Rainfall intensity-duration-frequency relationships for Andhra Pradesh, India: changing rainfall patterns and implications for runoff and groundwater recharge

Daniel Dourte[1], Sanjay Shukla[2], Piara Singh[3], Dorota Haman[4]

1 Department of Agricultural and Biological Engineering, University of Florida (UF),

Gainesville, Florida, USA

2 Southwest Florida Research & Education Center, UF, Immokalee, Florida, USA

3 International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India

4 Department of Agricultural and Biological Engineering, University of Florida (UF),

Gainesville, Florida, USA

ABSTRACT: Accurate and current rainfall characterization is an important tool for water-related system design and management. Updated rainfall intensity-duration-frequency (IDF) relationships in peninsular India were developed; impacts on runoff and groundwater recharge due to changes in rainfall characteristics are discussed. Two datasets were used from gauges in Hyderabad city, the capital of Andhra Pradesh: hourly rainfall data for the 19 years from 1993-2011 and daily rainfall data for the 30 years from 1982-2011. Hourly data were used to develop updated rainfall IDF relationships; daily data were used for trend analysis of threshold-based rainfall events. IDF curves were developed for return periods of 2, 5, 10, 15, 25, 50, 75, and 100 years for 1, 2, 4, 8, and 24 hour durations. The updated IDF relationships showed a significant change in rainfall characteristics compared to older relationships for the region surrounding Hyderabad, India; they showed greater rainfall

1

intensities across all durations and return periods. Greater intensity storms may reduce

groundwater recharge and increase runoff, making the surface storage of runoff

increasingly important to enhance recharge and reduce flooding risks.

KEY WORDS   IDF curves, India, rainfall characterization, rainfall change, groundwater
recharge

Introduction

Rainfall Characterization and Water Resource Management

The development and updating of rainfall intensity-duration-frequency (IDF)

relationships is important for almost all aspects of water-related design and management,

including flood control, groundwater recharge evaluation, water supply, irrigation,

agricultural drainage, and energy generation. With growing competition for freshwater

resources in much of the world and considering climate variability, the need for updated

IDF relationships for developing new water management strategies is becoming

increasingly important. Improved characterization of rainfall, through updated IDF

relationships, has been shown to benefit water resource planning and management

decisions (Karl et al. 1995; Angel and Huff 1997; Guo 2006). For example, a case study

of Chicago urban drainage systems showed that drainage systems designed using updated

IDF relationships, using shorter records of more recent data, performed significantly better

than those developed from older rainfall records (Guo 2006).

There is mounting evidence from global and regional studies that precipitation

patterns are shifting toward more common higher intensity storms and fewer light and

2

moderate events (Kunkel et al. 1999; Easterling et al. 2000; Trenberth et al. 2003; Goswami et al. 2006; Joshi and Rajeevan 2006; Douglas and 2011). These observed changes in rainfall characteristics suggest that IDF analyses be regularly updated to include more recent and shorter records of rainfall time series and exclude older, less-representative data (Guo 2006; Madsen et al. 2008). The analysis of Trenberth et al. (2003) notes that the Clausius–Clapeyron equation relating vapor pressure and temperature suggests a 7% increase in atmospheric water content for each $1^{\circ}C$ increase in average annual temperature. As a result of low-level moisture convergence, local rainfall rates greatly exceed average regional or global evaporation rates; therefore, rainfall intensities could be expected to increase at a rate at least as large as 7% / $^{\circ}C$. However, this differs from the accepted $1 - 2\%$ / $^{\circ}C$ increase in total annual precipitation depths (IPCC, 2001). To reconcile the differences in these predictions, it follows that low and moderate intensity precipitation events will be less common, and precipitation would trend toward less frequent, higher intensity events (Trenberth et al. 2003). This argument is supported by global climate model predictions (UKHI and CSIRO9; Hennessy et al. 1997) and by an investigation of rainfall records for the large region of central India (Goswami et al. 2006). Also, the recent of work of Bandyopadhyay et al. (2009) has shown increases in atmospheric water content in India, affirming the connection between atmospheric water and temperature. Although the spatial distribution of this change in precipitation character is uncertain, it would mean greater risk of both dry spells and floods for some regions even though annual precipitation totals may increase slightly.

