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Project Level

TECHNICAL REPORT

Gorakhpur, India

EXTREME RAINFALL, CLIMATE CHANGE, AND FLOODING

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KEY FINDINGS

Climate change is likely to increase the intensity—how much rain falls per hour—of rain events around Gorakhpur over the next 50 years. At the same time, the city's population will continue to increase and require housing, transportation, and other city services. Unless the city can manage growth in a more sustainable manner, flood depths will increase and waterlogging will last longer due to the projected climate change impacts on rainfall and current urbanization process.

Flooding occurs in some wards, like Mehewa Ward, after relatively small amounts of rain in 24 hours. Climate change may increase the intensity of such small rain events by 10 to 20% by the 2050s.

More severe 24-hour rain events have occurred in the past. Under climate change, the intensity of such events might increase 2 to 25% by the 2050s.

For more information about The Climate Resilience Framework, please visit: **www.i-s-e-t.org/CRF**

Summary

Gorakhpur is a rapidly growing city in eastern Uttar Pradesh, India. Gorakhpur district, which encompasses the city and peri-urban areas, is home to approximately 4.4 million people having experienced an 18% population increase between the 2001 and 2011 Census (Gov. of India, 2013). Historically, the area experienced low levels of flooding each year during the summer monsoon (~June–September), and depended upon such floods to replenish soil fertility. Yet, the depth and duration of floods in certain wards of the city has been increasing, as the city has expanded to encompass sections of both the Rapti and Rohini rivers, and due to other urbanization processes. Some factors that enhance flooding and waterlogging include (Mitra and Singh, 2011; Wajih, Singh, Bartarya, Basu, & ACCCRN ISET Team, 2010):

- Loss of water bodies and permeable areas that once absorbed monsoon rains;
- Construction in the floodplain zones of the Rapti and Rohini rivers;
- Inability of the city to provide services, such as solid waste management and wastewater/storm water networks, that reduce flooding;
- Inappropriately placed embankments that trap flood water for 2-3 months, causing waterlogging; and,
- Informal networks and irregularly maintained canal, check-dam, and barrage systems upstream of, and within the urban area.

These urbanization processes have changed the nature of flooding and waterlogging hazards for the city, and as they accelerate, further alter the hazardscape of the city. Flooding and waterlogging are triggered by rainfall events either in the city or upstream of the city in the Nepal Terai and Middle Hills. Climate change is likely to alter the frequency and intensity of rainfall events that contribute to Gorakhpur's flooding. The shifts in extreme rainfall due to climate change, coupled with the current city development trajectory, will continue to increase the flood and waterlogging risk.

The Gorakhpur Environmental Action Group (GEAG), ISET–International, and Arup have been working together to explore the factors that lead to endemic flooding and waterlogging within Gorakhpur, and identify resilience options that can reduce immediate disaster risk while building climate resilience. With support from the Rockefeller Foundation and Climate Development and Knowledge Network (CDKN), ISET–International conducted extreme rainfall event analysis of historical and projected rainfall (2006-2055) to generate plausible storm intensity profiles that were used by Arup, in combination with some development scenarios, to model how Gorakhpur's flooding and waterlogging might evolve by the 2050s. The rainfall analysis and flood model supports two projects: 1) Investigating how climate-resilient housing has a positive cost ratio and helps vulnerable populations (CDKN), and 2) Investigating the costs and benefits of using multiple interventions and activities to build overall city resilience rather than relying on individual interventions (Rockefeller Foundation). Both research programs are exploring the economic returns to key urban systems that alter development and land-use pathways in a manner that reduces vulnerability and increases resilience.

This report provides information of a more technical nature to individuals such as water managers, urban developers, or utilities managers, who require more detailed information as to how projected changes in an area's extreme rainfall events can be calculated. The information provided uses the case study example of calculations for Gorakhpur, but the methodology presented and all of the datasets, except for the station-level data, are applicable for repeating similar types of analyses throughout Asia. The cautions and assumptions section is pertinent to all extreme event analysis applications. This report does not provide extremely detailed information on the calculations; for this, we encourage readers to access the resources listed in the Further Reading/References section.

Methodology

DATA

No single climate model will ever be able to project the exact changes in rainfall, temperature, or other climate variables in any given year or period in the future for any part of the world. This is because no one knows exactly what emissions, populations, and land-use changes might occur in the future, and due to the limitations and assumptions of the models themselves. Global circulation models (GCMs) project how the climate might change, given changes to these human-controlled factors, which are accounted for as representative concentration pathways (RCPs) in the IPCC 5th Assessment models (van Vuuren et al., 2011). Because no single model can project exact changes to an area's climate, it is necessary to use projections from multiple GCMs, each driven by a couple of RCPs, to capture the possible range and trend of changes. Furthermore, climate is a description of an area's average weather over a period of time, typically 30 years. Therefore, climate change analysis involves comparing the statistics of an area's particular weather as projected for a period in the future that is at least 30 years long, with a period of historical climate of the same length.

With these two caveats, we accessed daily precipitation data (simulated historical and projected future) from the CMIP5 Multi-Model Ensemble Database: http://pcmdi9.llnl.gov/esgf-web-fe/. The ensemble set of projected daily rainfall was formed using projections from 9 GCMs, each running the RCP 4.5, for a total of 9 ensemble members against which to compare future rainfall with past rainfall. Simulated historical rainfall by the GCMs covered the period 1961–2005, whereas future projected rainfall spanned 2006–2055. At the time of data access from the CMIP5 Database (November 2012), only projections from RCP 4.5 were available, precluding the use of other RCPs for comparison.

