Policy and Advisory Technical Assistance 8089 IND Phase II

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

Downscaling GCM data for climate change impact assessments on rainfall: a practical application for the Brahmani-Baitarani basin

Review of Design Standards for Flood Protection in the Brahmani-Baitarani River Basin in India

Manuscripts

December 2015

Deltares in association with RMSI and JPS
Disclaimer

"The views expressed in this report are those of authors and do not necessarily reflect the views and policies of DFID nor the ADB, its Board of Governors or the governments it represent, and DFID, ADB and the Government cannot be held liable for its contents. DFID and the ADB do not guarantee the source, originality, accuracy, completeness or reliability of any statements, information, data, advice, opinion, or view presented in this publication and accept no responsibility for any consequences of their use. By making any designation of or reference to a particular territory or geographic area in this document, the Asian Development Bank does not intend to make any judgments as to the legal or other status of any territory or area."
Downscaling GCM data for climate change impact assessments on rainfall: a practical application for the Brahmani-Baitarani basin
R.J. Dahm, U.K. Singh, M. Lal, M. Marchand, F. Sperna Weiland, S.K. Singh, and M.P. Singh
Accepted on 10 December 2015 for publication by the Journal of Hydrology and Earth System Science (HESS) as discussion paper.

Review of Design Standards for Flood Protection in the Brahmani-Baitarani River Basin in India
M. Marchand, S. Sethurathinam, V. Kumar, C.P. Singh, J. Buurman, C. Sprengers, R. Dahm, J. Singh
Submitted to Current Science on 22 December 2015
Downscaling GCM data for climate change impact assessments on rainfall: a practical application for the Brahmani-Baitarani river basin

R.J. Dahm¹, U.K. Singh², M. Lal², M. Marchand¹, F.C. Sperna Weiland¹, S.K. Singh³, and M.P. Singh³

[1]{Deltares, Boussinesqweg 1, P.O. Box 177, 2600 MH Delft, the Netherlands}
[2]{RMSI, A-8 Sector 16, NOIDA 201 30, India}
[3]{Central Water Commission, R.K. Puram, New Delhi 110 066, India}

Correspondence to: R.J. Dahm (ruben.dahm@deltares.nl)
Abstract

The delta of the Brahmani-Baitarani river basin, located in the eastern part of India, frequently experiences severe floods. For flood risk analysis and water system design, insights in the possible future changes in extreme rainfall events caused by climate change are of major importance. There is a wide range of statistical and dynamical downscaling and bias-correction methods available to generate local climate projections that also consider changes in rainfall extremes. Yet the applicability of these methods highly depends on availability of meteorological observations at local level. In the developing countries data and model availability may be limited, either due to the lack of actual existence of these data or because political data sensitivity hampers open sharing.

We here present the climate change analysis we performed for the Brahmani-Baitarani river basin focusing on changes in four selected indices for rainfall extremes using data from three performance-based selected GCMs that are part of the 5th Coupled Model Intercomparison Project (CMIP5). We apply and compare two widely used and easy to implement bias correction approaches. These methods were selected as best suited due to the absence of reliable long historic meteorological data. We present the main changes – likely increases in monsoon rainfall especially in the Mountainous regions and a likely increase of the number of heavy rain days. In addition, we discuss the gap between state-of-the-art downscaling techniques and the actual options one is faced with in local scale climate change assessments.
1 Introduction

In the past extreme rainfall over India has resulted in landslides, flash floods, severe river floods, and crop damage that have had major impacts on society, the economy, and the environment (Goswami et al., 2006). Increases in rainfall extremes have quantifiable impacts on intensity-duration-frequency relations (Kao and Ganguly, 2011) and are expected to enhance coastal and river flood risks and will, without adaptive measures, substantially increase flood damages. Climate adaptation strategies for emergency planning, the design of engineering structures, reservoir management, pollution control, risk calculations rely on knowledge of the frequency of these extreme rainfall events (Guhathakurta et al., 2011; Goswami et al., 2006).

Several studies already investigated the trends in rainfall extremes over India (Parthasarathy et al., 1993; Dash et al., 2009; Ramesh Kumar et al., 2009; Chaturvedi et al., 2012 and many others). Goswami et al. (2006) found significant positive trends in the frequency and the magnitude of heavy rain events and a significant negative trend in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000. Climate change is expected to further alter the intensity and frequency of extreme rainfalls (Chatuverdi et al., 2012; Frei et al., 2006; Kharin et al., 2007). Globally the intensity of extreme rainfall is projected to increase even in regions where mean rainfall decreases (Semenov and Bengtsson, 2002). Moreover, future climate studies based on climate model simulations suggest that greenhouse warming is likely to intensify the monsoon rainfall over a broad region encompassing South Asia (Lal et al., 2000; May, 2011; Meehl and Arblaster, 2003; Rupakumar et al. 2006; Trenberth, 2011). However, precise assessments of future changes in the regional monsoon rainfall have remained ambiguous due to wide variations among the model projections (Kripalani et al., 2007; Sabade et al., 2011; Turner and Annamalai, 2012). And the simulated rainfall response to global warming by climate models is actually accompanied by a weakening of the large-scale South-West (SW) monsoon flow (Kripalani et al., 2003; Krishnan et al., 2013; Ueda et al., 2006). Nonetheless, the recently released CMIP5 projections confirm significant reduction in return times of annual extremes of daily rainfall for the late 21st century in India (Ramesh and Goswami, 2014) and increases in seasonal mean rainfall amounts (Menon et al., 2013). In addition, Chaturvedi et al. (2012) found a steady increase in the number of days with extreme rainfall for the period of 2060 and beyond.
Within this paper we try to assess future climate induced changes in several rainfall indices of relevance to water resources and flood risk management in the Brahmani-Baitarani river basin. The basin is located in the eastern part of India. It experienced severe floods in recent years of 2001, 2003, 2006, 2008, 2011 and 2013 (Government of Odisha, 2011; Government of Odisha, 2013).

To enable a quantitative climate change analysis we use Global Climate Model (GCM) data. GCM rainfall data normally have biases from observations and needs to be corrected to ensure its applicability at the local scale (Teutschbein and Seibert, 2012; Sperna Weiland et al., 2012; Christensen et al., 2008). There is a wide range of statistical and dynamical downscaling and bias-correction methods available to generate local climate projections that also consider changes in rainfall extremes. Yet the applicability of these methods highly depends on availability of meteorological observations at local scale. In this study, data from a limited number of rain gauges with incomplete time-series and a lower resolution gridded rainfall product – the APHRODITE dataset (Yatagai et al., 2012) – could be accessed and used. Due to this data quality issue we concentrate on two widely used and easy to implement bias correction procedures – Linear Scaling (LS) and Delta Change (DC). We evaluate the influence of these procedures on resulting changes in rainfall indices. Instead of using a large ensemble of GCMs we focus on three models that nearly span the full range of annual mean rainfall projections available for India – analysing in more detail the locally relevant biases within these three GCMs and the changes they project.

This paper is organized as follows. Section 2 presents an overview of the selected GCMs, reference dataset, and bias correction methods. This is followed by a short description of the impact analysis framework applied and the study area. In section 3 we report the main findings of our study and present the range of rainfall indices under climate change. Here, we are specifically concerned with an inter- and intra-comparison of the GCMs and downscaling methods. Next the limitations experienced for bias-correction techniques experienced in this study are discussed. Section 5 summarizes our main conclusions and provide outlook for future work and practical applications in the study area.
2 Methods

The method adopted in this study for the analysis of climate change impact on four rainfall indices is based on four steps described in subsequent sub-sections.

1. GCM selection by comparing observed (gauge and gridded time series) and simulated (GCM) variability of monthly rainfall.

2. A description of the selected reference rainfall dataset.

3. Bias correction of daily rainfall time series from the selected GCMs for the baseline and future projections using Linear Scaling and Delta Change method.

4. Rainfall indices analysis for the baseline and future projections focussing on water resources and flood risk management in Brahmani-Baitarani river basin.

2.1 Global Circulation Model selection

Data sets generated in simulations from three GCMs undertaken for the Fifth Coupled Model Inter-comparison Project (CMIP5 – Taylor et al., 2012; Knutti and Sedláček, 2013) have been downloaded which are the Hadley Center Global Environment Model 2 – Earth System (HadGEM2-ES), the GFDL-CM3, and the MIROC-ESM (see Table 1). Data for the time slices representing periods 1961-1990 (baseline), short term climate change projection (2030-2059), and long term projection (2060-2099) were used.

Almost all CMIP5 models show good performance for surface air temperature simulations averaged over South Asia and the Indian Sub-continent, with MIROC5 as one of the models closest to the observations. Yet for area-averaged annual and seasonal rainfall the models significantly deviate from observations over India (Chaturvedi et al., 2012). Here GFDL-CM3 is one of the best performing models. In addition, HadGEM2-ES is selected because it is one of the most commonly used GCMs. For India the three selected GCMs nearly span the uncertainty band for annual mean rainfall that was obtained with 18 Earth System Models (ESMs) used in a validation exercise (Mondal and Mujumdar, 2014; Rameshkumar and Goswami, 2014). Interpreting Menon et al. (2013), HadGEM2-ES could be regarded as ‘too dry’, GFDL-CM3 as ‘representative’, and MIROC-ESM as ‘quite wet’.
2.2 Representative Concentration Pathway (RCP) Selection

The RCPs as considered in IPCC AR5 (Vuuren et al., 2011) are compatible with the full range of stabilization, mitigation, and baseline emission scenarios, and span a full range of socio-economic driving forces (Hibbard et al., 2011). In this study, we considered RCP6.0 for the generation of the climate change projections as it follows a stabilizing CO$_2$ concentration close to the median range of all four policy pathways and will give us a not too extreme indication of what might change. Most likely the spread and uncertainty in projections will increase when including additional RCPs and changes may become more pronounced when using the extreme RCP8.5 (Hibbard et al., 2011).

2.3 Observed rainfall

Observed rainfall was obtained from the APHRODITE long-term daily gridded precipitation dataset (version V1101) for Monsoon Asia (Yatagai et al., 2012). The APHRODITE (Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources, Japan) is a long-term (1951-2007) continental-scale product that contains a dense network of daily rain gauge data for Asia including the Himalayas, South and Southeast Asia. The APHRODITE dataset consists of $0.25^\circ \times 0.25^\circ$ resolution gridded daily precipitation derived from the Global Telecommunication System (GTS), precompiled datasets and APHRODITE’s individual data collection. It covers the period 1951-2007. The data is quality controlled and corrected for orographic effects. It includes over 2000 stations over India and captures the large scale features of monsoon rainfall over the Indian region well (Rajeevan and Bhate, 2008). Hereafter it is referred to as the climatological rainfall dataset. Within this paper we perform additional validation focusing on extremes using observations from three rain gauges that were obtained from the Central Water Commission of India (CWC). Locations of the rain gauges are listed in Table 2 and shown in Figure 1. Gauge observations could not be used as reference since they do not overlap with the full GCM baseline period.

