-Rosera	m	50.0	51.1	51.2	51.2	51.3
Max WL-Khagaria	m	42.3	43.9	44.6	44.8	45.0
Max Q-LBG	m^3/s	1884.0	2916.2	3103.6	3139.0	3185.6
Max Q-Ahirwalia	m^3/s	2057.1	3060.8	3136.0	3159.6	3191.8
Max Q-Sikandarpur	m^3/s	2103.3	2986.3	3188.1	3217.7	3269.2
Max Q-Samastipur	m^3/s	2082.4	2970.4	3093.9	3101.0	3110.8
Max Q-Rosera	m^3/s	1615.6	2104.8	2198.3	2205.2	2214.0
Max Q-Khagaria	m^3/s	1742.0	2004.7	2142.5	2147.8	2154.8
Impact on society						
# inhabitants affected	#	45,55,281	81,04,041	92,17,875	94,93,686	96,72,284
Crop damage Kharif season						
Maize	Lacs Rs	1,827	3,228	3,736	3,890	3,998
Rice	Lacs Rs	8,736	15,752	17,872	18,339	18,743
Pulses	Lacs Rs	2,074	3,295	3,790	3,867	3,902
Damage to houses						
Huts	Lacs Rs	12,883	24,639	29,045	30,079	31,382
Kacha	Lacs Rs	17,971	40,417	50,973	54,031	57,545
Pucca	Lacs Rs	187,571	367,831	428,024	446,290	463,857

Cases 2 to 5 have been processed using the Hong Kong method as discussed in paragraph 7.4.2.

7.8.2 Flood impact reduction projects and strategies

For the evaluation of the impact of flood impact reduction projects we have compared 3 model simulation cases with different projects against the current situation, without any project implementation. The projects are:

- B. Masan Dam
- C. BG-NB-G link
- D. Embankment improvement

Furthermore, we combined projects into two strategies:

- E. Implementing the two planned projects
- F. Maximum flood control, both projects and embankmen improvement

An overview of results is given in table 7.5.

Table 7.5 Results of flood impact reduction projects

Burhi-Gandak basin		**Model simulation case**					
		Case 2	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**
Event							
Return period		1:25	1:25	1:25	1:25	1:25	1:25
Scenario							
Current situation		x	x	x	x	x	x
Strategy							
Flood impact reduction projects			B	C	D		
Combined strategies						E	F
Flooding	**Unit**						
Maximum flooding extent	km^2	1571.0	1488.8	1466.8	1484.0	1416.8	1340.5
Maximum flooding volume	Mm^3	2590.0	2609.2	2493.3	2560.7	2416.8	2255.6
Max WL-LBG	m	69.8	69.7	69.8	69.8	69.7	69.7
Max WL-Ahirwalia	m	62.3	62.2	62.3	62.3	62.2	62.2
Max WL-Sikandarpur	m	58.7	58.7	58.8	58.8	58.7	58.7
Max WL-Samastipur	m	53.3	53.3	53.2	53.4	53.1	53.1
Max WL-Rosera	m	51.1	51.0	50.6	51.1	50.5	50.5
Max WL-Khagaria	m	43.9	43.9	43.9	43.9	43.9	43.9
Max Q-LBG	m^3/s	2916.2	2773.1	2898.9	2905.3	2783.1	2788.2
Max Q-Ahirwalia	m^3/s	3060.8	2914.2	3032.7	3054.9	2927.3	2946.9
Max Q-Sikandarpur	m^3/s	2986.3	2947.3	3056.6	3064.3	2962.6	2971.6
Max Q-Samastipur	m^3/s	2970.4	2922.7	3037.9	3043.4	2943.5	2953.1
Max Q-Rosera	m^3/s	2104.8	2064.0	1856.4	2118.0	1811.5	1825.7
Max Q-Khagaria	m^3/s	2004.7	1971.3	1870.7	1991.5	1863.4	1864.8
Impact on society							
# inhabitants affected	#	81,04,041	77,19,293	77,20,199	65,97,499	75,90,319	59,72,164
Crop damage Kharif season							
Maize	Lacs Rs	3,228	3,183	3,143	2,423	3,138	2,330
Rice	Lacs Rs	15,752	14,729	15,000	14,785	14,453	13,499
Pulses	Lacs Rs	3,295	3,155	3,079	2,774	3,083	2,675
Damage to houses							
Huts	Lacs Rs	24,639	23,478	23,002	18,693	22,815	16,808
Kacha	Lacs Rs	40,417	39,811	38,973	26,570	38,593	23,899
Pucca	Lacs Rs	367,831	358,592	350,486	279,249	345,996	236,370

7.8.3 Impact of Climate Change

For the evaluation of the impact of Climate Change, we have compared 2 model simulation cases, baseline 2040 and baseline 2080 against the current situation, the Baseline 2015. An overview is given in table 7.6.