A 'super' historical daily rainfall dataset for Gorakhpur was compiled and interpolated from a number of data sources due to the incompleteness of available records. Additional historical data covering the period of 1961–2005 were accessed from the APHRODITE project database (Yatagai et al., 2012) to validate and supplement gaps in the sparse station records. The data were cleaned and underwent several quality control checks that are standard for meteorological and climatological data. Table 1 displays the datasets/models used.

TABLE 1

DATASETS AND MODELS USED FOR ESTIMATING FUTURE CHANGES TO GORAKHPUR'S EXTREME RAINFALL EVENTS

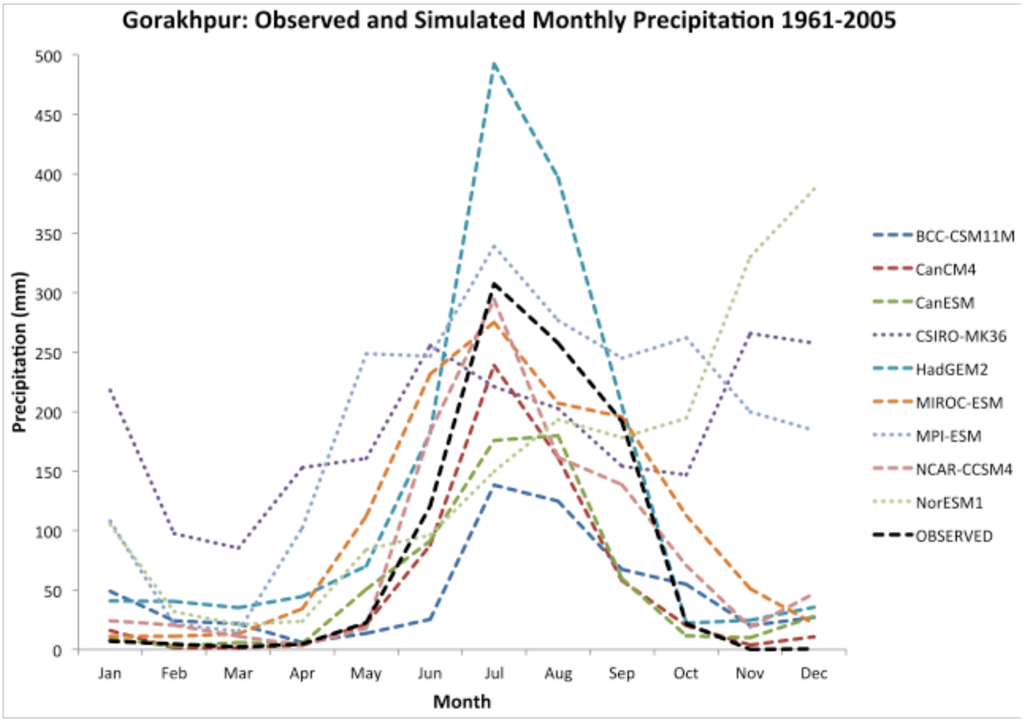
DATASET/MODEL	DATA PROVIDER	DESCRIPTION
APHRODITE	Research Institute For Humanity and Nature (RIHN), Meteorological Research Institute of Japan Meteorological Agency (MIR/JMA)	High-Resolution Daily Precipitation Datasets From Rain-Gauge Observation (Yatagai Et Al., 2012)
Station-Level: • Gorakhpur • Patna	India Meteorological Department (IMD), Global Summary Of The Day & Global Historical Climatology Network – National Climatic Data Centers (NCDC USA)	Daily, 6 Hourly, And Hourly Precipitation from Rain-Gauge Observation
CMIP5:		
BCC-CSM1.1(M)	Beijing Climate Center, China Met Administration	Simulated Daily Precipitation For: • Historical (1960–2005) • Rcp 4.5 (2006–2055) All Downloaded From Cmip5 Multi-Model Ensemble Dataset: Http://Pcmdi9.Llnl.Gov/Esgf-Web-Fe/
CANCM4, CANESM2	Canadian Centre For Climate Modelling & Analysis	
CSIRO-MK3.6.0	Commonwealth Scientific & Industrial Research Organization (CSIRO)/ Queensland Climate Change Centre Of Excellence	
HADGEM2	Met Office Hadley Centre	
MIROC-ESM	Japan Agency For Marine-Earth Science & Technology, Atmosphere & Ocean Research Institute (University Of Tokyo), And National Institute For Environmental Studies	
MPI-ESM-MR	Max Planck Institute For Meteorology (MPI-M)	
NCAR-CCSM4	National Center For Atmospheric Research	
NOR-ESM1-M	Norwegian Climate Centre	

MODEL VALIDATION

While multiple models must be used in estimating potential changes to an area's rainfall, it is necessary to use some validation tests to ensure that the selected models are able to replicate key rainfall statistics for that area if the modeling efforts are focused on the near-term (out to 2050s) changes. The Cautions and Assumptions section details the reasons for selecting a subset of GCMs out of all possible models. We used a moments comparison test, comparing the station-scale observed rainfall data with the grid-scale simulated rainfall of each GCM over the period 1961–2005. Six out of the nine GCMs were able to reasonably replicate the seasonality of Gorakhpur's rainfall, as well as the median and standard deviation (the first and second moments) of monthly rainfall totals as shown in Figure 1. The remaining three models were rejected due to their inability to capture the summer monsoon, which is currently responsible for about 80% of Gorakhpur's annual rainfall, and the period of the year in which the most extreme rainfall events occur.