2.4 Bias correction

There is often a clear bias from observations in the statistics of variables produced by GCMs such as temperature and rainfall due to limitations in among others the incorporation of local
topography and non-stationary phenomena within the GCMs. GCM outputs can therefore often not be directly applied for impact studies at the catchment scale (Christensen et al., 2008; Kay et al., 2006; Kotlarski, 2005; Fan et al., 2010). Dynamic downscaling, statistical downscaling, and bias correction are the most commonly used methods to generate locally applicable climate data (Bergstrom, 2001; Fowler et al., 2007; Schoof et al., 2009). Dynamic downscaling includes nesting of high resolution Regional Climate Models (RCMs) with GCM outputs at boundaries which ensures consistency between climatological variables. However, they are computationally expensive, their skill strongly depends on GCM boundary and for India there are no ready to use RCM scenarios for the RCP emission scenarios at hand. Statistical downscaling models, on the other hand, are based on statistical relationships between large-scale climate variables (predictors) and local-scale climate variables (predictant) and hence require less computational time. Yet for the establishment of reliable statistical relationships long historical observed records of both predictor and predictant variables should be available.

Simpler bias correction procedures consisting of general transformation techniques for adjusting the GCM output time series are often used. They assume a stationary bias between GCM output and observations for the baseline period and future climate (Teutschbein and Seibert, 2012a). With the more advanced Quantile Mapping method (Thrasher et al., 2012; Camici et al, 2014) changes in mean and extreme rainfall are corrected individually – yet this method requires reliable CDFs of observed rainfall and from the comparison between the APHRODITE dataset and station observations (Rana et al., 2014) we know that large biases in rainfall extremes exist.

Therefore, we restrict ourselves to two simple methods (1) the Delta Change method and (2) the Linear Scaling method and applied these to the data extracted for our region of interest from all three GCM outputs (Christensen et al., 2008; Chen et al., 2012), realizing that these methods only concentrate on the correction of monthly mean rainfall amounts and can thus affect our analysis of changes in extreme rainfall indices.

2.4.1 Delta Change method

The Delta Change method transforms historical observations into future projections using monthly average correction factors that are derived from the GCM simulations for the
baseline and future climate (Camici et al., 2014; Chen et al., 2013; Teutschbein et al., 2012b) according to:

\[ \Delta P_m = \frac{P_{GCM}^{fut}}{P_{GCM}^{BL}} \]  

(1)

\[ P_{OBS}^{fut} = \Delta P_m \cdot P_{OBS}^{BL} \]  

(2)

where \( fut \) refers to future climate, \( BL \) refers to baseline climate (i.e., 1961-1990), \( GCM \) refers to GCM simulations and \( OBS \) refers to either observations (\( BL \) period) or future projections (\( fut \)), \( P \) refers to daily rainfall values and \( P_m \) refers to monthly long term mean rainfall values. The disadvantage of this method is that the future and baseline scenarios differ only in terms of their means and intensity while all other statistics of the data, such as the skewness and number of wet days, remain almost unchanged (Camici et al., 2014). This will hamper the assessment of change in extreme rainfall frequency as the change in return period is essentially a derivative of the multiple factors.

### 2.4.2 Linear Scaling method

Within the Linear Scaling method the long-term average monthly bias between the baseline (i.e., 1961-1990) GCM simulations and observations is derived and this bias is applied to correct the future GCM simulations assuming a stationary bias over time, according to:

\[ BIAS_m = \frac{P_{OBS}^{BL}}{P_{GCM}^{BL}} \]  

(3)

\[ P_{OBS}^{fut} = BIAS_m \cdot P_{GCM}^{fut} \]  

(4)

where \( BIAS_m \) is the monthly average bias for the baseline climate and the correction factor for the future GCM simulations. The advantage of this method is that the variability of the corrected data, for both baseline and future climate is more consistent with the GCM data, which implies that changes in wet day frequencies and intensities can be derived, yet they are not individually corrected as all events are adjusted with the same monthly average correction factor (Teutschbein et al., 2012b).
2.5 Impact analysis framework

To study the impact of climate change on rainfall and associated fields like water resources and flood risk management, we selected the following four indices.

1. Mean annual and seasonal rainfall in order to explore possible effects of climate change on water resources and flood risk management.

2. Frequency of seasonal Wet Days (WD). According to the definition followed by the India Meteorological Department (IMD), a day with rainfall is considered a ‘wet day’ if the rainfall equals or exceeds 2.5 mm.

3. Seasonal frequency of days with light, moderate, and heavy rainfall (LRD, MRD, and HRD respectively). Table 3 shows the IMD classification for rainfall intensities. We clustered all ‘heavy rain’ classifications into one group to examine climate change induced alterations in potential flood inducing events.

4. One-day extreme rainfall return periods to investigate the potential impact of climate change on rainfall intensities. In this study we applied the Gumbel extreme value type-1 distribution (Gumbel, 1941) to derive rainfall intensities for different return periods (2, 5, 10, 25, 30, 50, and 100 years).

Table 4 shows the classification of seasons according to IMD.

2.6 Study area

This study focusses on the Brahmani-Baitarani river basin located in the eastern part of India. The Brahmani-Baitarani river basin and neighbouring Mahanadi river basin experienced serious floods in the years 2001, 2003, 2006, 2008, 2011 and 2013. During September 2011 heavy rainfall together with high sea levels led to the flooding of large parts of the Delta. It affected about 3.4 million people of which 45 people lost their life (Government of Odisha, 2011). In 2013 cyclone Phailin created havoc along the coastal districts of Odisha state. Due to storm surge up to 3.5 m, large areas were inundated. The Baitarani River, along with other rivers, experienced floods as a result of torrential downpour. No less than 13 million people were affected of which 44 people lost their life (Government of Odisha, 2013).

The basin is an inter-state basin and spreads across the states of Chhattisgarh, Jharkhand, and Odisha. The elevation ranges from >750 meter in the north-western part of the basin to approximately 10 meter in the delta region. The Baitarani River enters the Brahmani River in
the deltaic region before it drains into the Bay of Bengal. The catchment area is 51,822 km². The region is characterized by a sub-tropical monsoon climate zone with mean annual rainfall of approximately 1450 mm (CWC, 2011) most of which occurs during the SW monsoon season (June to September).

The basin is exposed to orographic effects with a positive elevation-rainfall depth slope during monsoon season and an inverse slope in the post-monsoon season when cyclones hit the coast of Odisha (Deltares, 2015). Due to the size and shape, the Brahmani-Baitarani river basin is captured by approximately one GCM grid cell in the deltaic region and one grid cell in the Mountainous region. This allows studying possible orographic effects present in the future projections (Prokop and Walanus, 2013). GCM and climatological observed rainfall values were taken from the grid cell with center coordinates closest to these regions. It was decided not to resample the climatological observed and GCM datasets to one common grid, since up-scaling or spatial-averaging would result in spatial smoothening of rainfall extremes. Figure 2 shows the locations of the grid cells used. Table 5 presents elevations of center grid points for both GCMs and observed climatological data derived from the SRTM 30.

3 Results

We will focus our discussion of the results on the SW monsoon season only as mainly changes in monsoon rainfall will affect water resources and flood risk management in the Brahmani-Baitarani river basin. The figures contain results for all seasons.

3.1 Comparison of climatological and gauge rainfall data

The climatological dataset covers the full GCM baseline period whereas the gauge observations are more recent and only available for a limited time-span, they can therefore not be used as baseline reference. We here verify the quality of the climatological dataset compared to gauge observations for the overlapping period 1990-2007. Overall the climatological dataset resembles the CWC rain gauges quite well (see figure 3). Yet during pre-monsoon and monsoon season climatological data underestimates the rainfall in comparison to the gauge observations (averaged for the three gauge stations 17% and 12% less rain during the pre-monsoon and monsoon period respectively). Climatological data underestimates the occurrence of ‘heavy rain’ events during the 1990-2007 period with 68% (24 instead of 74 events), 61% (17 instead of 44 events), and 90% (5 instead of 48 events) for
Akhuapada, Anandpur, and Tilga gauge respectively, with an average 0.3-1.3 of such events per year (a frequency of less than 1 and changes therein will affect the analysis of extreme value return periods). This underestimation is most likely caused by the smoothening introduced when interpolating point observations to the grid. Differences in rainfall extremes between the two datasets can clearly be seen from their respective CDFs (see figure 4). Still, based on (1) this analysis, (2) the period covered by the climatological dataset and (3) the work of Rajeevan and Bhate (2008) we conclude that the dataset is suitable as a gridded reference dataset for the Brahmani-Baitarani river basin. When quantifying the impact of climate change to strategic flood management studies in practice, the rainfall deviations between climatological and gauge extremes should be considered.

3.2 Comparison of climatological and GCM baseline data

The South-West (SW) monsoon, lasting from June to September, is the most important feature of the Indian climate. Its onset and withdrawal dates are highly variable. Over the period 2000-2012 the actual onset date over Kerala coast varied from the 23rd May to 8th June (Puranik et al., 2013). As per the IMD the normal monsoon onset date for the Brahmani-Baitarani river basin is 10th June. However, during 2005-2012, the actual onset dates varied from 6th to 26th June (Indian Meteorological Department n.d.(a)). As a consequence, total rainfall in the month of June varies significantly in the Brahmani-Baitarani river basin. The baseline simulations of the three GCMs show a fair comparison with the observed rainfall on annual basis (see figure 5). However, for the monsoon season, the baseline simulations show an underestimation of average seasonal rainfall. Rainfall amount in June is underestimated by both HadGEM2-ES and MIROC-ESM (11% and 19% respectively of observed), and June under-estimations are especially large for the deltaic region where the GCM cells cover both land and sea.

Monthly rainfall amounts of HadGEM2-ES are almost all below climatological values, this corresponds with findings of Menon et al. (2013) that HadGEM2-ES is ‘too dry’ compared to long-year observations. Their conclusion that MIROC-ESM is ‘quite wet’ does not hold throughout the year for the baseline period for the Brahmani-Baitarani river basin. MIROC-ESM underestimates rainfall in February-May in the delta region and during the monsoon in
the Mountainous region. GFDL-CM3 overestimates rainfall during the monsoon season in the
deltaic region but overall performs best.

3.3 Impact of downscaling method on future GCM projections

We made a modification to the LS method for the month June as the underestimation of
monsoon rainfall in June by HadGEM2-ES and MIROC-ESM would result in extreme large
correction factors, unrealistic rainfall amounts (up to 900 mm/day) and consequently an
unrealistic large increase in heavy rain events occurring in June when applying the LS
method, see Table 6. Therefore, we decided to apply the July multiplier also for June. By
doing so, the GCM total monsoon rainfall amount of MIROC-ESM and HadGEM2-ES
become closer to the climatological dataset. Only for GFDL-CM3 total monsoon rainfall
becomes slightly lower than that of climatological values. By applying the multiplier of July
in June the annual mean baseline rainfall amounts will be somewhat different between the LS
and DC method. Although the underestimation of rainfall by MIROC-ESM for the winter
season in the Delta region leads to high multipliers as well, we decided not to apply a tailored
correction here as it would only be applicable for one of the GCMs.