Table 7.6 Results for Climate Change impact

Burhi-Gandak basin		Model simulation case		
		Case 2	Case 11	Case 12
Event				
Return period		1:25	1:25	1:25
Scenario				
Current situation		x		
Situation 2040			x	
Situation 2080				x
Strategy				
A (baseline)		x	x	x
Flooding	**Unit**			
Maximum flooding extent	km^2	1571.0	1644.0	1911.5
Maximum flooding volume	Mm^3	2590.0	2650.1	2972.7
Max WL-LBG	m	69.8	69.9	70.1
Max WL-Ahirwalia	m	62.3	62.4	62.7
Max WL-Sikandarpur	m	58.7	58.8	58.9
Max WL-Samastipur	m	53.3	53.3	53.4
Max WL-Rosera	m	51.1	51.1	51.2
Max WL-Khagaria	m	43.9	43.9	43.9
Max Q-LBG	m^3/s	2916.2	2958.0	3129.2
Max Q-Ahirwalia	m^3/s	3060.8	3134.7	3407.8
Max Q-Sikandarpur	m^3/s	2986.3	3037.3	3238.9
Max Q-Samastipur	m^3/s	2970.4	3021.4	3102.6
Max Q-Rosera	m^3/s	2104.8	2131.6	2199.5
Max Q-Khagaria	m^3/s	2004.7	2105.6	2170.6
Impact on society				
# inhabitants affected	#	81,04,041	8,144,352	8,612,365
Crop damage Kharif season				
Maize	Lacs Rs	3,228	3,235	3,354
Rice	Lacs Rs	15,752	16,008	17,463
Pulses	Lacs Rs	3,295	3,364	3,556
Damage to houses				
Huts	Lacs Rs	24,639	24,861	26,128
Kacha	Lacs Rs	40,417	40,688	42,782
Pucca	Lacs Rs	367,831	369,027	390,133

7.8.4 Flood control strategies under Climate Change

For the evaluation of the impact of flood control strategies under Climate Change, we have compared 3 model simulation cases against the 2040 situation without implementation of any strategy. An overview is given in table 7.8.

Table 7.8 Results of flood control strategies under Climate Change

Burhi-Gandak basin		Model Simulation Case				
		Case 13	Case 14	Case 15	Case 16	Case 17
Event						
Return period		1:25	1:25	1:25	1:25	1:25
Scenario						
Situation 2040		x	x	x	x	x
Strategy						
A (Masan Dam)						x
C (BG-NB-G link)		x				
D (Embankment)			x			
E (Planned projects)				x		
F (Max. Flood control)					x	
Flooding	**Unit**					
Maximum flooding extent	km^2	1260.8	1279.3	1081.8	1099.5	1270.3
Maximum flooding volume	Mm^3	1755.9	1946.7	1498.4	1585.9	1900.2
Max WL-LBG	m	69.9	69.9	69.8	69.8	69.8
Max WL-Ahirwalia	m	62.4	62.4	62.3	62.3	62.2
Max WL-Sikandarpur	m	58.9	58.9	58.8	58.8	58.7
Max WL-Samastipur	m	53.2	53.5	53.1	53.1	53.3
Max WL-Rosera	m	50.6	51.1	50.5	50.6	51.0
Max WL-Khagaria	m	42.7	42.7	42.3	42.7	42.7
Max Q-LBG	m^3/s	2941.4	2948.8	2823.3	2830.0	2814.5
Max Q-Ahirwalia	m^3/s	3103.5	3130.6	2986.2	3005.8	2973.0
Max Q-Sikandarpur	m^3/s	3113.4	3127.4	3021.8	3030.5	3007.2
Max Q-Samastipur	m^3/s	3095.3	3110.6	3003.0	3010.8	2985.3
Max Q-Rosera	m^3/s	1888.6	2152.6	1843.6	1852.7	2092.4
Max Q-Khagaria	m^3/s	1890.6	2011.4	1882.1	1889.4	1815.8
Impact on society						
# inhabitants affected	#	61,58,959	61,50,631	59,05,062	55,63,303	63,36,748
Crop damage Kharif season						
Maize	Lacs Rs	2,200	2,122	2,020	2,034	2,377
Rice	Lacs Rs	14,187	14,461	13,292	13,296	14,146
Pulses	Lacs Rs	2,649	2,526	2,538	2,518	2,754
Damage to houses						
Huts	Lacs Rs	18,384	17,497	17,814	15,562	19,240
Kacha	Lacs Rs	25,088	23,865	23,373	21,596	26,978
Pucca	Lacs Rs	254,981	262,494	245,725	226,126	275,566