The recent rainfall character study (Goswami et al. 2006) of a large central Indian region used analyses of daily rainfall data from 1803 stations (1951 – 2000), and found significant increases in frequency and magnitude of high intensity rain events (>100 mm/day) and significant decreases in frequency of light and moderate events (>5 and <100 mm/day). It was concluded that these trends are more difficult to notice based on analyses from individual station data due to the large variability in daily data. The regional analysis, however, having much larger sample size due to the large number of stations, is better able to detect long term trends in rainfall intensity. If trends toward more episodic rainfall are observed, there are implications for groundwater recharge as changes in rainfall intensity characteristics may result in changes in runoff and infiltration partitioning.

Groundwater Resources in India

There is general agreement that water scarcity in India is severe (Alcamo et al. 2000; Yang et al. 2003). Total (761 km^3) and agricultural (688 km^3) water withdrawals for India are the highest in the world, and nearly 90% of withdrawals are for agricultural use (AQUASTAT, 2010). More than half of the irrigation requirements of India are met from groundwater (CGWB, 2002; Shah et al. 2003), and the number of mechanized borewells in India has increased from less than 1 million in 1960 to more than 20 million in 2000 (Shah, 2007). Groundwater in India is a highly important resource for irrigation and household use, and its extensive use is resulting in widespread groundwater depletion (Shah et al. 2003; CGWB 2007; Rodell et al. 2009).

4

Several states in northwestern and peninsular India are experiencing groundwater

depletion (CGWB 2007, Rodell et al. 2009). In Andhra Pradesh, for example, depleted

groundwater supply, resulting from irrigation withdrawal expansions, has severe

consequences for farmers that have invested in borewell infrastructure. Farmers bear

substantial costs of groundwater depletion: greater yield variability, costs of failed

borewells, and the expenses to develop new borewells. In the Andhra Pradesh district of

Medak, the Central Groundwater Board (CGWB) of India observed a 2 – 4 m decline in

groundwater levels in 26 observation wells during a 10 year period (1996 to 2005),

suggesting an annual decline of about 30 cm (CGWB 2007). A recent groundwater

depletion study (Rodell et al. 2009) in the northwestern Indian states of Haryana, Punjab,

and Rajasthan, is illustrative of common regional groundwater depletion problems in India.

Using the Gravity Recovery and Climate Experiment (GRACE) satellites to measure

changes in terrestrial water storage during the study period from August 2002 to October

2008, 109 km^3 of groundwater loss was estimated, or about 4 cm each year over the three-

state area. Considering the importance of groundwater resources in India, it is expected

that if rainfall becomes characterized by an increase in the frequency of rainfall events of

high intensity, the result would be a higher fraction of rainfall contributing to runoff and a

reduced fraction available for infiltration and groundwater recharge (de Vries and Simmers

2002; Gujja et al. 2009; Gupta et al. 2010, Rangan et al. 2010). This may put the already

reduced groundwater resources of India at even greater risk of depletion.

An area in northern Andhra Pradesh, near the major city of Hyderabad in the Medak

district is studied here as a case study to demonstrate the importance of updated IDF

relationships for water resource management for a region in India facing acute water

shortages. These IDF curves can be useful tools for numerous types of water resource

management projects in Hyderabad and the surrounding region.

The objectives of this study are to:

- Develop updated IDF relationships for Hyderabad, Andhra Pradesh, India

- Use updated IDF relationships to evaluate recent changes in precipitation intensity

- Estimate changes in predicted runoff and groundwater recharge using design

  storms from updated and original IDF relationships

Rainfall Characterization

Overview of IDF Analysis

Generally, the development of IDF curves follows four main steps. First, rainfall

intensity data are organized into an annual maximum series. This is done for each duration

of interest (1, 4, 8 hour, etc.) by finding the maximum rainfall intensity for the duration

specified for each year. Second, a probability distribution is fitted to the annual maximum

series using any choice of statistical techniques (maximum-likelihood, l-moments, or

other). Third, the cumulative distribution function (CDF) chosen and parameterized in

step two is used to calculate rainfall intensities from the frequencies (1/annual probability

of exceedance) desired (2, 5, 10 year, etc.) for each of the durations being considered.