3.3.1 Mean seasonal rainfall

Figure 6 presents the mean seasonal rainfall for baseline and future climate. Nine panels are
used to summarize our findings, showing for each GCM individually changes for the Delta
region (left), the Mountainous region (middle) and for the basin as a whole (right). Towards
the end of the century, monsoon rainfall is projected to increase throughout the basin with the
Delta region in MIROC-ESM as only exception. For the shorter time horizon the signal is
more variable, according to GFDL-CM3, monsoon rainfall will first decrease, whereas the
other regions project increases except for the Delta region in MIROC-ESM. Both HadGEM2-
ES and GFDL-CM3 also project increases for the pre-monsoon season. Increases are in
general larger for the DC method; the multipliers of the LS method may reduce the change
signal. These projections are in line with the study of Guhathakurta et al. (2011), Lal et al.
(2000), May (2011), Rupakumar et al. (2006) and Menon et al. (2013) who also reported
increases for monsoon rainfall in east and north east India.
3.3.2 Number of Wet days

The projected change in the number of wet days (WD – Figure 7) highly depends on the correction method used and the direction of the bias in the GCM data. For the DC method, the impact of climate change is given by the difference between the future GCM and the climatological data to which the DC method was applied. For the LS method there is a mismatch in the number of WD for the GCM data for the baseline period and the climatological data. The impact of climate change can thus only be derived when comparing future GCM data with the bias correction baseline when using the LS method.

Changes in this index cannot be captured well by the DC method. With the DC method the observed day-to-day variability remains unchanged in the future time-series and intensities are only scaled with monthly average correction factors (Teutschbein et al., 2012a; Camici et al. 2014). Changes are therefore directly related to the seasonal mean rainfall and only slightly differ due to the definition of the rainfall amount for a wet day. To project changes in the WD, while applying LS as correction method, the number of wet days has already been captured well by the GCMs for the future time period. Both HadGEM2-ES and MIROC-ESM show a distinct increase in WD in both regions and for both short and long term projections. While the ‘too dry’ and ‘too wet’ GCMs (Menon et al. 2013) show a clear trend, the trend in the ‘representative’ GCM (GFDL-CM3) is minimal from a small decrease for the short term projections to a small increase in WD in the long term projections. From the mixed signals presented in Figure 8, no clear conclusions on the potential direction of change in the WD during the monsoon season can be drawn, on average there is an indication for an increase. This increase was also found by Chaturvedi et al. (2012).

For the LS method we conclude that for a reliable projection of change in WD, the WD in the GCM baseline period should be close to observed, otherwise the correction method and bias from observations will disturb the change signal too much. For GFDL-CM3 we have seen that the number of WD during the baseline period is 103, which already nearly corresponds to the entire Monsoon season which explains the small increase found for this GCM. With the DC method the WD only increase based on the monthly linear increase in total precipitation.
3.3.3 Light, Moderate and Heavy rains

The impact of climate change on these indices is computed similar to the WD indices. As expected the projected changes obtained with the DC method are directly related to the change in mean seasonal rainfall with decreases in LRD (Figure 8) and increases in both MRD and HRD (Figure 9 and 10). Overall rainy days will become wetter with an exception the Delta region in MIROC-ESM that partially includes the sea. The increase in MRD and HRD is particularly visible during the long term climate projection (2080s). The general increase in HRD is confirmed by the results of the LS method applied to HadGEM2-ES and MIROC-ESM for the Mountainous region. Notable are the minimal changes in HRD obtained from GFDL-CM3. This change in day-to-day variability is a direct result of changes in rain intensity and frequency in the GCM itself.

3.3.4 Return periods

Both HadGEM2-ES and MIROC-ESM project decreases in return periods for extreme rainfall amounts for both the Delta and Mountainous regions (see Figure 11). In general changes derived after applying the DC method are more modest as a result of the unchanged day-to-day variability – changes will most likely be within the present day climate variability. Unfortunately, we find unrealistic high rainfall extremes for MIROC-ESM due to the high February-May multipliers that correct for the underestimation of winter and pre-monsoon rainfall in the Delta region. The possible increases in return periods for the delta region, obtained after applying the LS method to GFDL-CM3, is inconsistent with all other projections and is likely a result of correction multipliers below one that also decrease the extremes. The overall reduction in return times of annual extremes of daily rainfall for the late 21st century, which we find here, was also found by Ramesh and Goswami (2014).

The return period analysis once more illustrates the importance of focussing on relative changes. The precipitation amounts for a 100-year return period of a one-day rainfall event for the period 1990-2013 are 378 mm, 328 mm, and 229 mm for Akhuapada, Anandpur and Tilga rainfall gauge respectively, whereas the climatological data and the baseline rainfall for the LS method applied to all GCMs and regions show intensities of 100-200 mm for the same return period. Therefore, translating absolute future climate results of extreme rainfall events
based on the climatological dataset to rainfall intensities recognizable for local authorities familiar with the rainfall gauges remains a challenge.

4 Discussion

For this assessment the climatological dataset was the best available historical reference dataset as it provides continuous daily time-series for the full baseline period of the GCM simulations and performs relatively well for India (Rana et al., 2014). Yet our comparison with gauge observations showed large biases which are most likely as a result of spatial smoothening introduced by the interpolation to the grid. The biases in extreme rainfall amounts in the climatological dataset will have influenced the analysis of changes therein. In addition, with a more reliable reference meteorological dataset that better matches the CDF of gauge data, an advanced correction method could have been employed. With for example quantile-mapping realistic changes in extremes can be introduced and the day-to-day variability can be corrected towards observations (Van Pelt et al., 2012; Trenberth, 2011).

Instead we applied two relatively simple GCM correction methods. From both methods we know they have disadvantages for use in climate impact analysis. The DC method only provided reliable information on changes in seasonal means, as it leaves the day-to-day variability unchanged and changes in extremes are linearly scaled with changes in the mean (Camici et al., 2014; Chen et al., 2013; Teutschbein et al., 2012a). With the LS method we could obtain information on changes in rainfall frequency and intensity. Yet, as only monthly mean correction multipliers were applied, the day-to-day variability of corrected GCM baseline simulations remained different from the observed time-series. In addition, the monthly mean correction also influenced the values of the extremes, i.e. within an on average too wet month the extremes are linearly reduced with the same correction multiplier. Consequently, only relative changes in extremes could reliably be estimated from the baseline and future corrected GCM simulations.

We introduced an additional correction to the LS method by applying the multiplier for July to the data of June; this is to avoid the occurrence of extreme high rainfall amounts in the corrected data for June by compensating for the variable monsoon onset date. This introduces a deviation in the corrected baseline GCM data from observations and rainfall amounts for June in both the corrected baseline and also the future climate GCM data and will remain too low. In future work the selection of GCMs could be extended with more criteria, focussing
not only on annual rainfall amounts, but also on the onset and amount of monsoon rainfall. Hereby the need to apply such tailored corrections can be avoided. From the above we can conclude that the performed analysis is not based upon the latest state-of-the-art techniques as for example presented in Teutschbein and Seibert (2012b), Chen et al. (2012), Christensen et al. (2008), Fowler et al. (2007), Van Pelt et al. (2012) and many others. Yet this study illustrates the restrictions one is faced with when working in less data rich areas. As discussed, the quality in combination with the time-coverage of the historical observations did neither allow for statistical downscaling based upon predictor-predictant relationships nor for more advanced quantile mapping techniques. In addition, dynamically downscaled RCM data was not at hand. The simpler techniques that were applied did not allow for an analysis of all statistical quantities of interest. This demonstrates the gap between science and practice that still needs to be bridged in the area of local climate impact analysis (Ehret et al., 2012; Hagemann et al., 2011; Dosio et al., 2012).

This study focused on changes in rainfall only but could be extended with impact analysis for water resources and flood risk management. As discussed above the changes in daily rainfall and extreme events cannot be considered reliable, yet the seasonal and monthly changes provide information for (1) flood risk assessments for larger river basins where severe floods mainly occur as multiple day events due to result of medium/long-term (weeks to months) rainfall conditions upstream and for (2) water resources management, groundwater recharge and soil moisture conditions of relevance to agricultural production. For the latter application the baseline change assessment should be extended to all seasons.

5 Conclusions

- SW monsoon rainfall is in general projected to increase over the Brahmani-Baitarani river basin, especially in the Mountainous regions.
- The number of wet days is likely to increase in the Monsoon season; changes are largest and most pronounced towards the end of the century. The number of days with heavy rain is also likely to increase.
- Although the annual rainfall cycle is captured well by all three GCMs, biases from observed data exist, with as most important the too late onset of the monsoon in
HADGEM2-ES and MIROC-ESM and the underestimation of winter rainfall by MIROC-ESM in the delta region.

- The DC and LS correction methods disturb the projected changes in extremes. The LS method is preferred when analysing extremes and change in number of wet days, as the DC method leaves the day-to-day variability unchanged. Yet with the LS method the analysis should be restricted to the relative changes between corrected baseline and future GCM time-series.

- The climatological observation dataset APHRODITE underestimates the number of ‘heavy rain’ events when compared to observed data of CWC rain gauge stations. This affects the reliability of future climate change projections for precipitation.

- For proper correction and downscaling of GCM data more advanced techniques exist. However, these techniques require high quality reference meteorological datasets and/or computing resources which are sometimes not available for practical analysis in the developing countries. Assessment of the impact of these limitations to the actual climate change analysis will provide insight in the applicable bias correction methods and can improve the interpretation of the results.
Acknowledgements

The study was funded by ADB and DFID/UKAid under the Asian Development Bank Policy and Advisory Technical Assistance 8089 IND Phase II project. We acknowledge our colleagues of the TA8089 project and we would like to express our sincere thanks to S. Sethurathinam as well as Central Water Commission officers Vasanthakumar Venkatesan and Manoj Kumar. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in Table 1 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.
References

Bergstrom, S.: Climate change impacts on runoff in Sweden - Assessment by global climate models, dynamical downscaling and hydrological modelling, Clim. Res., 16(2): 101, 2001.

Camici, S., Brocca, L. Melones, F. and Moramarco, M.: Impact of climate change on flood frequency using different climate models and downscaling approaches, J. Hydrol. Eng., 2014.19, 2014.

Chen, H., Xu, C. Y., and Guo, S.: Comparison and evaluation of multiple GCMs, statistical downscaling and hydrological models in the study of climate change impacts on runoff, J. Hydrol., 434-435, 3645, 10.1016/j.jhydrol.2012.02.040, 2012.

Central Water Commission (CWC): Assessment of water resources at basin scale using space inputs. A pilot study by NRSC and CWC, pp 65, 2011.

Christensen, J.H., Boberg, F., Christensen, O.B., and Lucas-Picher, P.: On the need for bias correction of regional climate change projections of temperature and precipitation, Geo. Res. Lett., 35, L20709, doi:10.1029/2008GL035694, 2008.

Dash, S.K., Kulkarni, M.A., Mohanty, U.C., and Prasad, K.: Changes in the characteristics of rain events in India, Journal of Geophysical Research: Atmospheres, 114(D10): D10109, 2009.

Deltares.: Operational Research to Support Mainstreaming of Integrated Flood Management under Climate Change. PATA 8089 IND Phase II. Main Report. Deltares and Associates, Delft / New Delhi, 2015.
Dosio, A., Paruolo, P., and Rojas, R.: Bias correction of the ENSEMBLES high resolution climate change projections for use by impact models: Analysis of the climate change signal, J Geophys Res, 117(D17), D17110, doi:10.1029/2012JD017968, 2012.