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Appendix A

Table A.1 Parameter settings for the run-off nodes of the hydrological NAM model for the Burhi-Gandak basin

ID	Area (m^2)	Capacity Parameter Definition	Runoff Parameter Definition	Initial Values Definition	Meteo Station	Area Adjustment factor
RR41	116721000	test_cap	test_runoff	test_initial	sc41	1
RR42	152045100	test_cap	test_runoff	test_initial	sc42	1
RR45	168828300	test_cap	test_runoff	test_initial	sc45	1
RR53	126854100	test_cap	test_runoff	test_initial	sc53	1
RR46	183019500	test_cap	test_runoff	test_initial	sc46	1
RR48	126181800	test_cap	test_runoff	test_initial	sc48	1
RR47	111642300	test_cap	test_runoff	test_initial	sc47	1
RR74	139773600	test_cap	test_runoff	test_initial	sc74	1
RR73	492925500	test_cap	test_runoff	test_initial	sc73	1
RR103	213329700	test_cap	test_runoff	test_initial	sc103	1
RR134	160793100	test_cap	test_runoff	test_initial	sc134	1
RR43	134492400	CAP_ANAND	RUNOFF_ANAND	test_initial	sc43	1
RR40	378820800	CAP_ANAND	RUNOFF_ANAND	test_initial	sc40	1
RR35	148853700	CAP_ANAND	RUNOFF_ANAND	test_initial	sc35	1
RR37	207635400	CAP_ANAND	RUNOFF_ANAND	test_initial	sc37	1
RR33	128336400	CAP_ANAND	RUNOFF_ANAND	test_initial	sc33	1
RR36	146156400	test_cap	test_runoff	test_initial	sc36	1
RR38	144868500	test_cap	test_runoff	test_initial	sc38	1
RR39	209344500	test_cap	test_runoff	test_initial	sc39	1
RR24	322606800	CAP_ANAND	RUNOFF_ANAND	test_initial	sc24	1
RR18	100124100	CAP_ANAND	RUNOFF_ANAND	test_initial	sc18	1
RR21	246491100	CAP_ANAND	RUNOFF_ANAND	test_initial	sc21	1
RR10	219364200	CAP_ANAND	RUNOFF_ANAND	test_initial	sc10	1
RR16	370153800	CAP_ANAND	RUNOFF_ANAND	test_initial	sc16	1
RR8	401525100	CAP_ANAND	RUNOFF_ANAND	test_initial	sc8	1

RR11	165612600	CAP_ANAND	RUNOFF_ANAND	test_initial	sc11	1
RR29	236382300	CAP_ANAND	RUNOFF_ANAND	test_initial	sc29	1
RR26	129389400	CAP_ANAND	RUNOFF_ANAND	test_initial	sc26	1
RR20	318483900	CAP_ANAND	RUNOFF_ANAND	test_initial	sc20	1
RR25	66128400	CAP_ANAND	RUNOFF_ANAND	test_initial	sc25	1
RR17	122650200	CAP_ANAND	RUNOFF_ANAND	test_initial	sc17	1
RR22	105875100	CAP_ANAND	RUNOFF_ANAND	test_initial	sc22	1
RR23	197607600	CAP_ANAND	RUNOFF_ANAND	test_initial	sc23	1
RR6	305135100	CAP_ANAND	RUNOFF_ANAND	test_initial	sc6	1
RR13	328390200	CAP_ANAND	RUNOFF_ANAND	test_initial	sc13	1
RR19	516942000	CAP_ANAND	RUNOFF_ANAND	test_initial	sc19	1
RR67	196376400	test_cap	test_runoff	test_initial	sc67	1
RR68	210397500	test_cap	test_runoff	test_initial	sc68	1
RR72	96187500	test_cap	test_runoff	test_initial	sc72	1
RR58	219825900	test_cap	test_runoff	test_initial	sc58	1
RR59	314547300	test_cap	test_runoff	test_initial	sc59	1
RR61	80554500	test_cap	test_runoff	test_initial	sc61	1
RR57	113772600	test_cap	test_runoff	test_initial	sc57	1
RR56	164705400	test_cap	test_runoff	test_initial	sc56	1
RR50	121184100	test_cap	test_runoff	test_initial	sc50	1
RR64	283783500	test_cap	test_runoff	test_initial	sc64	1
RR66	252695700	test_cap	test_runoff	test_initial	sc66	1
RR81	172813500	test_cap	test_runoff	test_initial	sc81	1
RR70	366152400	test_cap	test_runoff	test_initial	sc70	1
RR49	164916000	test_cap	test_runoff	test_initial	sc49	1
RR77	106142400	test_cap	test_runoff	test_initial	sc77	1
RR79	118656900	test_cap	test_runoff	test_initial	sc79	1
RR78	126659700	test_cap	test_runoff	test_initial	sc78	1
RR89	55250100	test_cap	test_runoff	test_initial	sc89	1
RR91	184169700	test_cap	test_runoff	test_initial	sc91	1
RR90	123751800	test_cap	test_runoff	test_initial	sc90	1
RR112	135051300	test_cap	test_runoff	test_initial	sc112	1