Fourth, the curves can be fitted to a parametric equation; this final step is optional and is

useful if it is desirable to avoid using multiple CDFs for rainfall IDF prediction or if IDF

6

curves are to be estimated for durations or frequencies not in the period of record. A

common parametric equation form for IDF curves is (Bernard, 1932):

$$I_t^T = A1 \frac{T^{A2}}{t^{A3}}$$
<div style="text-align: right">Equation 1,</div>

where I_t^T is the rainfall intensity of a combination of T (frequency or return period, years)

and t (duration, hours) and the regional constants A1, A2, and A3. These constants are

fitted using multiple regression and empirical rainfall IDF relationships.

Limited IDF information is available for India. The study of Kothyari and Garde

(1992), using rainfall data (1950-1980) from 80 recording gages grouped geographically

based on rainfall characteristics, provided IDF curves for five regions of India: northern,

central, western, eastern, and southern. The Kothyari and Garde (1992) IDF relationships

are the most current IDF characterizations for India available in the literature, and these

IDF relationships were used for comparison with the updated IDF relationships. Their

analysis found that the performance of Equation 1 (Bernard, 1932) could be improved by

including some rainfall characteristic (R_{char}) in the expression. R_{char} was chosen from

among four rainfall properties that were considered as candidates for inclusion in the

equation: $I_t^T = C1 \frac{T^{C2}}{t^{C3}} (R_{char})^{C4}$, where I_t^T is the rainfall intensity of a combination of T

(frequency or return period, years) and t (duration, hours), R_{char} is the variable rainfall

characteristic, and C1, C2, C3, and C4 are constants fitted to IDF data generated from the

CDF which was fitted to observed data. Options considered for R_{char} were mean annual

rainfall (R), mean of the maximum monthly rainfall (R_{max}), ratio (R/R_{max}), and the 24-hr

duration, two-year return period rainfall depth (R_{24}^2). The four options for R_{char} were each

<div style="text-align: center">7</div>

used to fit $I_t^T = C1 \frac{T^{C2}}{t^{C3}}(R_{char})^{C4}$ to observed IDF data. It was found by comparing

multiple regression correlation coefficients that R_{24}^2 was most effective at improving IDF

curve fit to observed data, giving the IDF equation of the form (Kothyari and Garde 1992):

$$I_t^T = C1 \frac{T^{C2}}{t^{C3}}(R_{24}^2)^{C4} \qquad\qquad \text{Equation 2.}$$

Methods for Rainfall IDF Development for Hyderabad

Two rainfall data sets (Piara Singh 2009, personal communication) obtained from

recording gages at the International Crops Research Institute for the Semi-arid Tropics

(ICRISAT) near Hyderabad, Andhra Pradesh, India were used in this study. The first set

consisted of 140,256 records of hourly rainfall (19 year period, 1993-2011), and was used

for development of IDF relationships. The second set consisted of 12,784 records of daily

rainfall (30 year period, 1982-2011), and was used to analyze long term trends in

occurrence of threshold-based high intensity rainfall events. Sub-daily rainfall records are

important in rainfall IDF analyses for accurate determination of short duration (2, 4, 8

hour) storm intensities, and hourly rainfall records for India are sparse and are generally

only available since the early 1990's (Jain et al. 2007). Therefore, the hourly dataset used

was shorter than the daily dataset. Average annual rainfall in Hyderabad is 880 mm; 75%

of that rainfall arrives during the rainy season which spans from June to September and is

locally known as Kharif season. The studies of Indian monsoon rainfall variability (May,

2004) and spatial coherence of tropical rainfall (Moron et al. 2007) suggest that the IDF

relationships developed here, based on rainfall records from a recording station at

ICRISAT are applicable for the Medak district.

Using the hourly rainfall data, annual maximum series (AMS) for all durations

considered were developed by calculating a moving average intensity for each duration and

then finding the maximum average intensity for each duration during a calendar year. This

is step one of IDF curve development. The Weibull probability distribution was chosen

based on graphical and log-likelihood value comparisons of the fit of AMS data to

Weibull, Generalized Extreme Value, Gamma, and Log-Normal probability distributions.