FIGURE 1

GCM SIMULATED AND STATION OBSERVED HISTORICAL MONTHLY TOTAL RAINFALL. THE DASHED LINES CORRESPOND WITH GCMS THAT REPLICATED OBSERVED STATISTICS WELL; DOTTED LINES CORRESPOND WITH MODELS THAT HAVE BEEN REJECTED. THE BLACK DASHED LINE IS THE OBSERVED STATION-DERIVED MONTHLY TOTAL RAINFALL.



EXTREME RAINFALL EVENT ANALYSIS

Extreme rainfall events are by statistical definition rare. A rainfall event that happens frequently, such as every year is not considered an extreme event. Because extreme rainfall events happen so rarely, they do not follow normal statistics and different calculations must be used to ascertain how frequently they occur (return period), and their corresponding intensity (mm/hr) over particular durations of time (hours). Therefore, when calculating how extreme events might change in the future, it is not possible to simply multiply historical storm rainfall amounts by projected changes in seasonal or monthly rainfall totals.

Extreme rainfall event analysis is often represented through intensity-duration-frequency (IDF) curves for an area when the analysis is needed for flood modeling and other water resource management purposes. They are formed by fitting one of the extreme value distributions to a dataset formed from the maximum annual daily rainfall value, from at least 30 years of daily or sub-daily rainfall data. Generalized IDF curves follow the form:

$$i = a(T) / b(d) \qquad (Eq.\ 1)$$

$$a(T) = \mu + \sigma F^{-1}(1-1/T) \qquad (Eq.\ 2)$$

$$b(d) = d\hat{}\eta \qquad (Eq.\ 3)$$

where i is the rainfall intensity of particular duration d and return period T, a(T) is a function determined through fitting an extreme value probability distribution, and b(d) is a scaling function for rainfall of different durations but the same return period. Mu (μ) and sigma (σ) are parameters of EVI distribution, while nu (η) is a scaling parameter (Menabde, Seed, & Pegram, 1999; Koutsoyiannis, Kozonis & Manetas, 1998; Chow, Maidment & Mays, 1988). For greater detail on understanding and generating IDF curves, the Further Reading section contains the full citations of the references just listed.

Figure 2 displays the IDF curves for Gorakhpur for select durations and return periods. To read the table, look at the duration of the event and then look at the corresponding intensity. The total precipitation of an event lasting a particular amount of time, with a given return period, can be determined from looking at an area's IDF curve/table. For example, the average total amount of rainfall associated with Gorakhpur's 10-Year, 12-Hour event is 145.2mm (12.1 mm/hr x 12 hours). The Further Reading section contains resources describing the formation and uses of IDF curves.

FIGURE 2

IDF CURVES FOR GORAKHPUR FOR VARIOUS RETURN PERIODS AND DURATIONS UP TO 24 HOURS, CORRESPONDING TO THE URBAN FLOOD MODEL NEEDS.

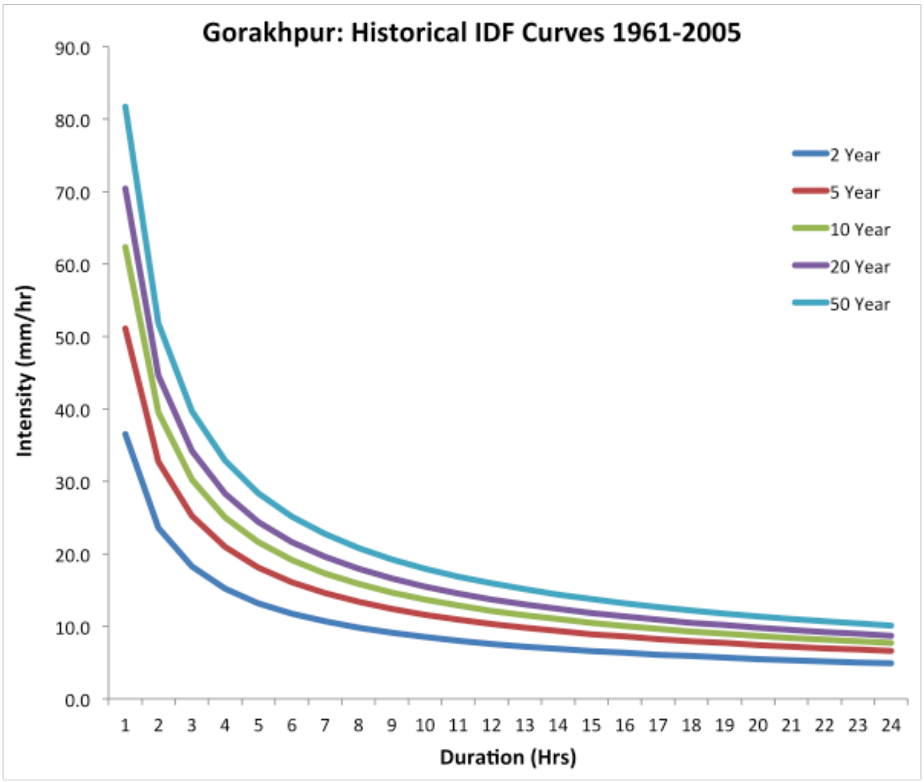


TABLE 2

IDF TABLE FOR GORAKHPUR FOR SELECT DURATIONS AND RETURN PERIODS FROM THE HISTORICAL PERIOD 1961–2005. THE FULL IDF CURVES OUT TO 24-HOUR DURATION EVENTS FOR THESE RETURN PERIODS ARE SHOWN FIGURE 2.