RR105	217444500	test_cap	test_runoff	test_initial	sc105	1
RR98	74868300	test_cap	test_runoff	test_initial	sc98	1
RR111	145719000	test_cap	test_runoff	test_initial	sc111	1
RR119	172319400	test_cap	test_runoff	test_initial	sc119	1
RR113	105186600	test_cap	test_runoff	test_initial	sc113	1
RR106	355841100	test_cap	test_runoff	test_initial	sc106	1
RR121	343099800	test_cap	test_runoff	test_initial	sc121	1
RR122	222976800	test_cap	test_runoff	test_initial	sc122	1
RR114	142001100	test_cap	test_runoff	test_initial	sc114	1
RR116	246531600	test_cap	test_runoff	test_initial	sc116	1
RR76	297302400	test_cap	test_runoff	test_initial	sc76	1
RR85	266214600	test_cap	test_runoff	test_initial	sc85	1
RR87	118737900	test_cap	test_runoff	test_initial	sc87	1
RR75	141077700	test_cap	test_runoff	test_initial	sc75	1
RR94	104328000	test_cap	test_runoff	test_initial	sc94	1
RR95	346906800	test_cap	test_runoff	test_initial	sc95	1
RR93	70567200	test_cap	test_runoff	test_initial	sc93	1
RR115	119264400	test_cap	test_runoff	test_initial	sc115	1
RR104	153235800	test_cap	test_runoff	test_initial	sc104	1
RR96	344144700	test_cap	test_runoff	test_initial	sc96	1
RR92	253619100	test_cap	test_runoff	test_initial	sc92	1
RR101	268806600	test_cap	test_runoff	test_initial	sc101	1
RR100	109609200	test_cap	test_runoff	test_initial	sc100	1
RR99	347303700	test_cap	test_runoff	test_initial	sc99	1
RR118	106596000	test_cap	test_runoff	test_initial	sc118	1
RR126	162761400	test_cap	test_runoff	test_initial	sc126	1
RR127	129567600	test_cap	test_runoff	test_initial	sc127	1
RR129	171387900	test_cap	test_runoff	test_initial	sc129	1
RR132	281329200	test_cap	test_runoff	test_initial	sc132	1
RR133	298857600	test_cap	test_runoff	test_initial	sc133	1
RR131	115068600	test_cap	test_runoff	test_initial	sc131	1
RR65	78318900	test_cap	test_runoff	test_initial	sc65	1