In step two, the maximum likelihood estimation of parameters α and β (Weibull scale and

shape parameters) for the Weibull CDF was completed independently for each of the five

durations: 1, 2, 4, 8, and 24 hour. The two-parameter Weibull probability density and

cumulative distribution functions are: $f(I) = \alpha\beta^{-\alpha}I^{\alpha-1}e^{-(I/\beta)^{\alpha}}$ (Equation 3) and

$F(I) = 1 - e^{-(\frac{I}{\alpha})^{\beta}}$ (Equation 4), respectively, where f is probability, F is cumulative

probability, I is rainfall intensity, α is Weibull scale parameter, and β is Weibull shape

parameter. The five resulting CDFs were used to calculate rainfall intensity for the five

durations at all the frequencies required; in this case 2, 5, 10, 15, 25, 50, 75, and 100 year

return periods were considered (step 3). The IDF data were then fitted to Equation 2 for

comparison to the Kothyari and Garde (1992) equation to examine differences in IDF

relationships for the region between those developed from old (Kothyari and Garde 1992;

1950-1980) and new (ICRISAT; 1993-2011) rainfall records. The coefficients of Equation

2 (C1, C2, C3, and C4) were fitted separately for each duration and then also for all

durations combined; fitting was achieved using an automated iterative routine with the

goal of minimizing the average root mean squared error (RMSE) between intensities from

the CDF and those from Equation 2. Hereafter, the original and updated IDF relationships

will be referred to as K&G IDF and updated IDF.

Exploration of Trends in Occurrence of Rainfall Events of High and Low Intensity

Differences between the K&G IDF curves and the updated IDF curves can give

evidence for a change in character of precipitation for the region near Hyderabad, India.

As an auxiliary data source, the trends in the total annual numbers of threshold-based high

and low/moderate intensity rainfall events for single recording station can add to the

available evidence for changing rainfall characteristics. Using the daily rainfall dataset

from ICRISAT (30 year period, 1982-2011), days were counted as high intensity (I) event

days if $I \geq 50$ mm/day; low to moderate days were those having $5 < I < 50$ mm/day. These

intensity classes are commonly used to group rainfall days into high and low/moderate

classes (Angel and Huff 1997; Goswami et al. 2006). For each calendar year, days in each

class were summed.

Prediction of Storm-based Runoff

Design storms of 4-hour duration and return periods of 2, 5, and 10 years were

generated separately from the updated and K&G IDF relationships. Four-hour storm

duration was the most common storm event length in the hourly (1993-2011) rainfall

record. To evaluate the impacts on runoff, and thereby on groundwater recharge, that

could be expected from design storms developed from the different IDF relationships, a

plot-scale runoff model was used to simulate infiltration and runoff. The Green-Ampt

infiltration model (Green and Ampt, 1911; Mein and Larson, 1973) was used to predict

10

runoff for 4-hour design storms in an agricultural area near Hyderabad; a 20-minute time

step was used. Green-Ampt infiltration is represented by:

$$F = K_{se}\left(t - t_p + t_p'\right) + \psi_f\, M \ln\left(1 + \frac{F}{\psi_f\, M}\right) \qquad\qquad \text{Equation 5,}$$

where F is cumulative infiltration, K_{se} is effective hydraulic conductivity, t is time

beginning at onset of rainfall, t_p is the time to ponding ($t_p = F_p/i$), F_p is the cumulative

infiltration at the time of ponding ($F_p = (\Psi_f M) / (i/K_{se} - 1)$), i is rainfall intensity, t'$_p$ is the

time to infiltrate F_p if ponding started from the beginning of the rainfall event, Ψ_f is wetting

front suction, $M = \theta_s$ and θ_i, θ_s and θ_i are saturated and initial soil water content.