	Return Period (Years)		
Duration (Hrs)	**2 Years**	**10 Years**	**50 Years**
1	36.5 mm/hr	62.3 mm/hr	81.8 mm/hr
6	11.8 mm/hr	19.2 mm/hr	25.1 mm/hr
12	7.6 mm/hr	12.1 mm/hr	15.9 mm/hr
18	5.9 mm/hr	9.3 mm/hr	12.2 mm/hr
24	4.9 mm/hr	7.7 mm/hr	10.1 mm/hr

PROJECTED IDF CURVE ANALYSIS

Estimating how climate change will impact the frequency and intensity of rainfall events for an area requires scaling between a GCM's IDF curves of simulated historical rainfall and the observed, station-scale IDF curves at a location (Mailhot, Duchesne, Caya & Talbot, 2007). GCMs will usually underrepresent an area's rainfall if most of its rainfall is due to thunderstorms, because the average grid cell of a GCM is between ~75–150km and thunderstorms are on a smaller scale of ~1–20km. Much of Gorakhpur's most intense rainfall is associated with thunderstorms along monsoon troughs during the Indian Summer Monsoon. Furthermore, GCMs have a particularly difficult time with extreme rainfall events and tend to underrepresent them. As can be seen in Figure 1, most of the GCMs underrepresent Gorakhpur's total monthly rainfall during the rainy season of June–September, which is expected and quite normal. Thus, it is necessary to scale the simulated historical IDF curves from GCMs against the observed, station-scale curves, and apply these areal reduction factors to the future IDF curves. The areal reduction factors are calculated as:

$$\mathrm{ARF}(T,d) = \frac{x_P^{(g)}(T,d)}{x_P^{(s)}(T,d)} \qquad \text{(Eq. 4)}$$

where $x^{(s)}(T,d)$ and $x^{(g)}(T,d)$ are average rainfall depths of particular events of duration d and return periods T at the station scale (superscript s) and grid box scale (superscript g) in the control climate (subscript p) (Mailhot et al., 2007).

By comparing the 1961–2005 (past) IDF curves of each GCM with the observed, station-scale IDF curves for the same period, we developed separate scaling (areal reduction) factors for each GCM. We then calculated the IDF curves for the projected rainfalls from BCC-CSM1.1M, HadGEM2, and NCAR-CCSM4, each running the RCP 4.5, for the period 2006-2055. These three GCMs were selected based on their reasonable replication of historical extreme rainfall statistics and representation of the broad range of projected change for Gorakhpur across the full set of six GCMs. The sets of projected IDF curves were compared with the historical, station-scale IDF curves to see how things changed between the future and the past.

Possible Changes to Gorakhpur's Extreme Rainfall by 2050s

In the future, according to a range of a combination of different climate model and emission scenarios, the intensity and frequency characteristics of rainfall events for Gorakhpur are likely to change. For 24-hour and longer duration events of all return periods, all of the models project a potential increase in precipitation intensity. That all models are in agreement about the direction of the change in trend (increasing) provides some measure of confidence in the projections. Figures 3-6 and Table 3 and 4 display projected changes in rainfall intensities for various return periods and durations.

TABLE 3

PERCENTAGE CHANGE IN RAINFALL INTENSITY FOR 24-HOUR DURATION EVENTS BETWEEN MULTI-MODEL PROJECTED (2006-2055) AND HISTORICAL OBSERVED (1961-2005) EVENTS FOR GORAKHPUR.

	RETURN PERIOD				
MODEL	**2 YEAR**	**5 YEAR**	**10 YEAR**	**20 YEAR**	**50 YEAR**
HADGEM2	9.6%	6.1	4.3	3.4	2.2
NCAR-CCSM4	10.0	16.1	19.1%	20.1	22.5
BCC-CSM1.1M	20.4	22.7	23.4	24.1	24.8%

TABLE 4

PERCENTAGE CHANGE IN RAINFALL INTENSITY FOR EVENTS OF SELECT DURATIONS (1, 12 AND 24 HOURS) FOR SELECT RETURN PERIODS (2, 10 AND 50 YEARS). PERCENT CHANGES ARE DERIVED FROM COMPARING IDF CURVES FROM MULTIPLE GCMS FOR THE FUTURE (2006-2050) WITH HISTORICAL IDF CURVES (1961-2005).

	RETURN PERIOD (YEARS)		
Duration (hrs)	**2**	**10**	**50**
1	11 TO 18%	-12 TO 52%	-22 TO 68%
12	10 TO 17%	1 TO 30%	-4 TO 33%
24	10 TO 20%	4 TO 23%	2 TO 25%

FIGURE 3

PROJECTED 5-YEAR RETURN PERIOD IDF CURVES FOR GORAKHPUR. THE SOLID BLACK LINE IS THE OBSERVED.