RR62	100755900	test_cap	test_runoff	test_initial	sc62	1
RR63	173105100	test_cap	test_runoff	test_initial	sc63	1
RR83	325409400	test_cap	test_runoff	test_initial	sc83	1
RR109	130377600	test_cap	test_runoff	test_initial	sc109	1
RR120	257021100	test_cap	test_runoff	test_initial	sc120	1
RR125	306163800	test_cap	test_runoff	test_initial	sc125	1
RR102	190941300	test_cap	test_runoff	test_initial	sc102	1
RR117	130936500	test_cap	test_runoff	test_initial	sc117	1
RR107	345578400	test_cap	test_runoff	test_initial	sc107	1
RR137	269397900	test_cap	test_runoff	test_initial	sc137	1
RR80	234478800	test_cap	test_runoff	test_initial	sc80	1
RR82	385260300	test_cap	test_runoff	test_initial	sc82	1
RR86	262213200	test_cap	test_runoff	test_initial	sc86	1
RR88	197729100	test_cap	test_runoff	test_initial	sc88	1
RR97	289137600	test_cap	test_runoff	test_initial	sc97	1
RR84	113772600	test_cap	test_runoff	test_initial	sc84	1
RR108	250533000	test_cap	test_runoff	test_initial	sc108	1
RR135	111269700	test_cap	test_runoff	test_initial	sc135	1
RR123	319261500	test_cap	test_runoff	test_initial	sc123	1
RR124	132702300	test_cap	test_runoff	test_initial	sc124	1
RR130	207781200	test_cap	test_runoff	test_initial	sc130	1
RR128	131673600	test_cap	test_runoff	test_initial	sc128	1
RR60	187992900	test_cap	test_runoff	test_initial	sc60	1
RR71	203455800	test_cap	test_runoff	test_initial	sc71	1
RR69	102618900	test_cap	test_runoff	test_initial	sc69	1
RR110	161173800	test_cap	test_runoff	test_initial	sc110	1
RR136	196927200	test_cap	test_runoff	test_initial	sc136	1
RR51	463123300	test_cap	test_runoff	test_initial	sc51	1
RR52	386728700	test_cap	test_runoff	test_initial	sc52	1
RR1	114882300	CAP_ANAND	RUNOFF_ANAND	test_initial	sc1	1
RR4	112841100	CAP_ANAND	RUNOFF_ANAND	test_initial	sc4	1
RR3	445086900	CAP_ANAND	RUNOFF_ANAND	test_initial	sc3	1

RR2	93028500	CAP_ANAND	RUNOFF_ANAND	test_initial	sc2	1
RR9	60831000	CAP_ANAND	RUNOFF_ANAND	test_initial	sc9	1
RR12	132183900	CAP_ANAND	RUNOFF_ANAND	test_initial	sc12	1

Table A.2 Parameter settings for the routing links of the hydrological NAM model of the Burhi-Gandak basin

#	ID	Name	x-value	k-value
1	'RR1'	'1_1'	0.22	0.4691
2	'RR2'	'2_1'	0.14	0.1421
3	'RR3'	'3_1'	0.13	0.2988
4	'RR4'	'4_1'	0.11	0.3924
5	'RR5'	'5_1'	0.11	0.1368
6	'RR6'	'6_1'	0.17	0.0568
7	'RR7'	'7_1'	0.12	0.338
8	'RR8'	'8_1'	0.12	0.1546
9	'RR9'	'9_1'	0.15	0.0735
10	'RR10'	'10_1'	0.14	0.1014
11	'RR11'	'11_1'	0.13	0.2709
12	'RR12'	'12_1'	0.15	0.0559
13	'RR13'	'13_1'	0.14	0.1497
14	'RR14'	'14_1'	0.12	0.314
15	'RR15'	'15_1'	0.31	0.0199
16	'RR16'	'16_1'	0.13	0.603
17	'RR17'	'17_1'	0.16	0.4066
18	'RR19'	'19_1'	0.15	0.3853
19	'RR20'	'20_1'	0.2	0.0511
20	'RR21'	'21_1'	0.11	0.0694
21	'RR22'	'22_1'	0.11	0.2618
22	'RR23'	'23_1'	0.4	0.0185
23	'RR25'	'25_1'	0.15	0.3829
24	'RR26'	'26_1'	0.11	0.2664
25	'RR27'	'27_1'	0.11	0.4682
26	'RR28'	'28_1'	0.11	0.1309
27	'RR29'	'29_1'	0.14	0.1268
28	'RR30'	'30_1'	0.18	0.1205
29	'RR31'	'31_1'	0.11	0.5967
30	'RR32'	'32_1'	0.13	0.2622
31	'RR33'	'33_1'	0.11	1.0451
32	'RR34'	'34_1'	0.11	0.5543
33	'RR35'	'35_1'	0.11	0.2426
34	'RR36'	'36_1'	0.11	0.4019
35	'RR37'	'37_1'	0.13	0.0403
36	'RR38'	'38_1'	0.11	0.4794
37	'RR39'	'39_1'	0.11	0.7095
38	'RR40'	'40_1'	0.11	0.9633
39	'RR41'	'41_1'	0.12	0.5222
40	'RR42'	'42_1'	0.11	0.4886
41	'RR43'	'43_1'	0.12	0.2068