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., and Liebert, J.: HESS Opinions “Should we apply bias correction to global and regional climate model data?”, Hydrol Earth Syst Sci, 16(9), 3391–3404, doi:10.5194/hess-16-3391-2012, 2012.

Fan, F., Mann, M.E., Lee, S., and Evans, J.L.: Observed and Modeled Changes in the South Asian Summer Monsoon over the Historical Period, J. Clim., 23(19): 5193-5205, 2010.

Frei, C., Schöll, R., Fukutome, S., Schmidli, J., and Vidale, P.L.: Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models, J. Geophys. Res., 111(D6): D06105, 2006.

Fowler, H.J., Blenkinsop, S., and Tebaldi, C.: Linking climate change modeling to impacts studies: Recent advances in downscaling techniques for hydrological modeling, International Journal of Climatology, 27(12): 1547-1578, 2007.

Guhathakurta, P.: Highest recorded point rainfall over India, Weather, 62(12), 2007.

Guhathakurta, P., Sreejith, O. P. and Menon, P.A.: Impact of climate change on extreme rainfall events and flood risk in India, J. Earth Syst. Sci. 120, No. 3, June 2011, pp. 359–373.

Gumbel E.J.: The return period of flood flows, The Annals of Mathematical Statistics, 12, 163–190, 1941.
Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S., and Xavier, P.K.: Increasing Trend of Extreme Rain Events over India in a Warming Environment, Science, 314(5804): 1442-1445, 2006.

Government of Odisha: Annual Report on Natural Calamities 2010-2011. Revenue & Disaster Management Department, Special Relief Commissioner. Bhubaneswar, India, 2011.

Government of Odisha: Memorandum on the Very Severe Cyclone Phailin and the Subsequent Flood, 12 -15 October 2013. Special Relief Commissioner, Revenue & Disaster Management Department, Government of Odisha, Bhubaneswar, 2013.

Hagemann, S., Chen, C., Haerter, J.O., Heinke, J., Gerten, D., and Piani, C.: Impact of a Statistical Bias Correction on the Projected Hydrological Changes Obtained from Three GCMs and Two Hydrology Models, J Hydrometeorol, 12(4), 556–578, doi:10.1175/2011JHM1336.1, 2011.

Hibbard, K.A., Van Vuuren, D.P., and Edmonds, J.: A primer on the representative concentration pathways (RCPs) and the coordination between the climate and integrated assessment modeling communities. CLIVAR Exchanges, 16, 12–15, 2011.

Kao, S.-C. and Ganguly, A.R.: Intensity, duration, and frequency of precipitation extremes under 21st-century warming scenarios, J. Geophys. Res., 116(D16): D16119, 2011.

Kay, A.L., Reynard, N.S., and Jones, R.G.: RCM rainfall for UK flood frequency estimation. I. Method and validation, J. Hydrol., 318(1–4): 151-162, 2006.

Kharin, V.V., Zwiers, F.W., Zhang, X., and Hegerl, G.C.: Changes in Temperature and Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations, J. Clim., 20(8): 1419-1444, 2007.
Kotlarски, S.: Regional climate model simulations as input for hydrological applications: evaluation of uncertainties, Advances in geosciences, 5: 119, 2005.

Knutti, R. and Sedláček, J.: Robustness and uncertainties in the new CMIP5 climate model projections, Nature Climate Change, Volume: 3, Pages: 369–373, DOI: doi: 10.1038/nclimate1716, 2013.

Kripalani, R.H., Kulkarni, A., Sabade, S.S., and Khandekar, M.L.: Indian Monsoon Variability in a Global Warming Scenario, Nat. Hazards, 29(2): 189-206, 2003.

Kripalani, R.H., Oh, J.H., Kulkarni, A., Sabade, S.S., and Chaudhari, H.S.: South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4, Theor. Appl. Climatol., 90(3-4): 133-159, 2007.

Krishnan, R., Sabin, T.P., Ayantika, D.C., Kitoh, A., Sugi, M., Murakami, H., Turner, A.G., Slingo, J.M., and Rajendran, K.: Will the South Asian monsoon overturning circulation stabilize any further? Climate Dynamics, 40(1-2): 187-211, 2013.

May, W.: Simulation of the variability and extremes of daily rainfall during the Indian summer monsoon for present and future times in a global time-slice experiment, Climate Dynamics, 22(2-3): 183-204, 2004.

Meehl, G.A. and Arblaster, J.M.: Mechanisms for projected future changes in south Asian monsoon precipitation, Climate Dynamics, 21(7-8): 659-675, 2003.

Menon, A., Levermann, A., Schewe, J., Lehmann, J. and Frieler, K.: Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models, Earth Syst. Dynam. Discuss. 4, 1–24, 2013.
Mitchell, T.D. and Jones P.D.: An improved method of constructing a database of monthly climate observations and associated high resolution grids, Int. J. Climatol., 2005, 25, 693–712; doi: 10.1002/joc.1181, 2005.

Mitra, S. and Mishra, A.: Hydrological response to climatic change in the Baitarani river basin, Journal of Indian Water Resources Society, Vol 34(1), 24-33, 2014.

Mondal, A. and Mujumdar, P.P.: Modeling Non-Stationarity in Intensity, Duration and Frequency of Extreme Rainfall over India, Journal of Hydrology. Vol 521, pp. 217-231, 2014.

Lal, M., Meehl, G.A., and Arblaster, J.M.: Simulation of Indian summer monsoon rainfall and its intraseasonal variability in the NCAR climate system model, Reg Environ Change, 1(3-4):163-179, 2000.

Parthasarathy, B., Rupa Kumar, K. and Munot, A.: Homogeneous Indian monsoon rainfall: variability and prediction; Proc. Indian Acad. Sci. (Earth Planet Science) 102 121-155, 1993.

Patwardhan, S., Kulkarni, A., and K. Krishna Kumar.: Impact of Climate Change on the Characteristics of Indian Summer Monsoon Onset, International Journal of Atmospheric Sciences, Volume 2014, Article ID 201695, 11 pages; http://dx.doi.org/10.1155/2014/201695, 2014.

Prokop. P. and Walanus, A.: Variation in the orographic extreme rain events over the Meghalaya Hills in northeast India in the two halves of the twentieth century, Theor Appl Climatol, 121:389–399 DOI 10.1007/s00704-014-1224-x, 2015.

Puranik, S. S., Sinha Ray, K.C., Sen P.N., and Pradeep Kumar P.: An index for predicting the onset of monsoon over Kerala, Current Science, 105: 954-961, 2013.
Rajeevan, M. and Bhaṭe, J.: A High Resolution Daily Gridded Rainfall Data Set (1971-2005) for Mesoscale Meteorological Studies, National Climate Center India, Research Report No: 9/2008.

Ramesh, K.V. and Goswami, P.: Assessing reliability of regional climate projections in CMIP5 Models: the case of Indian monsoon, Nature, Scientific Reports Volume: 4, Article number: 4071 DOI:doi:10.1038/srep04071, 2014.

Rupakumar K, Krishna Kumar S.A., Patwardhan S.K., Mishra P.K., Revadekar J.V., Kamala K., and Pant G.B.: High-resolution climate change scenarios for India for the 21st century, Current Science, 90: 334-345, 2006.

Rameshkumar, M.R., Krishnan, R., Sankar, S., Unnikrishnan, A.S., and Pai, D.S.: Increasing Trend of Break-Monsoon Conditions Over India - Role of Ocean-Atmosphere Processes in the Indian Ocean, 2013: Geoscience and Remote Sensing Letters, IEEE, 6(2): 332-336, 2009.

Sabade, S.S., Kulkarni, A., and Kripalani, R.H.: Projected changes in South Asian summer monsoon by multi-model global warming experiments, Theor. Appl. Climatol., 103(3-4): 543-565, 2011.

Schoof, J.T., Shin, D.W., Cocke, S., LaRow T.E., Lim, Y.-K., and O'Brien J.J.: Dynamically and statistically downscaled seasonal temperature and precipitation hindcast ensembles for the southeastern USA, International Journal of Climatology, 29(2): 243-257, 2009.

Semenov, V.S. and Bengtsson, L.B.: Secular trends in daily precipitation characteristics: greenhouse gas simulation with a coupled AOGCM, Climate Dynamics, 19(2): 123-140, 2002.
Sperna Weiland, F. C., van Beek, L. P. H., Kwadijk, J. C. J., and Bierkens, M. F. P.: Global patterns of change in discharge regimes for 2100, Hydrol. Earth Syst. Sci., 16, 1047-1062, doi:10.5194/hess-16-1047-2012, 2012.

Taylor, K.E., Stouffer, R.J., and Meehl, G.A.: An overview of CMIP5 and the experiment design, Bull. Amer. Meteor. Soc., 93, 485-498, doi:10.1175/BAMS-D-11-00094.1, 2012.

Trenberth, K.: Changes in precipitation with climate change, Clim. Res., 47(1-2): 123-138, 2011.

Teutschbein, C. and Seibert, J.: Is bias correction of Regional Climate Model (RCM) simulations possible for non-stationary conditions?, Hydrol. Earth Syst. Sci. Discuss., 9, 12765-12795, doi:10.5194/hessd-9-12765-2012, 2012a.

Teutschbein, C. and Seibert, J.: Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods, Journal of Hydrology 456–457, 12–29, doi.org/10.1016/j.jhydrol.2012.05.052, 2012b.

Turner, A.G. and Annamalai H.: Climate Change and the South Asian Monsoon, Nature Climate Change 2: 587-595, doi:10.1038/nclimate1495, 2012.

Ueda, H., Iwai, A., Kuwako, K., and Hori, M.E.: Impact of anthropogenic forcing on the Asian summer monsoon as simulated by eight GCMs, Geophys. Res. Lett., 33(6): L06703, 2006.