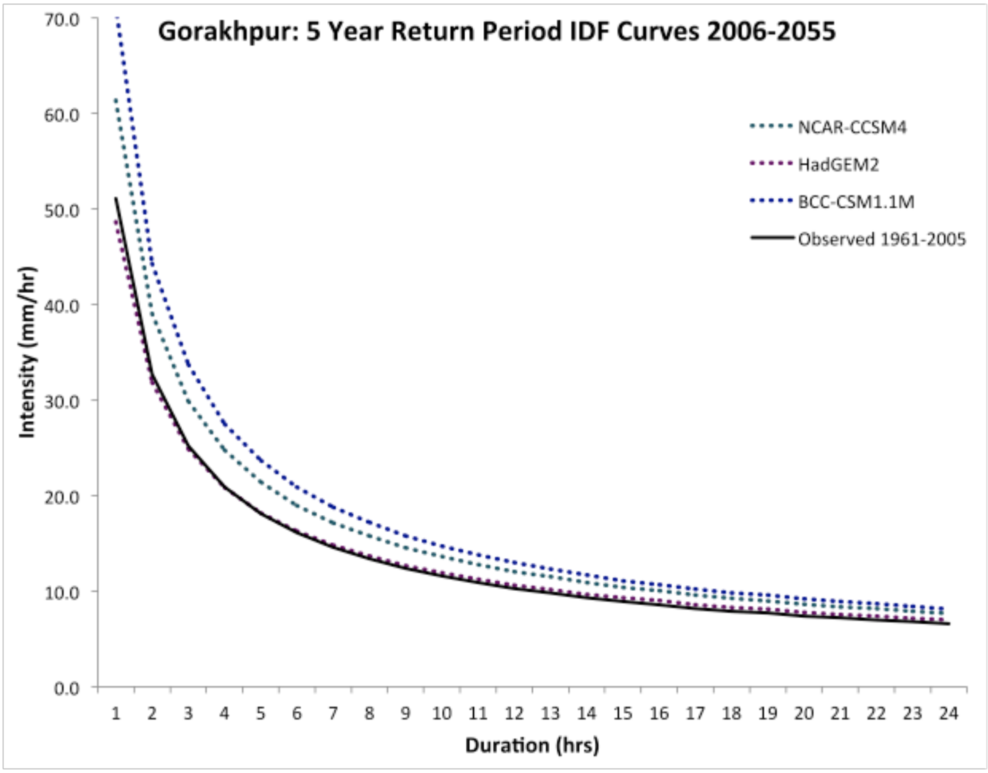


FIGURE 4

PROJECTED 10-YEAR RETURN PERIOD IDF CURVES FOR GORAKHPUR. THE SOLID BLACK LINE IS THE OBSERVED.

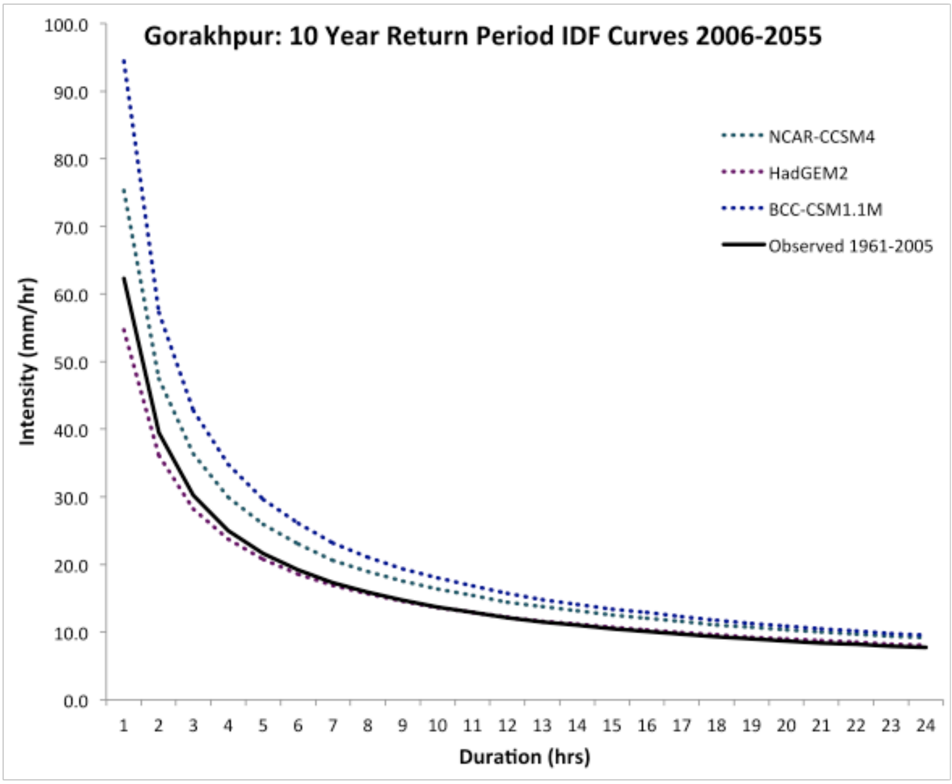


FIGURE 5

PROJECTED 20-YEAR RETURN PERIOD IDF CURVES FOR GORAKHPUR. THE SOLID BLACK LINE IS THE OBSERVED.