   Laboratory measurements of saturated hydraulic conductivity, K_s, were performed

on undisturbed soil cores collected from a 510 hectare agricultural watershed (centered at

17.769460° N, 78.628330° E). This small watershed near Hyderabad was being

investigated as a case study for illustrating agricultural management impacts on the

groundwater balance using hydrologic modeling. Soil samples were taken in variable

depth increments from 0 – 1 m (136 samples from N = 37 locations; Reddy, 2009). There

were typically samples from 4 soil layers at each location. Values of K_s ranged from 0.131

to 165 mm/hr, based on constant head permeameter K_s measurements (Klute and Dirksen,

1986). For use in Green-Ampt, K_s values only in the top soil layer (0 – 30 cm) were used;

the average K_s in this layer was 31.8 mm/hour. The effective hydraulic conductivity (K_{se})

in the Green-Ampt equation accounts for air entrapment making $K_{se} < K_s$. The

recommendation of Bouwer (1966) is to approximate K_{se} using $K_{se} = 0.5*K_s$; this

approximation was used here in the absence of field measurements of K_{se}. The measured

values of K_s and particle size (Reddy, 2009) showed that most soils (20 of 37 samples) in

11

the watershed were a sandy loam (Soil Survey Staff, 1999). This texture was used to

estimate the remaining Green-Ampt parameters: wetting front suction, saturated soil water

content, and initial soil water content (Ψ_f, Θ_s, and Θ_i, respectively) from tables of Rawls et

al. (1983) and Fangmeier et al. (2005). Green-Ampt parameters for the watershed were:

K_{se} = 1.59 cm/hr, Ψ_f = 11.04 cm, Θ_s = 0.45 cm/cm, and Θ_i = 0.12 cm/cm.

Results

Updated IDF Curves, Event Intensity Trends, Predicted Runoff Changes

The 1, 2, 4, 8, and 24 hour annual maximum rainfall intensities for the 19 year

record (1993-2011) that were used to develop IDF are shown in Table 1. Annual and rainy

season (Kharif) rainfall totals and number of rainy days are also presented.

Table 1. Annual maximum series rainfall intensity generated from hourly rainfall data and annual and Kharif season (June-September) total rainfall and rainy days for Hyderabad, Andhra Pradesh, India

The IDF curves developed from the inversion of the fitted Weibull CDF for each duration,

using the various probabilities (1/frequency) and solving for intensity, are shown in Figure

1. The CDF parameters and the coefficients used in the parametric IDF form of Equation 2

are shown in Table 2.

Table 2. Parameters for Weibull CDF: $F(I) = 1 - \exp(-(I/\alpha))^\beta$, where I is rainfall intensity, and C1, C2, C3, and C4 are parameters of the IDF function: $I_t^T = C1 \frac{T^{C2}}{t^{C3}} (R_{24}^2)^{C4}$

Figure 1. Intensity duration frequency curves for 1, 2, 4, 8, and 24 hour durations developed from hourly rainfall data (1993-2011) from Hyderabad, India

Table 3 presents rainfall intensities calculated from the CDF's and from the newly parameterized Equation 2. The RMSE shows good agreement between intensities from the Weibull CDF and those from the updated IDF following the form of Equation 2 (RMSE = 6.4 mm/hour.

Table 3. Rainfall intensity values from Weibull cumulative distribution functions (CDFs) and from formula of K&G IDF fitted to recent rainfall data (hourly data 1993-2011) and original data (daily data 1950-1980)[1]. RMSE is calculated based on CDF intensities.

Using the coefficients in Table 2, RMSE of rainfall intensities between updated and K&G IDF relationships is 26.8 mm/hour. Mean difference (intensities from original K&G IDF minus intensities from updated IDF following Equation 2 form) is -23.5 mm/hour (Table 4), and percent difference from K&G IDF is greater than 100% for most return periods for storms of four hour or greater duration (Tables 3 and 4). These results are caused by: significant increases in intensity of rainfall events during the last three decades, or the inclusion of recently available hourly rainfall records significantly altering the IDF relationships, or the spatial aggregation of rainfall records used for K&G IDF is too coarse for local planning and design in the Hyderabad area. Any of these causes should alert water resource managers in India to use IDF relationships that incorporate recently available hourly rainfall data from a recording gage(s) sufficiently close to the area of interest.