Van Pelt, S. C., Beersma, J. J., Buishand, T. A., van den Hurk, B. J. J. M., and Kabat, P.: Future changes in extreme precipitation in the Rhine basin based on global and regional climate model simulations, Hydrol. Earth Syst. Sci., 16, 4517-4530, doi:10.5194/hess-16-4517-2012, 2012.
Vuuren D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., and Rose, S.K.: The representative concentration pathways: an overview; Climatic Change, 109:5–31, DOI 10.1007/s10584-011-0148-z, 2011.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., and Kitoh, A.: APHRODITE: Constructing a Long-term Daily Gridded Precipitation Dataset for Asia based on a Dense Network of Rain Gauges, Bulletin of American Meteorological Society, doi:10.1175/BAMS-D-11-00122.1, 2012.
Table 1. List of GCMs used in this study

| Institute | GCM | Spatial resolution | Emission scenario |
|-----------|-----|--------------------|-------------------|
| Hadley Center (UK) | HadGEM2-ES | 1.87° × 1.25° | RCP6.0 |
| Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies | MIROC-ESM | 2.81° × 2.79° | RCP6.0 |
| National Oceanic and Atmospheric Administration (United States) | GFDL-CM3 | 2.5° × 2.0° | RCP6.0 |

Table 2. Latitude and longitude of the CWC rain gauge stations and nearest climatological dataset (APHRODITE) center grid cell point.

| Name | Geographic location | Rain gauge station | APHRODITE |
|------|---------------------|--------------------|-----------|
|      |                     | Latitude (°N)     | Longitude (°E)     | Latitude (°N) | Longitude (°E) |
| Tilga Mountainous | 22° 37' | 84° 24' | 22° 22' | 84° 22' |
| Anandpur Delta | 21° 12' | 86° 7' | 21° 7' | 86° 22' |
| Akhuapada Delta | 20° 54' | 86° 16' | 20° 52' | 86° 22' |
### Table 3. Indian Meteorological Department classification of rainfall intensity

| Event                | Abbreviation | Rainfall                           |
|----------------------|--------------|------------------------------------|
| Wet Day              | WD           | Daily rainfall ≥2.5 mm             |
| Light rain           | LRD          | Daily rainfall between 2.5 mm and 7.5 mm |
| Moderate rain        | MRD          | Daily rainfall between 7.6 mm and 35.5 mm |
| Rather heavy rain    | HRD          | Daily rainfall between 35.6 mm and 64.4 mm |
| Heavy rain           |              | Daily rainfall between 64.5 mm and 124.4 mm |
| Very heavy rain      |              | Daily rainfall between 124.5 mm and 244.4 mm |
| Extremely heavy rain |              | Daily rainfall > 244.5 mm          |

### Table 4. Classification of seasons

| Season            | Months                                | Abbreviation |
|-------------------|---------------------------------------|--------------|
| Winter            | December, January, February           | DJF          |
| Pre-monsoon       | March, April, May                     | MAM          |
| SW monsoon        | June, July, August, September         | JJAS         |
| Post monsoon      | October, November                     | ON           |

### Table 5. SRTM30 elevation of center grid points (in m+MSL)

| Region       | Data source | HadGEM2-ES | MIROC-ESM | GFDL-CM3 |
|--------------|-------------|------------|-----------|----------|
| Delta        | GCM         | 257        | 0         | 29       |
|              | Observation | 27         | 2         | 13       |
| Mountainous  | GCM         | 375        | 665       | 888      |
|              | Observation | 353        | 503       | 506      |
Table 6. Original average correction factors for the month June. Light grey values are $\geq 1.5\times$ the July correction factor, and dark grey values are $\geq 3\times$ the July correction factor.

| Region     | Method | Reference | HadGEM2-ES | MIROC-ESM | GFDL-CM3 |
|------------|--------|-----------|------------|------------|----------|
| Delta      | LS     |           | 8.28       | 7.34       | 0.75     |
|            | DC     | 2040      | 1.87       | 8.54       | 0.99     |
|            |        | 2080      | 1.09       | 4.57       | 0.97     |
| Mountainous| LS     |           | 11.1       | 3.85       | 1.30     |
|            | DC     | 2040      | 1.95       | 2.69       | 0.98     |
|            |        | 2080      | 2.33       | 1.69       | 1.17     |
Figure 1. Map showing location of the Brahmani-Baitarani river basin as study area and the boundaries of the three surrounding Indian states.
Figure 2. Locations of the GCMs center points (in black): HadGEM2-ES (square), MIROC-ESM (triangle), and GFDL-CM3 (round). The nearest climatological dataset center points have the same marker (in grey). CWC rain gauges are shown with station name (black star).

Figure 3. Monthly mean precipitation for the period 1990-2007 as observed in the climatological dataset (grey) and by CWC (black).
Figure 4. CDF curves of daily rainfall for the period 1990-2007 as observed in the climatological dataset (grey) and by CWC (black) for the entire year (top) and monsoon season (bottom).

Figure 5. Monthly mean rainfall for the period 1961–1990 as observed (black) and simulated by the three GCMs (grey).
Figure 6. Mean seasonal rainfall. Observations (black), 2040 short term climate projection (dark grey: LS, dashed dark grey: DC), and 2080 long term climate projection (light grey: LS, dashed light grey: DC).

Figure 7. Difference in number of Wet Days: 2040 short term climate projection (dark grey: LS, dashed dark grey: DC), and 2080 long term climate projection (light grey: LS, dashed light grey: DC).
Figure 8. Difference in number of LRD: 2040 short term climate projection (dark grey: LS, dashed dark grey: DC), and 2080 long term climate projection (light grey: LS, dashed light grey: DC).

Figure 9. Difference in number of MRD: 2040 short term climate projection (dark grey: LS, dashed dark grey: DC), and 2080 long term climate projection (light grey: LS, dashed light grey: DC).
Figure 10. Difference in number of HRD: 2040 short term climate projection (dark grey: LS, dashed dark grey: DC), and 2080 long term climate projection (light grey: LS, dashed light grey: DC).

Figure 11. Return periods based on annual maximum. Observations (black), 2040 short term climate projection (dashed: LS, dashed with circle: DC), and 2080 long term climate projection (dotted: LS, dotted with circle: DC).
Review of design standards for flood protection in the Brahmani-Baitarani river basin in India

M. Marchand¹, S. Sethurathinam², V. Kumar³, C.P. Singh⁴, J. Buurman⁴, C. Sprengers¹, R. Dahm¹, J. Singh⁵

[1] Deltares, Boussinesqweg 1, P.O. Box 177, 2600 MH Delft, the Netherlands
[2] RMSI, A-8 Sector 16, Noida 201 30, India
[3] Central Water Commission, R.K. Puram, New Delhi 110 066, India
[4] National University of Singapore, Institute of Water Policy, Lee Kuan Yew School of Public Policy, 469C Bukit Timah Road, 259772, Singapore
[5] National Water Mission, New Delhi, India.

Correspondence to: M. Marchand (marcel.marchand@deltares.nl)

ABSTRACT
In India, return periods of 25 and 100 years are currently being used for designing flood protection works such as embankments for protecting rural lands and urban/industrial areas, respectively. Since these standards were set in 1980 much has changed: India’s population has almost doubled and per capita income increased with a factor of 5. This is sufficient reason to review flood design standards as they may not provide optimum safety. We used a risk approach and calculated current flood risks for a predominantly agricultural case study area as part of the Brahmani-Baitarani river-basin in Odisha. A combined hydrological-hydraulic model was developed together with a damage model to analyse the annual average damage. Results showed that more than 90% of the total flood risk would be controlled with embankments giving a protection level of once in 25 years. Upgrading the embankment system to that level would give an indicative benefit cost ratio of 5.8.

Keywords: Flood protection, design standards, flood risk assessment, Brahmani River, India
Introduction

Floods are a common natural hazard in most parts of India and are mainly caused by the country’s extreme spatial and temporal variation in the rainfall pattern. The three to four months monsoon period receives 75% of the total annual rainfall, resulting in a very heavy discharge from rivers during this period. An estimated 5 million hectares of land were affected annually over the years 2000-2009\(^1\). The annually affected cropped area ranges from 3.5 to 10 million ha. The five most flood prone states are Uttar Pradesh, Bihar, West Bengal, Assam and Odisha\(^2\).

The most common flood protection method in India is building embankments\(^3\). An estimated total of 15 million hectare of area prone to flood has been protected by construction of embankments\(^3\). Notwithstanding problems such as the risk of breaches and overtopping as well as waterlogging of the areas they are supposed to protect, embankments remain one of the key flood protection measures. One of the main reasons is that these measures are relatively easy to construct, often using locally obtained material and cheap, unskilled labour. The costs are therefore relatively low. Design procedures with respect to the degree of protection, spacing of embankments relative to the river, slopes, material to be used etc., are laid down in guidelines prepared by the Central Water Commission, Ganges Flood Control Commission and others.

Embankments have been designed to withstand a design load, which is equal to a certain threshold flood intensity and is almost always expressed in terms of a return period, e.g. a ‘once in a hundred years flood’. A common way of determining the design is then to estimate the load, such as water level or water height corresponding to a certain desired return period, making a design that can withstand this load and adding a safety factor (‘freeboard’) to account for uncertainties in the calculations\(^4\) or to account for wave setup and soil subsidence. Thus, a crucial component in this approach is the determination of the return period or, in other words, safety level.

Designing flood safety levels

In methods for flood protection a distinction needs to be made between setting safety standards versus calculating the water level belonging to that safety level and designing flood protection infrastructure. Setting safety standards is influenced by cultural processes: social debate and values, politics, and major floods – often a catalyst for policy change – create
different conditions under which safety standards are determined (Samuels 2006). Many
countries seem to have set the safety standard at once in hundred years$^{6,7,8}$, though in rural or
high-value urban areas standards may be lower or higher, respectively. The Netherlands is the
only country where the safety standards are legally determined, and are set at a much higher
level than in most other countries$^6$: they range mostly between once in 1,250 years for the
Rhine and Meuse Rivers to once in 10,000 years for densely populated areas including major
cities like Amsterdam and Rotterdam. In the Netherlands, safety standards are (partly) based
on a cost benefit analysis to determine economically efficient flood protection levels$^9$. Other
ways to determine safety levels include simply build above expected flood water levels,
which used to be the case in for instance Bangladesh$^4$ or deciding on a safety level that is
socially acceptable.

From an economic perspective the safety standard for flood protection is when the marginal
costs (costs of additional infrastructure or measures) equals marginal benefits (reduction in
flood damage). Although conceptually simple, this point is difficult to determine, especially
if changes over time, such as economic growth, are to be included$^9$. Furthermore, while
determining the costs of flood protection is usually straightforward, the benefits are much
harder to estimate and require extensive modelling$^{10}$. If all models and information are
available, an economically efficient safety standard for each area (dike ring) can be
determined. In addition to costs and benefits, also other criteria, such as potential loss of life,
can be included, though this is often difficult to quantify.

Many methods exist to calculate the water level belonging to a safety level and significant
research has been carried out in this area. A flood frequency analysis uses historical water
level records and statistical techniques to predict probabilities of occurrence. Regional and
non-stationary flood frequency analysis can be used for rivers with insufficient historical
records$^{11}$, and uses data from rivers with similar characteristics. Probabilistic approaches use
hydraulic models and historical data to simulate flood events$^{12}$ and can also take into account
joint occurrences of events, such as a heavy rainfall event coinciding with high sea levels,
that lead to flooding$^{13}$.

Flood protection guidelines in India

Standards for flood protection works (such as embankments) have been formalised in the
Guidelines for Planning and Design of River Embankments (levees), issued by the Bureau of
Indian Standards$^{14}$. In these Guidelines it is stipulated that ‘The essential requirements for the
design of the embankment are the determination of the design high flood level (HFL), hydraulic gradient, free board, side slopes, top width etc.’. The Guidelines propose two optional methods for determining the HFL for embankment design:

1. Calculating the benefit cost (BC) ratio for different flood frequencies and selecting the HFL as design water level for embankments corresponding with a flood frequency which gives the maximum BC ratio. This requires a risk approach, i.e. calculating potential damages with different probabilities;

2. Calculating the HFL for 1:25 and 1:100 years for agricultural and urban/industrial areas using a flood frequency analysis.