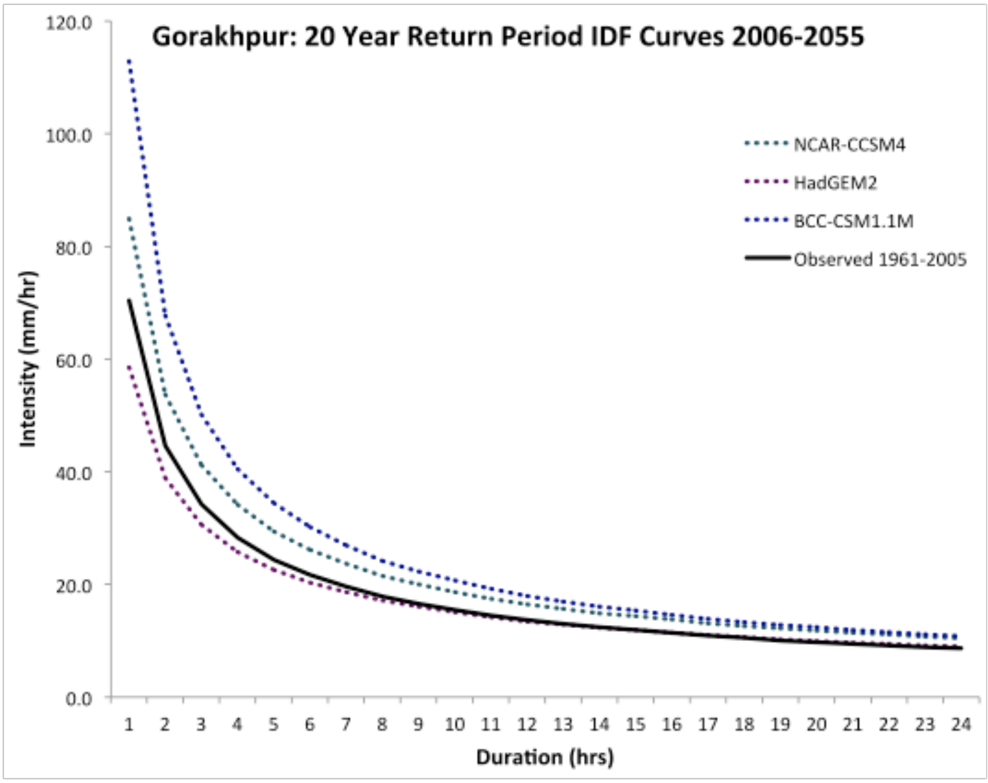
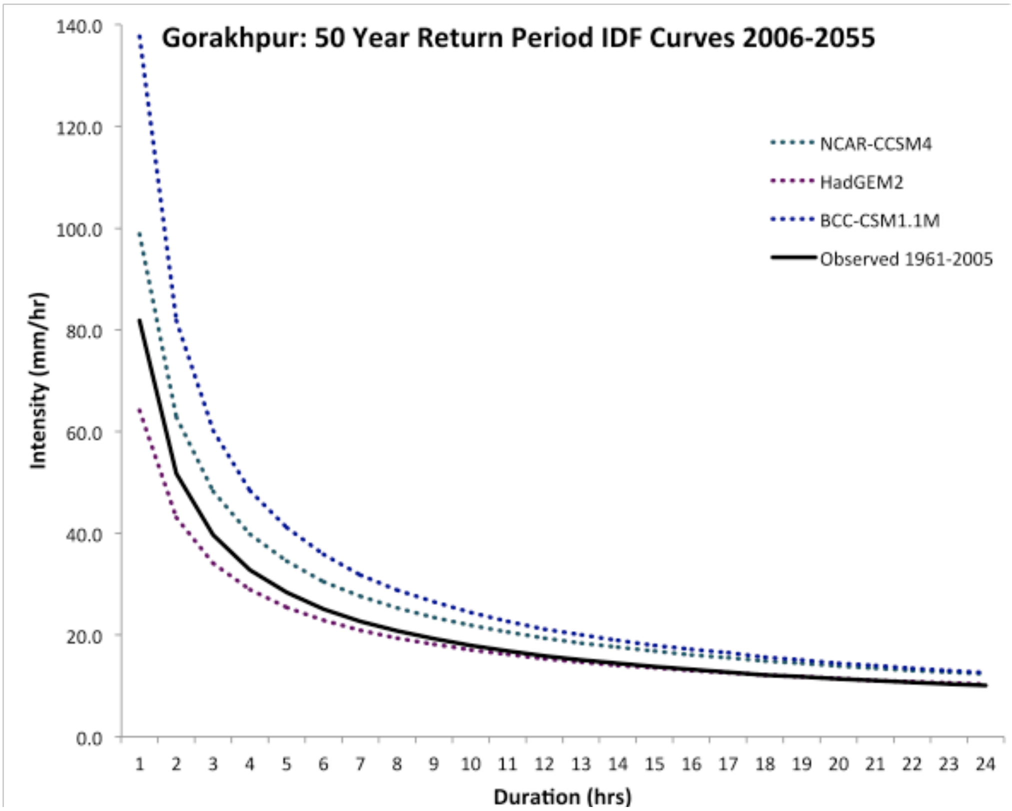


FIGURE 6

PROJECTED 50-YEAR RETURN PERIOD IDF CURVES FOR GORAKHPUR. THE SOLID BLACK LINE IS THE OBSERVED.