Table 4. Differences (mm/hour) in predicted rainfall intensity values between K&G and updated IDF curves[1]

Trends in Rainfall Intensity

Analyzing the daily rainfall data from Hyderabad (1982-2011), noticeable trends of

increasing annual numbers of high intensity rainfall events (I ≥ 50 mm/day) and decreasing

numbers of low and moderate intensity events (5< I <50 mm/day) were observed (Figure

2). These trends have high and negligible statistical significance based on t-tests of the

hypothesis of no trend; p-values of 0.003 and 0.5 for slopes of decreasing trend of low and

moderate events and increasing trend of high intensity events and, respectively. The non-

parametric Mann-Kendall test of trend significance showed a highly significant (α = 0.05)

decreasing trend for annual numbers of low/moderate intensity rainfall events, but no

significant trend for annual numbers of high intensity events. The lack of statistical

significance of the trend in high intensity event days is consistent with the observations of

Goswami et al. (2006) that the high variability of single-gage records makes it difficult to

observe trends of high statistical significance. However, the directions of the trends are

consistent with their analysis for all of central India.

Figure 2. Annual numbers of high (I ≥ 50 mm/day) and light intensity (5 < I < 50 mm/day)
rainfall days (1982-2011)

Rainfall Intensity Effects on Runoff and Groundwater Recharge

Increased intensities of rainfall events may result in greater runoff depths. Runoff

(RO) and infiltration (F) were simulated with the Green-Ampt model using 4-hour design

storms from the updated and from the K&G IDF relationships. Predicted RO depths were

104% greater for the updated IDF design storms than those from the K&G IDF

relationships (Table 5). Also, the proportion of total storm rainfall that becomes runoff

was increased for the updated IDF storms: on average across the three return periods, 14%

of rainfall became runoff under the K&G IDF storms and 19% of rainfall became runoff under the updated IDF storms (a 37% increase). Accordingly, infiltration depths were 81% and 86% of storm-based rainfall for the updated and K&G IDF design storms (a 6% decrease).

These storm-based estimates of infiltration and runoff may have implications for changes in annual groundwater recharge depth. Annually, about 70% of rainfall infiltrates soils and about 11% of rainfall infiltration becomes groundwater recharge in the region near Hyderabad (CGWB, 2006). If it is assumed that the changes in the proportion of total annual rainfall that infiltrates are consistent with those suggested by simulations under the 4-hour, 2-year design storm, then there would be a 4% decrease in the proportion of annual rainfall contributing to groundwater recharge. Groundwater recharge as a percent of rainfall depth for the design storms (Table 6) is 4% lower based on the updated IDF design storm compared to the recharge from the K&G IDF design storm; this results from an increase in the runoff/infiltration ratio under the updated rainfall regime (RO/F of 0.12 for updated IDF storm compared to 0.07 for K&G design storm).

High intensity rainfall patterns are characteristic of the region, meaning that the rainfall runoff/infiltration ratio simulated under the design storms can be considered to be not much larger than would be observed for a typical rain event. This is supported by the proportion of annual rainfall infiltration of 70% (CGWB, 2006) that is actually less than that predicted by the design storms. Therefore, the observed differences in predicted groundwater recharge as a proportion of rainfall based on design storms can be assumed to

be a reasonable estimate of annual differences in proportion of rainfall contributing to

recharge.

Table 5. Green-Ampt simulated runoff (RO) and infiltration (F) for 4-hour design storms
developed from updated IDF and original IDF for the region near Hyderabad, India

Table 6. Estimated changes in proportion of annual rainfall contributing to groundwater
recharge between precipitation character described by K&G IDF and by Updated IDF.
Storm-based rainfall is for a 4-hour, 2-year design storm developed from each of the IDF
relationships

Discussion: Precipitation Characterization and Groundwater in India

A change in rainfall intensity characteristics generally has important impacts on the

hydrology of a region. In semi-arid regions, like that of the region near Hyderabad, the

annual potential evapotranspiration is much greater than precipitation, runoff generation is

generally Hortonian, and groundwater recharge in these regions depends largely on high

intensity storms and the storage of excess rainfall in surface depressions (de Vries and

Simmers 2002). Channelized flow is highly seasonal, meaning most groundwater recharge

results from areal infiltration and percolation of surface storage of excess rainfall. Due to

the required amount of observations of groundwater levels, withdrawals, soil

characteristics, and land use changes, it is probably beyond the ability of available data to

assess changes in natural groundwater recharge resulting from precipitation intensity

trends. The analysis presented here merely serves to suggest that increases in rainfall

intensities may be one of the many factors contributing to the regional groundwater depletion problems in India.