The Guidelines do not provide a justification of the design standards of a flood of 25 and 100 years frequency for the different areas mentioned in method 2. Since these standards were set in 1980 much has changed: India’s population has almost doubled and per capita income increased with a factor of five. Even if there would be no change in the hazard (i.e. the frequency of floods), the increase in exposed assets (value) would increase the potential damage. Higher safety levels could be rational from an economic point of view (using a cost-benefit approach).

At least three problems derive from using method 2 of the guidelines:

a. Method 2 uses historic time series and therefore is insensitive to future developments (for instance socio-economic growth, climate change or land subsidence during the life cycle of the embankment) and can give a distorted picture of the present hydrological (catchment) behaviour, due to changes in the past, such as land use change or reservoir construction.

b. When only relatively short time series are available, joint probabilities of extreme events in the forcing factors like rainfall upstream, sudden reservoir releases or high sea levels downstream are not accurately captured because these events are less likely to have been measured;

c. The method cannot derive the optimum economic protection level (maximum BC ratio).

Meanwhile, the current National Water Mission (NWM) in India in its report Vol. 2 Section ‘Surface Water Management’ considered the issue of increasing flood frequency due to climate change and economic growth and recommended the return period to be used on
historic datasets as 75 and 150 years for rural and urban areas, respectively (see Table 1). By using 150 years return period for urban areas, based on historical data, instead of the current standard of 100 years, it is assumed that this may be ‘somewhat similar to the 100 year floods with the likely increased frequency of flooding’ due to climate change. The desired return period for the rural areas is proposed to be increased from the current preference of 25 years to 50 years to reflect the better economic conditions of the rural area. In addition, to account for climate change, it is assumed that a 75 year return period flood, based on the historical data, may be somewhat similar to the 50 year floods with the likely increased frequency of flooding.

These considerations renew the question if it would be opportune to calculate safety levels based on its BC ratio as recommended by the Guidelines instead of determining embankment elevation through frequency analysis for the predetermined return periods of 1:25 and 1:100 years for agricultural and urban areas, respectively. It would entail a risk based approach requiring sufficient data. This provided the objective of this paper: to show the feasibility of the flood risk approach for designing embankments in a representative river basin in India from an economic perspective. The most common approach to calculate the expected damage for a given flood event, involves combining data on the characteristics of the event (hazard) with information on the assets that would be affected by it (exposure) and information about the susceptibility of those exposed assets to the particular hazard (vulnerability). The study focused on the Brahmani-Baitarani river basin in the eastern part of India (Figure 1). The basin was selected due to the frequent occurrence of floods in the delta and significance for state water resources controlled by the Rengali reservoir. It is an inter-state river basin and spreads across the states of Chhattisgarh, Jharkhand and Odisha. The elevation ranges from >750 meter in the north-western part of the basin to approximately 10 meter in the delta region. The Baitarani River enters the Brahmani River in the deltaic region before it drains into the Bay of Bengal. The catchment area is 51,822 km². The region is characterized by a sub-tropical monsoon climate zone with mean annual precipitation of approximately 1450 mm, most of which occurs during the southwest monsoon season (June to September). Downstream, large parts of the rivers are embanked, the crest levels of which are derived from the HLF observed in history at the gauge stations. Hence this is one of those special cases mentioned in the BIS Guideline, where ‘the maximum observed flood may also be considered’. 

1. historic datasets as 75 and 150 years for rural and urban areas, respectively (see Table 1). By using 150 years return period for urban areas, based on historical data, instead of the current standard of 100 years, it is assumed that this may be ‘somewhat similar to the 100 year floods with the likely increased frequency of flooding’ due to climate change. The desired return period for the rural areas is proposed to be increased from the current preference of 25 years to 50 years to reflect the better economic conditions of the rural area. In addition, to account for climate change, it is assumed that a 75 year return period flood, based on the historical data, may be somewhat similar to the 50 year floods with the likely increased frequency of flooding.

These considerations renew the question if it would be opportune to calculate safety levels based on its BC ratio as recommended by the Guidelines instead of determining embankment elevation through frequency analysis for the predetermined return periods of 1:25 and 1:100 years for agricultural and urban areas, respectively. It would entail a risk based approach requiring sufficient data. This provided the objective of this paper: to show the feasibility of the flood risk approach for designing embankments in a representative river basin in India from an economic perspective. The most common approach to calculate the expected damage for a given flood event, involves combining data on the characteristics of the event (hazard) with information on the assets that would be affected by it (exposure) and information about the susceptibility of those exposed assets to the particular hazard (vulnerability). The study focused on the Brahmani-Baitarani river basin in the eastern part of India (Figure 1). The basin was selected due to the frequent occurrence of floods in the delta and significance for state water resources controlled by the Rengali reservoir. It is an inter-state river basin and spreads across the states of Chhattisgarh, Jharkhand and Odisha. The elevation ranges from >750 meter in the north-western part of the basin to approximately 10 meter in the delta region. The Baitarani River enters the Brahmani River in the deltaic region before it drains into the Bay of Bengal. The catchment area is 51,822 km². The region is characterized by a sub-tropical monsoon climate zone with mean annual precipitation of approximately 1450 mm, most of which occurs during the southwest monsoon season (June to September). Downstream, large parts of the rivers are embanked, the crest levels of which are derived from the HLF observed in history at the gauge stations. Hence this is one of those special cases mentioned in the BIS Guideline, where ‘the maximum observed flood may also be considered’.

1. historic datasets as 75 and 150 years for rural and urban areas, respectively (see Table 1). By using 150 years return period for urban areas, based on historical data, instead of the current standard of 100 years, it is assumed that this may be ‘somewhat similar to the 100 year floods with the likely increased frequency of flooding’ due to climate change. The desired return period for the rural areas is proposed to be increased from the current preference of 25 years to 50 years to reflect the better economic conditions of the rural area. In addition, to account for climate change, it is assumed that a 75 year return period flood, based on the historical data, may be somewhat similar to the 50 year floods with the likely increased frequency of flooding.

These considerations renew the question if it would be opportune to calculate safety levels based on its BC ratio as recommended by the Guidelines instead of determining embankment elevation through frequency analysis for the predetermined return periods of 1:25 and 1:100 years for agricultural and urban areas, respectively. It would entail a risk based approach requiring sufficient data. This provided the objective of this paper: to show the feasibility of the flood risk approach for designing embankments in a representative river basin in India from an economic perspective. The most common approach to calculate the expected damage for a given flood event, involves combining data on the characteristics of the event (hazard) with information on the assets that would be affected by it (exposure) and information about the susceptibility of those exposed assets to the particular hazard (vulnerability). The study focused on the Brahmani-Baitarani river basin in the eastern part of India (Figure 1). The basin was selected due to the frequent occurrence of floods in the delta and significance for state water resources controlled by the Rengali reservoir. It is an inter-state river basin and spreads across the states of Chhattisgarh, Jharkhand and Odisha. The elevation ranges from >750 meter in the north-western part of the basin to approximately 10 meter in the delta region. The Baitarani River enters the Brahmani River in the deltaic region before it drains into the Bay of Bengal. The catchment area is 51,822 km². The region is characterized by a sub-tropical monsoon climate zone with mean annual precipitation of approximately 1450 mm, most of which occurs during the southwest monsoon season (June to September). Downstream, large parts of the rivers are embanked, the crest levels of which are derived from the HLF observed in history at the gauge stations. Hence this is one of those special cases mentioned in the BIS Guideline, where ‘the maximum observed flood may also be considered’.
Methods and models

Flood frequency analysis

A flood frequency analysis uses past records of events to predict the probabilities of occurrence. Statistical methods are needed to estimate the magnitude of an event that corresponds with a specific return period which goes beyond the length of a record at hand. There are different methods mentioned in the literature: such as Gumbel’s Extreme Value distribution (Type I Extreme value) and the Log Pearson Type III distributions. For the analysis of flood risks the modelling framework as presented in Figure 2 was developed. It contains calculations for the three risk components: Hazard, Exposure and Vulnerability.

Hazards: Hydrological-Hydrodynamic modelling

To simulate the hydrological and hydrodynamic river processes the SOBEK modelling suite has been used. The applied hydrodynamic model for Brahmani-Baitarani river basin consists of the SOBEK channel (HD) and overland flow (2D) components combined with a semi-distributed hydrological model using the Nedbør Affstrømnings Model concept and a real-time control module to address structure operations, such as reservoir releases. The HD model included the rivers and larger channel system of the Brahmani-Baitarani river basin downstream of the Rengali Dam. In addition to existing cross section data, a survey was executed to measure 60 cross sections of the rivers’ branches. For the overland flow module the SRTM 30 m DEM has been processed, using toposheet elevation data from the Survey of India and terrain levels from the surveyed cross sections. Bias correction was executed with these data by determining the relationship between elevation errors and their spatial distribution in the study area. The vertically adapted DEM was smoothened by applying low pass filtering.

To calibrate and verify the hydrological and HD-2D flow model, two monsoon periods (2011 and 2008 respectively) were selected, simulated and compared to CWC gauge data. Forcing time series regarding precipitation, evaporation, reservoir spilling and downstream tidal levels were evaluated and applied for the selected flood events. The goodness-of-fit criterion for calibration and validation of the model was based on the Nash-Sutcliffe Efficiency (NSE) and the flood extent (km²). NSE values for calibration and validation simulations were 0.58 and 0.70, respectively. The model simulated the June 2008 observed flood extent.
of 2419 km² with a difference of -1.5%. Therefore, it was concluded that the model has been validated successfully for practical applications related to the development of understanding of the system behaviour.

**Exposure**

The potential flood damages occurring at different return periods were analysed using the maximum flood extent and flood depths for various boundary conditions from the HD-2D model. Exposure to floods was determined by overlaying the flood maps and land use maps. The availability of the exposure data limited the number of damage categories: 3 types of houses and 3 types of crops (rice, maize and pulses). Damages other than to housing and agriculture were not included in the analysis. Housing data was retrieved from the Census 2011 Taluka (sub-district) level and were grouped into three classes: huts, kacha and pucca houses. The available district level crop data has been distributed at Taluka level using Land Use Land Cover map of LISS III satellite data. This provided information on the current flood risk, which was used to evaluate the present safety standards for rural and urban areas.

**Vulnerability**

Vulnerability was expressed as damage functions linking damage percentages of total value of exposed assets to flood depth. Damage functions for the residential buildings and selected crops were derived from RMSI archive database. This database was developed as part of its internal research and product development (RMSI unpublished data). The process followed for this included extensive field observations to understand the building types and characteristics across India including Bihar and Odisha and carrying out analytical and statistical analysis. This was complemented with expert engineering or heuristic judgment based on local and/or international experiences.

**Probability 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 the record of observation is too short to have witnessed all potential flood events and 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. The principal approach is to define the range of potential (extreme)
events that may cause floods and then to subsequently i) simulate these events with a
hydrodynamic model to obtain the inundation depths in the project area and ii) derive the
probability of occurrence of each event\textsuperscript{12}.

An extensive probabilistic analysis of the Brahmani-Baitarani river basin would involve
assessment of the probabilities that extreme events occur due to either an extreme forcing or
due to the concurrence of events:

- Sea levels, i.e. extreme levels due to cyclone driven storm surge,
- Rainfall, either an extreme downpour in the Monsoon season or cyclone driven, and
- Operational control, i.e. outflow of Rengali Reservoir, discharge of Anandapur barrage
  and the inflow from the Mahanadi river in the Brahmani River.