There is greater uncertainty (larger spread in the model projections and/or unclear direction of increasing or decreasing intensity) in how climate change might alter short duration events—those lasting less than 12 hours—than in events lasting longer than 12 hours as shown in the table and the following figures. There is also greater uncertainty in how much the intensity of really extreme events-those with a return period of 20 years or greater-might increase in the future. Much of this uncertainty is due to gaps in the historical observation records that affected the statistical distributions and will improve with time through efforts such as GEAG's automatic weather station, and coordination with the local Indian Meteorological Department office. Other sources of uncertainty are due to natural climate variability (not influenced by climate change), the differences between GCMs in how they model interactions between the land, ocean, and atmosphere to influence climate, and the fact that no-one really knows what the world's population, energy use, greenhouse gas emissions, and land-use will look like in 2050. This is why it is important to use projections from multiple models, and build cities smartly to reduce natural hazard risks.

Cautions and Assumptions

GCM VALIDITY AND SELECTION

Any interpretations of climate projections for adaptation purposes should use projections from multiple GCMs, each running a couple of RCPs, in order to capture the possible range and trend of changes. Theoretically, the projections of every climate model have equal probability of occurrence. When investigating possible changes in the more distant future—2070 and later—one should use the projections from every available model. However, scientists are divided about how many models should be used for near-term (2020s through 2050s) climate change analysis. Some scientists argue that all models should still be used; other scientists argue that only models that are able to broadly replicate a region's key historical climate statistics and seasonality should be used. This second group argues that because future projection runs are initialized from the simulations of historical climate, the errors of the historical simulations are propagated forward into the future projections. If a climate model is not able to sufficiently replicate a region's broad climate characteristics—in the case of Gorakhpur, the Indian Summer Monsoon—it might not be as valid in providing projections of possible changes in the near-term.

We agree with this second interpretation of climate model projections, as this investigation focused on near-term changes in Gorakhpur's extreme rainfall events. Furthermore, at the time of data access from the CMIP5 Multi-Model Ensemble Dataset (November–December 2012), only daily projected rainfall from RCP 4.5 was available for all GCMs selected for this investigation; projections generated using RCP 6 or RCP 8.5 were not uploaded for all the models. Given the time constraints of this investigation, we therefore were limited to using projections from only RCP 4.5. The limitation to one RCP is not too significant because of the time frame focus of this study, as the RCPs do not deviate greatly from each other until after 2050. *While one should use as many models and RCP or emission scenarios as possible for analysis, judgment is required when deciding how many models to retain, depending on the purpose of the analysis and how far into the future it covers.*

DATASET LENGTH AND QUALITY

As discussed previously, extreme event analysis is conducted for rare events. Ideally, one would have fifty years or more of daily or sub-daily data to establish statistics for the more severe, and rare events, such as those with return periods of 1 in 100 years or more. Extreme event analysis requires datasets longer than 30 years to be really rigorous, yet few locations have complete records of such length. The more rare events may be extrapolated from the probability distributions of existing data, but will not be as accurate for shorter datasets as they are for longer datasets.

The quality and completeness of datasets can greatly impact extreme event analysis. The original, historical IDF curves for Gorakhpur were calculated from a 'super' dataset compiled from daily and sub-daily rainfall data records sourced from the Indian Meteorology Department (IMD) and National Climatic Data Center (NCDC, U.S.), and completed in December 2012. Significant segments of data were missing between the years 1978–2005, necessitating the interpolation of daily values from a limited number nearby stations. The IDF curves generated from this interpolated set had to be interpreted cautiously, as well as the resulting projected IDF curves, because the missing data did skew extreme statistics. We repeated the extreme event analysis for Gorakhpur in February 2013 using supplemental data from the Aphrodite project (Yatagai et al., 2012) and found that both the historical and projected IDF curves changed. The analysis and results presented in this Technical Report are derived using data supplemented and validated against the Aphrodite set. We feel more comfortable using the Aphrodite sets, which while also interpolated, because they incorporated data from many more stations and record sets than we were able to access during the first round of analysis and are more robust for statistical analysis.

NON-STATIONARITY

It is evident in many regions that precipitation regimes have been changing (non-stationarity), but it is difficult to determine for some locations whether the changes are due to inherent decadal variations, changes in station situation and monitoring, climate change, or some combination because of the shortness of those locations' records. It becomes all the more difficult to detect non-stationarity in an area's extreme events, or potential causes of those changes if they can be detected, because of the rarity of extreme events and the requirement of longer records for robust extreme event analysis. Intensity-duration-frequency curves once relied on the concept of stationarity, but are now being modified, as in this investigation, to account for the possible influence of climate change on the frequency and intensity of extreme rainfall events. It is possible that the frequency and intensity of extreme events in and around Gorakhpur have changed between the early 1900s and today; the historical records to which we had access are not long enough to allow for such trend detection. On the other hand, the rapid pace of development and urbanization in Gorakhpur district and lack of coordination in managing water systems has influenced the changes in flood depth and duration much more than any possible recent changes in rainfall extremes.