42	'RR44'	'44_1'	0.23	0.0267
43	'RR45'	'45_1'	0.11	0.8665
44	'RR46'	'46_1'	0.12	0.321
45	'RR47'	'47_1'	0.11	0.2565
46	'RR48'	'48_1'	0.14	0.0456
47	'RR49'	'49_1'	0.12	0.3875
48	'RR50'	'50_1'	0.19	0.3352
49	'RR51'	'51_1'	0.11	0.2625
50	'RR52'	'52_1'	0.11	1.0041
51	'RR13'	'130_1'	0.11	0.4745

Table A.3 Surveyed cross sections in the lower part of the Burhi-Gandak basin

# Lot surveyed	CS	Level	Northing	Easting
1	CS 1 Borna	41.642	2813481	461289.52
1	CS 10 Suratpur	51.098	2860812	387341.2
1	CS 11 Samastipur	51.168	2861375	379081.6
1	CS 110 Kuriawa	41.022	2834784	420446.04
1	CS 12 Gopalpur	54.079	375569.7	2870206.3
1	CS 13 Mada Chhapra	54.197	2875868	366814.61
1	CS 14 Pilkhi Gajpati	55.44	2881084	356281.96
1	CS 15 Budh Nagra	56.169	2889631	351473.38
1	CS 16 Muzaffarpur CS Data Fn.csv	55.831	339915.8	2892157.5
1	CS 2 Khagariya	44.895	2819665	447307.41
1	CS 3 Rajura Fatehulla	44.051	2820108	439751.29
1	CS 37 Gangour	44.034	2821039	433951.06
1	CS 47 Mohammadpur Sakra	48.773	2843161	391719.39
1	CS 48 Rupali Khurd	49.023	2848364	388086.46
1	CS 5 Naokothi	37.713	2821917	419022.39
1	CS 50 Mohiuddinpur	48.095	2834417	390961.76
1	CS 51 Dalsingh Sarai	49.893	382389.6	2839297
1	CS 7 Rampur	48.347	2833802	401217.53
1	CS 8 Mohanpur	49.906	2844653	400802.75
1	CS 9 Bujurg Dwar	50.577	2852507	394644.11
2	CS 17 Dumaria	55.901	2904450.985	331740.394
2	CS 18 Meghua	61.242	2910002.241	321264.592
2	CS 30 Bakulahar	40.776	2820062.829	437783.98
2	CS 38 Dhodhraha	38.511	2825715.864	433956.027
2	CS 39 Rahima	40.681	2826051.426	432980.092
2	CS 4 Mohanpur	37.864	2821139.799	428299.361
2	CS 40 Bhagwan chak	39.576	2827082.25	433939.043
2	CS 41 Sisauni	42.046	2827993.185	424273.343
2	CS 6 Mozafra with Panapur	45.716	2825716.878	409169.431
2	CS 101 Sobhni	43.081	2821190.982	437995.634

2	CS 103 Panapur	44.123	2827612.203	408207.613
2	CS 104 Bhithsarai Gopalpur	43.187	2827443.179	407830.171
2	CS 109 Bahadurpur	40.082	2831742.594	429807.332
2	CS 42 Tulsi Chak	39.26	2829367.507	421454.616
2	CS 44 Telan	42.156	2826116.613	406407.09
2	CS 45 Mamapari	42.627	2826265.317	406108.231
2	CS 46 Maripur	42.114	2835284.848	398229
2	CS 49 Churaman	46.232	2825809.846	398695.996
2	CS 53 Musapur	54.122	2841163.887	373516.094
3	Bisunathpur	44.693	2852700	399250.6
3	Pakridih	49.521	2876111	383079.5
3	Gopalpur Raja Ram	56.028	2868613	348567.8
3	Byaspur	50.364	2847599	369176
3	Chhapra Bahabal	59.43	2918788	316393.6
3	Chakia	63.513	308049	2922796
3	Bairiya	63.121	2932282	304867.6
3	Madhubani	64.64	2943268	305562.1
3	Siswa	67.372	2956594	298259.9
3	Loknathpur	67.705	295065.8	2958113
3	Madhumalti	75.502	2974201	272217.4
3	Belwaliya Chanpatia	77.97	2983971	259262.2
3	Phulwariya	47.095	2851357	397870.3
3	Ghogha	54.73	2897697	336627.3
3	Deora	43.021	2831185	418104.1
3	Purkhottimpur	48.77	2843355	365376.2
3	Maura Khurd	51.326	2851129	363230.9
3	Chak Rasulabad	52.582	2859415	361323.5
3	Harilochanpur Suki	51.25	2865053	351526.5
3	Bachhuman	55.364	2874704	338032.3