Higher intensity rainfall patterns may lead to greater runoff and a lower proportion of rainfall being infiltrated and available for groundwater recharge. For the agricultural regions of semi-arid India, groundwater recharge is of major concern: groundwater depletion is common as a result of large irrigation withdrawals. Given the scarcity and seasonality of surface water resources in the region, increased rainfall variability increases the reliance on groundwater resources for irrigation. The evidence from this study suggests rainfall in peninsular India is becoming increasingly characterized by higher intensity events and fewer low and moderate intensity events. This result has a variety of management applications, but for agricultural areas dependent on groundwater for irrigation, one application would be to increase investments in reservoirs, farm ponds, and water harvesting tillage to enhance infiltration and groundwater recharge.

Conclusions

Rainfall IDF relationships are useful tools for various hydrologic analyses, and the updating and maintenance of these relationships is important for decision-making that requires information about the character of rainfall. The recent evidence from the literature of more common high-intensity rainfall events, based on numbers of threshold-based events, was extended in this study to utilize differences in IDF relationships based on old and new rainfall records to identify changes in rainfall intensities. This analysis reaffirms that IDF relationships should be regularly updated using more recent rainfall records. The updated IDF relationship for Hyderabad city in Andhra Pradesh, India, using the formula

17

of Kothyari and Garde (1992) with updated parameters based on 1993-2011 rainfall data, including the 2 year, 24 hour rainfall of 103.2 mm, is $I_t^T = 7.11 \frac{T^{0.243}}{t^{0.49}}(103.2)^{0.391}$. These updated IDF curves show noticeably greater rainfall intensity patterns – on average 24 mm/hour or 114% greater for 1 to 24 hour durations – compared to the previously available rainfall characterization (Kothyari and Garde 1992) for the southern region of India, $I_t^T = 7.11 \frac{T^{0.2}}{t^{0.71}}(103.2)^{0.33}$.

The runoff depths predicted in this study from design storms developed from updated IDF relationships were more than 150% greater than those predicted based on design storms from older IDF curves. The proportion of rainfall contributing to groundwater recharge was conservatively estimated to be decreased by more than 4% for the design storm from the updated IDF curves compared to recharge estimated from the K&G design storm. This suggests that the annual proportion of rainfall contributing to groundwater recharge may be declining as a result of increasing rainfall intensity. These results are consistent with the growing consensus that precipitation patterns are shifting, especially in lower latitudes, toward higher intensity rainfall events and a decrease in moderate and low intensity rainfall (Owor et al. 2009; Pall et al. 2006; Trenberth et al. 2003; Allen and Ingram, 2002). Similar studies of changing IDF relationships using shorter, recent rainfall records in other regions of India and in other parts of the world may provide increased evidence that the character of rainfall is changing.

References

Alcamo, J., Henrichs, T., Rosch, T. (2000). World water in 2025: global modeling and
scenario analysis. In, *World Water Scenarios Analyses*, Rijsberman FR (Ed.). World
Water Council, Marseille, France.

Angel JR, Huff HA. (1997). Changes in heavy rainfall in the Midwestern United States.
Journal of Water Resources Planning and Management, 121, 246-249.

AQUASTAT database search results. (2010). Food and Agriculture Organization, Water
Resources Development and Management Service.
http://www.fao.org/nr/water/aquastat/main/index.stm

Bandyopadhyay A, Bhadra A, Raghuwanshi NS, Singh R. 2009. Temporal trends in
estimates of reference evapotranspiration over India. *Journal of Hydrologic Engineering*
14(5), 508-515.

Bernard MM. (1932). Formulas for rainfall intensities of long durations. *Transactions of
the American Society of Civil Engineers*, 96, 592-624.

Bouwer H. (1966). Rapid field measurement of air-entry value and hydraulic conductivity
of soil as significant parameters in flow system analysis. *Water Resources Research*, 2,
729-738.

Central Groundwater Board. (2002). Master Plan for Artificial Recharge to Groundwater
in India. http://cgwb.gov.in/index.html.