We must also note that this analysis only investigated possible changes in extreme rainfall event intensities for the purpose of developing storm profiles, conditioned on climate change projections, that are being used in an urban flood model. This study did not investigate potential changes in overall Indian Summer Monsoon precipitation or distributions of breaks and active periods within the monsoon. Research is indicating that the ISM has undergone a small decrease in average precipitation amount since the 1960s, which may be partially attributed to the regular 30 to 40-year interdecadal variability of the monsoon with periods of above/below normal precipitation and potentially to an emergent climate change signal (Goswami, 2004; Joshi and Pandey, 2011; Annamalai, Hafner, Sooraj & Pillai, 2012). This interdecadal variability does impact the extreme event analysis however. We only had access to records from the 1960s onward, which might have skewed the IDF curves for Gorakhpur downward from what they might actually be if a longer period of record were used. At the same time, break periods between rainfall events seem to be increasing, with the total number of rain days decreasing. When rain does occur during the ISM, it appears to be happening in fewer, yet more intense events (Goswami, 2004; Dash, Kulkarni, Mohanty & Prasad, 2009), which also might be reflected in the analysis. Without reliable rainfall records prior to the 1960s, we cannot say exactly how the IDF curves from this analysis are skewed. Yet, the observations of other researchers of India's monsoon rain occurring in fewer, more intense events, coupled with the analysis here, would suggest that flooding and waterlogging will become more problematic for Gorakhpur unless better development and land-use practices are implemented.

Broad Implications

Climate change will likely alter the frequency and intensity of Gorakhpur's extreme rainfall events, as demonstrated with this analysis. The changes projected for Gorakhpur are consistent with changes already being observed in other regions of the world and that are broadly projected to occur (IPCC, 2012). It is important to remember, however, that the projected changes produced in this analysis will most definitely change, and the analysis should be repeated 5 to 10 years from now. Ultimately, the degree of change in the frequency and intensity of extreme climate events is highly dependent on human choices around land-use, energy and natural resource consumption, and emission rates over the next decade.

GEAG, with support from ISET, conducted a series of consultations with communities at the sub-ward scale in Maheva ward of Gorakhpur city. The aim of the consultations was to identify climatic-thresholds related to rainfall intensities, duration, and magnitude that contributed to critical waterlogging in particular areas. The consultations facilitated a qualitative understanding of the various magnitudes of waterlogging and flooding events in past, the extent of resulting impacts, and specific characteristics of rainfall (intensity and duration) that contributed to such waterlogging/ flooding. The data collected via community consultations was corroborated with government records, such as data on dates and duration of pumping by the Irrigation Department/Jal Nigam to drain water from the impacted areas.

It was found that specific magnitudes of rainfall over one, two, and three days (individually and cumulative) caused critical waterlogging/ flooding problems in particular wards. For example, 100 mm rainfall cumulative over three days caused severe waterlogging problems in Maheva ward. This particular rainfall threshold (intensity and duration) is being investigated in the urban flood model developed by Arup. Additional, more severe thresholds are also being investigated in the model, as these events have occurred historically and will occur again in the future.

Flooding within Gorakhpur, and any urban area, is not solely dependent upon climate hazards like heavy rain or storms.

The depth, duration, and location of floodwaters within a city are largely determined by land-use and urban development, solid waste and wastewater/storm water management systems, and coordination with upstream and downstream water managers. Destruction of vegetation and wetland areas and construction of roads and buildings increases impervious surface area, leading to greater flood depths and waterlogging. Development in river floodplains and loss of riparian ecosystems reduces a city's natural barriers against flooding. Even without climate change altering the frequency and intensity of Gorakhpur's extreme rainfall events, flooding is likely to increase in severity and frequency in the city because of urban and peri-urban development.

Concrete Actions For Building City Resilience

Flooding already occurs in many of the low-lying wards of Gorakhpur, often after less than 100 mm of rain in 24 hours—a common rain event with a return period of two years and average intensity of 4.2 mm/hr. Climate change will likely increase the intensity of similar rainfall events by 10 to 20% in the future. While embankments do protect some communities from initial flooding, they trap the rains and can lead to waterlogging lasting 2–3 months.

As a result, citizens, community groups, and GEAG are undertaking a variety of activities to build awareness about the multiple causes contributing to flooding and waterlogging, and taking steps to reduce vulnerability. Such activities include:

- Promoting flood resilient housing with raised plinth heights and raised storage areas for protecting household assets;
- Protection of Ramgarh Lake and other water bodies and green spaces as drainage areas and areas that provide critical ecosystem services supporting peri-urban livelihoods;
- Developing and funding a municipal solid waste management program to remove trash that clogs waterways;
- Working with the Municipal Corporation to improve sanitation and access to potable water, hopefully reducing vector-borne disease incidences especially during floods; and,
- Pushing for a citywide ban on plastic bags that contribute significantly to waterway clogging.

GEAG, with the support of groups like CDKN and the Rockefeller Foundation, is working with community groups and other organizations to improve Gorakhpur's climate resilience. Through GEAG's and ISET–International's efforts, Gorakhpur joined the Asian Cities Climate Resilience Network (ACCCRN). GEAG is expanding their action research activities to other cities in Assam, Bihar, and West Bengal. With the outcomes of this analysis and the flood model by Arup, GEAG, and ISET–International are sponsoring a flood resistant housing design competition. Winning designs will be evaluated for their cost effectiveness and promoted to the Gorakhpur Municipal Corporation, other policy makers and community groups.

Further Reading and Resources

For more in-depth discussions on extreme rainfall event analysis and resilience activities in Gorakhpur, the following references that were listed in this brief are suggested:

Annamalai, H., Hafner, J. Sooraj, K., & Pillai, P. (2012). Global Warming Shifts the Monsoon Circulation, Drying South Asia. *Journal of Climate doi:10.1175/JCLI-D-12-00208.1, in press.*

Chow, V.T., Maidment, D.R., & Mays, L.W. (1988). *Applied Hydrology* (International Edition ed.). Singapore: McGraw-Hill Book Company.

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