When five return periods for each forcing would represent the statistical characteristics of
that component, then an extensive probabilistic approach for the Brahmani-Baitarani river
basin would entail 3125 ($5^5$) simulations. This number of simulations would need to be run
for each strategy (e.g. flood protection measure) and each scenario (e.g. climate change). This
was considered unfeasible.

In order to simplify the necessary assessments, an approximate pragmatic approach is
applied which states that the T-year flood level is the maximum of two hydraulic conditions:
a T-year sea level in conjunction with relatively moderate X-year rainfall event and a T-year
rainfall event in conjunction with a moderate X-year sea level. The combination of a less
frequent event of a specific forcing with the moderate occurrence of other conditions
originates from the idea when using the same return period for all will lead to an
underestimation (hence, a much less frequent event) of the actual return period The return
period X of the conjugate event is either 2 or 10 years, depending on the return period of the
main event T:

\begin{equation}
X=10 \text{ years for } T=50, 100 \text{ or } 200 \text{ years}
\end{equation}

\begin{equation}
X=2 \text{ years for } T=2, 5 \text{ or } 10 \text{ years}
\end{equation}

For example, to calculate the flood level of a river segment (design return period 50 years),
the design water level is calculated as the maximum of two situations: (1) a T=50-year
rainstorm event in conjunction with a 10-year sea level and (2) a T=50-years sea level in
conjunction with a 10-year rainfall event. Instead of all possible combinations of sea level
and rainfall intensity, only two situations need to be considered. This saves significant computing and analysis time and makes the results easier to understand and explain.

Economic evaluation model

For estimating optimal safety levels the floodplain just downstream of the bifurcation at Jenapur was selected. At that location the Brahmani River splits into the Brahmani River and Kharsuan River, and confluences again 45 kilometres downstream. Therefore, the area is suitable for the construction of a dike-ring (Figure 3). The area currently inundates even during 1:2 year flood events, because the present embankments have gaps. Analysis revealed (Table 2) that approximately 42.5 km is currently without embankment. Using a risk approach economic optimal safety levels can be derived. Consequently, the damages occurring during different flood events for each Taluka due to these embankment gaps were computed using the flood model. The Average Annual Damage (AAD) is found by integrating the damages with each probability (see Figure 4) using the formula:

\[
AAD = \int_0^1 D_F dp \approx \sum_{i=1}^N (D_{i+1} + D_i) \times (p_{i+1} - p_i) / 2
\]

where \(D_F\) = flood damage, \(D_i\) = damage of a flood event I, and \(P_i\) = probability of a flood event i. Based on these damage calculations the AAD for different safety levels are calculated, as well as the benefits. These benefits occur every year in perpetuity. The present value (PV) of an annual benefit (perpetuity) can be calculated using the formula:

\[
PV = AAD \times (1 / ((1 + r)^n))
\]

with r being the discount rate for government infrastructure investments. The AAD is an annuity; formula (3) can be simplified to:

\[
PV = AAD / r
\]

Results

Flood frequency analysis for design standards in Brahmani River

Flood frequency analysis was calculated for Jenapur, a CWC Gauge-discharge Station close to the bifurcation point of the area of interest for economic evaluation (Figure 3). The total length of water level time series analysed was 34 years, from 1979 to 2013. Gumbel’s Extreme Value Type I, Pearson Type III, and Log Pearson Type III distribution have been
tested to adopt for flood level return period estimation. The latter two did not reject the hypothesis of no significant difference between observed and theoretical distribution at 5% significance level. This was tested with the Binomial, the Kolmogorov-Smirnov, and the Chi-Square goodness of fit tests. Visual inspection proved the Pearson Type III to fit best. The analysis provided results as given in Figure 5.

The HFL adopted at Jenapur is 23.76 m based on the flood level observation on September 26, 2011. Depending on the method used, this corresponds to a return period of only 18.5 year per Gumbel analysis and to about 25 years in Pearson Type III.

Analysis was also done using observed maximum annual discharges. The Return Period Discharges were estimated by frequency analysis for the same return periods as for the water levels. Because the trend line of the gauge-discharge relation and its equation was available (Approximate Gauge-discharge Rating Curve) we could use this relation to convert the discharges into gauge levels. To these return period gauges, the zero of the gauge was added to get the respective return period HFL. Contrary to the analysis using water levels, the HFLs computed were unrealistic by showing under-estimated results, compared to ground conditions. There could be errors in the approximate rating curve or in the zero elevation of the gauge.

Probabilistic flood modelling

For reasons of limited data availability and preventing the need to carry out thousands simulations with a HD-2D hydrodynamic model only rainfall and sea level were considered as main probabilistic drivers in the Brahmani-Baitarani river basin. This was of course a major simplification of the actual system; however the amount of rainfall strongly relates to other drivers in this river basin; the outflow of the Rengali reservoir, the discharge from Anandapur barrage and the inflow from the Mahanadi river basin. Furthermore, rank correlation analysis revealed strong correlation (0.81) between inflow to Rengali reservoir and Anandapur barrage. Therefore this study assumed joint occurrence resulting in grouping rainfall, Rengali reservoir outflow, Anandapur barrage discharge, and inflow into Mahanadi.

The main focus of this case study was on the flood extends, benefits and damages with return periods corresponding to the flood protection levels (25, 50, 75, 150-year return period) mentioned by the NWM and the 2-year return period. The maximum hydraulic conditions
corresponding with each of these five return periods were derived by only 10 (5 x 2) simulations. Consequently, this number of simulations was also carried out to assess the impact of constructing a dike-ring as flood protection strategy.

Probabilistic modelling derived HFL for a 25 and 100 year return period at Jenapur is 24.47m and 25.03m, respectively. These HFLs are on the upper part of the confidence interval of the Pearson Type 3 frequency analysis, as shown in Figure 5. By applying the probabilistic HD-2D model flood extends were derived for both return periods. These flood extends were used to analyse flood damage and corresponding AAD.

**Economic evaluation**

By using the maximum water levels from the flood model for different flood events (1:2, 1:25, 1:75 and 1:150 years) for each Taluka the damages were calculated (Table 3) for the existing flood protection situation. These results were used to calculate the Average Annual Damage (AAD), using formula (2), giving 1,533 million Rs for a 1:150 year flood. Likewise the AAD was calculated for the other return periods (Table 4). With these results the benefits of improved flood protection, which is the annual avoided damage (which equals the AAD) for different protection levels of embankments, was estimated. This shows that for instance if we can reach a safety level of 1:25 years, the average annual benefits would be 1,436 million Rs.

It also shows that this safety level would reduce the risk (being the combination of probability and damage) with 93.6%.

The BC ratio was calculated using the discounted annual benefits or present value (PV). The PV in the case of a 1:25 year protection level, assuming 12% discount rate, would be 11,966 million Rs. In order to obtain such safety, new embankments have to be constructed for 42.5 km. The costs of such investment would be 1,125 million Rs. (assuming a 5.3 m high dike and using a unit cost of 26.5 million Rs. per km). This would imply that in one year the investment costs have been recovered by the avoided damage already. Even if annual maintenance costs would be included (at an assumed 10% of the investment costs), the present value of the costs would be 1125+((1125*0.1)/12%)=2,063 million Rs., which is far lower than the present value of the benefits. This would result in a BC ratio of 5.8 (Table 6).

Hence, from a macro-economic viewpoint, and looking at avoided damage and levee costs only, this would be a rational investment. When applying the same method for other safety standards, it is found that the BC ratio reduces, because the costs of higher embankments
increase substantially (6m high embankment is 30% more expensive than a 5m one), whereas
the marginal benefits only increase with about 6%.

4. Discussion

The practical application of a probabilistic flood risk assessment, developed in data rich areas, to study the benefits and costs of flood defence measures might be questioned for the Indian context. It could be argued that the findings are of limited use due to the degree of uncertainty resulting from limited data availability. However, the uncertainty could be reduced by a sensitivity analysis of the BC results. If in majority of the cases the BC-ratio remains at least >1, then the flood defence measures can be considered economically effective. Therefore, the application of a probabilistic approach can still be useful, even in the relatively data-poor Indian context.

The return periods derived via probabilistic analysis with the SOBEK model differ from the extreme value analysis as is shown by Figure 4. This can occur as the selected calibration and validation events might not represent the water systems’ full behaviour during extreme events or observational errors influencing the time series. Therefore the model conceptualisation of the water system might show differences to the statistics of the observed water levels when a range of extreme events is simulated. Although this affects the AAD it allows economic assessment of flood protection strategies under different scenarios, e.g. socio-economic or climate change, and therefore remains very useful.

The CBA pilot is a crude calculation which should be considered useful only at a pre-feasibility decision level. Time and budget constraints as well as limitations in data availability necessitated a number of assumptions, which are discussed below.

- The limited set of assets (houses and crops only) used for the damage calculations are a conservative estimation because other assets (e.g. livestock, public infrastructure) are not included. On the other hand important flood characteristics for actual agricultural damage, such as the flood duration and the timing of the flood during the growing season were taken as worst cases. It is assumed that floods have a duration longer than two weeks after which maximum damages occur.
- Not only the gaps in the current embankments need to be closed. In fact several river branches run through the area which either have to be embanked as well, or closed off from the main river. But up to 200 km extra embankments the BC ratio remains above 1.
The assumption that there will be no future changes in land use is not realistic because improving the protection level would attract more investments (leading to higher agricultural yields for instance), which would increase the benefits of protection.

- The embankment costs should also take into account land acquisition, opportunity costs, sluices for drainage, reduced preparedness of the people for larger floods, the loss in soil fertility and aquifer recharge, etc.

Therefore, a more detailed cost-benefit analysis should take into account the whole range of benefits and dis-benefits of embankment construction and should also compare it with other options for reducing the flood damage in the area. Furthermore, attention should be given to the distribution of costs and benefits among the different stakeholders, which would broaden the current macro-economic scope of the analysis.

The advantage of the used method is that it can easily simulate future conditions, for instance based on downscaled projections of climate change models for the river catchment. This exercise was performed as part of the PATA8089 study, using the delta change method. Rainfall events for the 1:25 year return period have been simulated with the SOBEK model and showed an increase in high flood levels at Jenapur of about 60cm for the year 2040. Embankments would need to be heightened by the same in order to keep the safety level of 1:25yr. If this would be done straight away, it would give the area a protection level corresponding to 1:75 year (still with a high BC ratio), which would then be reduced year by year till it reaches 1:25 year in 2040. This is more or less what the National Water Mission advises through their ‘ad hoc’ adoption of 1:75 year safety level, although it is difficult to compare because the Mission did not indicate the time horizon for their desired 1:50 year protection level ‘after climate change’. In fact, to determine the optimum timings of embankment heightening (periodical investments) would require a more detailed economic analysis (see for an example of the Netherlands: Reference 28 and 9).