Table A.4 Friction settings for river sections (reaches) in the Burhi-Gandak basin

Reach ID	Friction Type	Value
Santi Nadi	Manning	0.025
101	Manning	0.025
126	Manning	0.025
132	Manning	0.025
180	Manning	0.025
139	Manning	0.025
Jamwari Nadi	Manning	0.025
52	Manning	0.025
Chaknaha N	Manning	0.025
Chanha Nadi	Manning	0.025
94	Manning	0.025
96	Manning	0.025
98	Manning	0.025
Nuna Nadi	Manning	0.025
137	Manning	0.025
138	Manning	0.025
Bainti Nadi	Manning	0.025
140	Manning	0.025
156	Manning	0.025
97	Manning	0.025
99	Manning	0.025
Thalhi N	Manning	0.025
133	Manning	0.025
144	Manning	0.025
148	Manning	0.025
145	Manning	0.025
Baghmati R	Manning	0.025
54	Manning	0.025
8	Chezy	45
1	Chezy	45
48	Manning	0.025
3	Chezy	45
16	Chezy	45
4	Chezy	45
43	Manning	0.025
6	Chezy	45
4	Manning	0.025
39	Manning	0.025
Baghmati Nadi	Manning	0.025
122	Manning	0.025
95	Manning	0.025
128	Manning	0.025

182	Manning	0.025
Non Nadi	Manning	0.025
141	Manning	0.025
42	Manning	0.025
27	Chezy	45
7	Chezy	45
9	Chezy	45
10	Chezy	45
55	Manning	0.025
15	Chezy	45
5	Chezy	45
12	Chezy	45
17	Chezy	45
18	Chezy	45
19	Chezy	45
21	Chezy	45
13	Chezy	45
14	Chezy	45
26	Chezy	45
25	Chezy	45
31	Chezy	45
146	Manning	0.025
2	Chezy	45
11	Chezy	45
20	Chezy	45
22	Chezy	45
23	Chezy	45
24	Chezy	45
28	Chezy	45
29	Chezy	45
30	Chezy	45

Table A.5 Water level time series at different return periods for the confluence of the Burhi-Gandak river and the Ganga river.

Day	Normalized WL distribution	WL - T=2	WL - T=5	WL - T=10	WL - T=25	WL - T=50	WL - T=75	WL - T=100	WL - T=125	WL - T=150
-30	0.94	35.3	36.2	36.7	37.4	38.0	38.3	38.5	38.6	38.8
-29	0.94	35.4	36.2	36.8	37.5	38.0	38.3	38.5	38.7	38.9
-28	0.94	35.4	36.3	36.9	37.6	38.1	38.4	38.6	38.8	38.9
-27	0.94	35.5	36.4	36.9	37.7	38.2	38.5	38.7	38.9	39.0
-26	0.95	35.6	36.5	37.0	37.8	38.3	38.6	38.8	39.0	39.1
-25	0.95	35.7	36.6	37.2	37.9	38.4	38.7	38.9	39.1	39.3
-24	0.95	35.9	36.7	37.3	38.0	38.6	38.9	39.1	39.3	39.4
-23	0.95	36.0	36.8	37.4	38.1	38.7	39.0	39.2	39.4	39.5
-22	0.96	36.0	36.9	37.4	38.2	38.7	39.0	39.2	39.4	39.6
-21	0.96	36.0	36.9	37.4	38.2	38.7	39.0	39.2	39.4	39.5
-20	0.96	36.0	36.9	37.5	38.2	38.7	39.0	39.3	39.4	39.6
-19	0.96	36.1	36.9	37.5	38.3	38.8	39.1	39.3	39.5	39.6
-18	0.96	36.1	37.0	37.6	38.3	38.9	39.2	39.4	39.6	39.7
-17	0.96	36.2	37.1	37.7	38.4	38.9	39.2	39.5	39.6	39.8
-16	0.96	36.2	37.1	37.6	38.4	38.9	39.2	39.4	39.6	39.8
-15	0.96	36.2	37.1	37.7	38.4	38.9	39.2	39.5	39.6	39.8
-14	0.96	36.2	37.1	37.7	38.4	38.9	39.3	39.5	39.7	39.8
-13	0.96	36.3	37.1	37.7	38.4	39.0	39.3	39.5	39.7	39.8
-12	0.96	36.3	37.2	37.8	38.5	39.1	39.4	39.6	39.8	39.9
-11	0.96	36.4	37.2	37.8	38.6	39.1	39.4	39.6	39.8	40.0
-10	0.97	36.4	37.3	37.9	38.6	39.1	39.4	39.7	39.8	40.0
-9	0.97	36.5	37.4	38.0	38.7	39.2	39.6	39.8	40.0	40.1
-8	0.97	36.6	37.5	38.1	38.8	39.4	39.7	39.9	40.1	40.2
-7	0.97	36.7	37.6	38.2	39.0	39.5	39.8	40.0	40.2	40.4
-6	0.98	36.9	37.8	38.4	39.1	39.7	40.0	40.2	40.4	40.6
-5	0.98	37.1	38.0	38.5	39.3	39.8	40.2	40.4	40.6	40.7
-4	0.99	37.2	38.1	38.7	39.4	40.0	40.3	40.5	40.7	40.8
-3	0.99	37.3	38.2	38.8	39.6	40.1	40.5	40.7	40.9	41.0
-2	1.00	37.5	38.4	39.0	39.8	40.3	40.7	40.9	41.1	41.2
-1	1.00	37.6	38.5	39.1	39.9	40.4	40.8	41.0	41.2	41.3
0	1.00	37.7	38.6	39.2	40.0	40.5	40.8	41.1	41.3	41.4
1	1.00	37.6	38.5	39.1	39.9	40.5	40.8	41.0	41.2	41.3
2	0.99	37.5	38.4	39.0	39.7	40.3	40.6	40.8	41.0	41.2
3	0.99	37.3	38.2	38.8	39.5	40.1	40.4	40.6	40.8	41.0
4	0.99	37.1	38.0	38.6	39.4	39.9	40.3	40.5	40.7	40.8
5	0.98	37.0	37.9	38.5	39.2	39.8	40.1	40.3	40.5	40.6
6	0.98	36.8	37.7	38.3	39.1	39.6	39.9	40.2	40.3	40.5
7	0.97	36.7	37.6	38.2	38.9	39.5	39.8	40.0	40.2	40.4
8	0.97	36.6	37.5	38.1	38.8	39.3	39.7	39.9	40.1	40.2
9	0.97	36.5	37.3	37.9	38.7	39.2	39.5	39.8	39.9	40.1

10	0.96	36.3	37.2	37.8	38.5	39.1	39.4	39.6	39.8	39.9
11	0.96	36.2	37.1	37.6	38.4	38.9	39.2	39.4	39.6	39.8
12	0.96	36.1	36.9	37.5	38.3	38.8	39.1	39.3	39.5	39.6
13	0.95	36.0	36.8	37.4	38.1	38.7	39.0	39.2	39.4	39.5
14	0.95	35.9	36.8	37.3	38.1	38.6	38.9	39.1	39.3	39.4
15	0.95	35.8	36.7	37.3	38.0	38.5	38.8	39.1	39.2	39.4
16	0.95	35.7	36.6	37.2	37.9	38.4	38.7	39.0	39.1	39.3
17	0.95	35.7	36.5	37.1	37.8	38.4	38.7	38.9	39.0	39.2
18	0.94	35.6	36.4	37.0	37.7	38.2	38.6	38.8	38.9	39.1
19	0.94	35.5	36.3	36.9	37.6	38.1	38.4	38.6	38.8	39.0
20	0.94	35.4	36.2	36.8	37.5	38.0	38.3	38.5	38.7	38.8
21	0.94	35.3	36.1	36.7	37.4	37.9	38.2	38.4	38.6	38.7
22	0.93	35.1	36.0	36.6	37.3	37.8	38.1	38.3	38.5	38.6
23	0.93	35.1	35.9	36.5	37.2	37.7	38.0	38.2	38.4	38.5
24	0.93	35.0	35.8	36.4	37.1	37.6	37.9	38.1	38.3	38.4
25	0.93	34.9	35.7	36.3	37.0	37.5	37.8	38.0	38.2	38.3
26	0.92	34.8	35.7	36.2	36.9	37.5	37.8	38.0	38.2	38.3
27	0.92	34.8	35.6	36.2	36.9	37.4	37.7	37.9	38.1	38.2
28	0.92	34.7	35.5	36.1	36.8	37.3	37.6	37.8	38.0	38.1
29	0.92	34.6	35.4	35.9	36.6	37.2	37.5	37.7	37.8	38.0
30	0.92	34.6	35.4	35.9	36.6	37.2	37.5	37.7	37.8	38.0