Conclusions

This pilot showed two important messages: first, it introduced the dike-ring concept which would improve flood management at the local level. It could be used as a management unit similar to the Dutch ‘polder’, for which all water related issues, including flood, drainage and irrigation are optimised. Second, it showed that from a macro-economic viewpoint the upgrade of current embankment conditions up to 1:25 years safety could be a rational decision.
Currently, many rural areas are still flooded on an annual or bi-annual basis, because embankments are too low, easily breached or non-existing. Raising embankments to a 1:25 year safety, however, is often constrained by a limited annual government budget for flood control. For instance in 2011 the flood control budget for Odisha State was approx. 700 million Rs.\textsuperscript{29}. Hence, the closure of the Jenapur dike-ring would cost more than the whole annual budget for the entire State. Nevertheless, with historical averaged annual damages in the state of around 7840 million Rs.\textsuperscript{30} (i.e. ten times the government budget for flood control) and a relief budget of about 4000 million Rs., a reappraisal of such budget allocations seems justified.

\textbf{Acknowledgements}

The study was funded by DFID/UKAid and ADB under the Asian Development Bank Policy and Advisory Technical Assistance 8089 IND Phase II project. We acknowledge our colleagues of the TA8089 project and we would like to express our sincere thanks to the Central Water Commission and National Water Mission of India.
References

1. CWC, Water and related Statistics. Central Water Commission, New Delhi, 2010.
2. Gupta, S., Javed, A. and Datt, D., Economics of flood protection in India. *Natural Hazards*, 2003, **28**(1), 199-210.
3. Government of India, Disaster management in India. National Report for the World Conference on Disaster Reduction, 2004.
4. Sayers, P. B., Hall, J. W. and Meadowcroft, I. C., Towards risk-based flood hazard management in the UK. Paper presented at the ICE, 2002.
5. Samuels, P., Klijn, F. and Dijkman, J., An analysis of the current practice of policies on river flood risk management in different countries, *Irrigation and Drainage*, 2006, **55**(S1), S141-S150.
6. Wesselink, A. J., Flood safety in the Netherlands: The Dutch response to Hurricane Katrina, *Technology in Society*, 2007, **29**(2), 239-247.
7. Ntelekos, A., Oppenheimer, M., Smith, J. and Miller, A., Urbanization, climate change and flood policy in the United States, *Climatic Change*, 2010, **103**(3-4), 597-616.
8. Zhang, L. M., Xu, Y., Liu, Y. and Peng, M., Assessment of flood risks in Pearl River Delta due to levee breaching, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 2013, **7**(2), 122-133.
9. Kind, J. M., Economically efficient flood protection standards for the Netherlands, *Journal of Flood Risk Management*, 2014, **7**(2), 103-117.
10. Merz, B., Kreibich, H., Schwarze, R. and Thieken, A., Review article "Assessment of economic flood damage", *Nat. Hazards Earth Syst. Sci.*, 2010, **10**(8), 1697-1724.
11. Leclerc, M. and Ouarda, T.B.M.J., Non-stationary regional flood frequency analysis at ungauged sites, *Journal of Hydrology*, 2007, **343**(3-4), 254-265.
12. Dahm R.J., Diermanse F.H.M., Ho L.P., On the flood and inundation management of Ho Chi Minh City, Viet Nam. International Conference on Flood Resilience, Exeter, United Kingdom, 2013.
13. Klerk, W. J., Winsemius, H. C. Verseveld, W. J. v. Bakker, A.M.R. and Diermanse, F. L., M., The co-incidence of storm surges and extreme discharges within the Rhine–Meuse Delta, *Environmental Research Letters*, 2015, **10**(3), 035005.
14. BIS, Guidelines for planning and design of river embankments (levees). First Revision. ICS93.160. Bureau of Statistics. New Delhi, 2000.
15. World Bank, World Development Indicators. World Bank
   (http://data.worldbank.org/indicator/NY.GDP.PCAP.CD accessed 11 October 2015)
16. NWM, National Water Mission under National Action Plan on Climate Change.
   Comprehensive Mission Document. Vol. II. Ministry of Water Resources, Government of
   India, New Delhi, 2012.
17. Ward, P. J., Moel, H. de, and Aerts, J., How are flood risk estimates affected by the
   choice of return-periods? Natural Hazards and Earth System Sciences, 2011, 11, 3181-3195.
18. Government of Odisha, Annual Report on Natural Calamities 2010-2011. Revenue &
   Disaster Management Department, Special Relief Commissioner. Bhubaneswar, India,
   2011.
19. Chow, V.T.; Maidment, D.R.; Mays, L.W., Applied Hydrology. McGraw-Hill Series in
   Water Resources and Environmental Engineering. McGraw-Hill, New York, 1988.
20. Deltares, SOBEK: 1D2D modelling suite for integral water solutions. User Manual.
    Netherlands, 2014.
21. Nielsen, S.A. & Hansen, E., Numerical simulation of the rainfall runoff process on a daily
    basis, Nordic Hydrology, 1973, 4(3), 171–190.
22. NASA, http://www2.jpl.nasa.gov/srtm/images/SRTM_Jan2015.gif, 2015.
23. Sanyal, J. Carbonneau, P, and Densmore, A.L., Hydraulic routing of extreme floods in a
    large ungauged river and the estimation of associated uncertainties: a case study of the
    Damodar River, India. Natural Hazards, 2013, 66 (2). Pp. 1153-1177.
24. Nash, J. E. and Sutcliffe, J. V., River flow forecasting through conceptual models, Part I -
    A discussion of principles, J. Hydrol., 1970, 10, 282–290.
25. Becker J.V.L., Diermanse, F.L.M, Verwey, A., Tse M.L., Kan, F.Y.F., and Yiu C.C.,
    Design of flood protection in Hong Kong. In: Comprehensive Flood Risk Management –
    Klijn & Schweckendiek (eds), 2013.
26. Deltares, Volume 5b. Modelling Report Brahmani-Baitarani. Operational Research to
    Support Mainstreaming of Integrated Flood Management under Climate Change. Deltares
    and Associates, Delft, 2015.
27. Dahm, R.J., Singh, U.K., Lal, M., Marchand, M., Sperna Weiland, F., Singh, S.K. and
    Singh M.P., Downscaling GCM data for climate change impact assessments on rainfall: a
    practical application for the Brahmani-Baitarani basin. Submitted to Journal of
    Hydrology and Earth System Science Discussions (HESSD).
28. Eijgenraam C., Optimal safety standards for dike-ring areas. CPB discussion paper No. 62, 2006.

29. CWC, Financial Aspects of Flood Control, Anti-Sea Erosion and Drainage Projects. Central Water Commission, New Delhi, 2013.

30. OSDMA, Cited in PATA 8086 Phase 1 Report Annex G. The Economics of IFM. Government of India / ADB, 2014.
Table 1. Suggested changes in return period of flood for acceptability of performance of flood protection works (NWM, 2008)

| Land use category | Current Return Period stipulated by BIS 2000 | Desired Return Period considering the changed regime after climate change | Ad-hoc Return Period to be used on historical data |
|-------------------|---------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------|
| Urban areas       | 100 years                                   | 100 years                                                                | 150 years                                        |
| Rural areas       | 25 years                                    | 50 years                                                                 | 75 years                                         |

Table 2. Dike-ring requirement

| Item                                      | Length (km) |
|-------------------------------------------|-------------|
| Present length of embankment at the area of interest (AOI) | 122.3       |
| Total proposed embankment/ dike-ring length | 164.8       |
| Length of new dike-ring construction       | 42.5        |
| Total Embanked AOI                         | 503.3 km²   |

Table 3. Damages of the area of interest (talukas within the dike-ring area) for different return periods

| Taluka                  | Dike Protected Area (% to total taluka area) | Case1 (1:2) | Case2 (1:25) | Case3 (1:75) | Case4 (1:100) | Case5 (1:150) |
|-------------------------|---------------------------------------------|-------------|--------------|--------------|---------------|---------------|
| Bari - Ramachandrapur   | 96.52                                       | 8,877       | 14,461       | 16,076       | 16,438        | 17,004        |
| Kuakhia                 | 85.20                                       | -           | 7,318        | 8,183        | 8,250         | 8,496         |
| Jajpur Sadar            | 36.74                                       | -           | 2,741        | 3,612        | 3,744         | 3,887         |
| Aali                    | 26.73                                       | 3,803       | 5,990        | 8,195        | 8,240         | 8,307         |
| Balichandrapur          | 25.74                                       | 588         | 1,894        | 2,281        | 2,386         | 2,520         |
| Dharmasala              | 20.76                                       | 1,253       | 3,038        | 3,360        | 3,374         | 3,310         |
| Pattamundai             | 12.47                                       | 2,487       | 3,792        | 4,259        | 4,306         | 4,366         |
| Binjharpur              | 12.21                                       | 1,646       | 1,695        | 1,930        | 1,952         | 1,975         |
| Nikirai                 | 2.67                                        | 114         | 179          | 201          | 195           | 199           |
| Jenapur                 | 2.02                                        | -           | 158          | 210          | 223           | 233           |
| Jajapur Road            | 0.11                                        | -           | 4            | 7            | 7             | 7             |
| TOTAL Dike-ring         | 18,767                                      | 41,269      | 48,313       | 49,116       | 50,305        |               |
Table 4. Data for Cost-Benefit Analysis

| Return period          | 1:2       | 1:25      | 1:75      | 1:100     | 1:150     |
|------------------------|-----------|-----------|-----------|-----------|-----------|
| Jenapur HFL m          | 21.4      | 25.1      | 25.7      | 25.8      | 26        |
| assumed base level m    | 21        | 21        | 21        | 21        | 21        |
| freeboard m            | 1.2       | 1.2       | 1.2       | 1.2       | 1.2       |
| dike height m          | 5         | 5.3       | 5.9       | 6         | 6.2       |
| construction cost /km  | Rs million| 24.4      | 26.5      | 30.4      | 31.9      | 33.6      |
| dike length km         |           | 42.47     | 42.47     | 42.47     | 42.47     | 42.47     |
| total construction cost| Rs million| 1,036     | 1,125     | 1,291     | 1,355     | 1,427     |
| annual O&M Rs million  | 104       | 113       | 129       | 135       | 143       |
| PV total cost Rs million| 1,900     | 2,063     | 2,367     | 2,484     | 2,616     |
| avoided damage (AAD) Rs million| 432 | 1,436 | 1,508 | 1,525 | 1,533 |
| PV avoided damage Rs million| 3,597 | 11,966 | 12,570 | 12,706 | 12,776 |
| BC ratio               | 1.9       | 5.8       | 5.3       | 5.1       | 4.9       |
Figures

1. **Figure 1.** Location of the Brahmani-Baitarani river basin
2. **Figure 2.** Flow chart of modeling steps carried out to calculate flood risk
3. **Figure 3.** Proposed dike-ring in the Jenapur bifurcation area
4. **Figure 4.** Damage curve showing the Annual Average Damage (AAD)
5. **Figure 5.** Results from the frequency analysis and probability model
Figure 1. Location of the Brahmani-Baitarani river basin
Figure 2. Flow chart of modeling steps carried out to calculate flood risk
Figure 3. Proposed dike-ring in the Jenapur bifurcation area
Figure 4. Damage curve showing the Annual Average Damage (AAD)
Figure 5. Results from the frequency analysis and probability model