Central Groundwater Board. (2006). Dynamic Groundwater Resources of India.
http://www.indiawaterportal.org/sites/indiawaterportal.org/files/DGWR2004.pdf.

Central Groundwater Board. (2007). Groundwater Information, Medak District, Andhra
Pradesh. http://cgwb.gov.in/documents/SR/Medak.pdf.

Allen MR, Ingram WJ. (2002). Constraints on future changes in climate and the
hydrologic cycle. *Nature*, 419, 224-232.

De Vries JJ, Simmers I. (2002). Ground water recharge: an overview of processes and
challenges. *Hydrogeology Journal*, 10, 5-17.

Douglas EM, Fairbank CA. 2011. Is precipitation in northern New England becoming
more extreme? Statistical analysis of extreme rainfall in Massachusetts, New Hampshire,
and Maine and updated estimates of the 100-year storm. *Journal of Hydrologic
Engineering*, 16, 203-217.

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO. (2000). Climate extremes, observations, modeling, and impacts. *Science*, 298, 2068-2074.

Fangmeier DD, Elliot WJ, Workman SR., Huffman RL, Schwab GO. (2005). *Soil and Water Conservation Engineering*, 5th ed. Thomson-Delmar, New York.

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier PK. (2006). Increasing trends of extreme rain events over India in a warming environment. *Science*, 314, 1442-1445.

Green WH, Ampt GA. (1911). Studies on soil physics part I - the flow of air and water through soils. *Journal of Agricultural Science*, 4, 1-24.

Gujja B, Dalai S, Shaik H, Goud V. (2009). Adapting to climate change in the Godavari River basin of India by restoring traditional water storage systems. *Climate and Development*, 1, 229-240.

Guo Y. Updating Rainfall IDF Relationships to Maintain Urban Drainage Design Standards. (2006). *Journal of Hydrologic Engineering*, 11(5), 506-509.

Gupta PK, Panigrahy S, Parihar JS. (2010). Modeling the spatiotemporal changes in the runoff of major basins in India under the future climate change scenario. *Bulletin of the National Natural Resources Management System*, 35, 57-62.

Haan CT, Barfield BJ, and Hayes JC. (1994). *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, San Diego.

Hennessy KJ, Gregory JM, Mitchell JFB. (1997). Changes in daily precipitation under enhanced greenhouse conditions. *Climate Dynamics*, 13, 667-680.

Huff FA. (1990). Time Distributions of Heavy Rainstorms in Illinois. *Illinois State Water Survey Circular*, 173.

IPCC (Intergovernmental Panel on Climate Change). (2001). *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge.

IWMI (International Water Management Institute). (2010). World Water and Climate Atlas On-Line Climate Summary Service. http://www.iwmi.cgiar.org/watlas/AtlasQuery.htm

Jain SK, Agarwal PK, Singh VP. (2007). Hydrology and water resources of India. Water Science Technology Library 57. Springer, Dordrecht, The Netherlands.

Joshi U, and Rajeevan M. (2006). Trends in precipitation extremes over India. India. Tech. Rep. 3, National Climate Centre.

Karl TR., Knight RW, Plummer N. (1995). Trends in high-frequency climate variability in the twentieth century. *Nature*, 377, 217-220.

Klute A, Dirksen C. (1986). Hydraulic conductivity and diffusivity: laboratory methods. *Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, 2nd ed. Agron. Monogr. 9*, A. Klute, ed., ASA, Madison, WI, 687-734.

Kothyari UC, Garde RJ. (1992). Rainfall intensity-duration-frequency formula for India. *Journal of Hydraulic Engineering*, 118, 323-336.

Kunkel KE, Andsager K, Easterling DR. (1999). Long-term trends in extreme precipitation events over the conterminous United States and Canada. *Journal of Climate*, 12, 2515-2527.

Madsen H, Arnbjerg-Nielsen K, Mikkelsen PS. (2008). Update of regional intensity-duration-frequency curves in Denmark: Tendency towards increased storm intensities. *Atmospheric Research*, 92, 343-349.

May W. (2004). Variability and extremes of daily rainfall during the Indian summer monsoon in the period 1901-1989. *Global and Planetary Change*, 44, 83-105.

Mein RG, Larson CL. (1973). Modeling infiltration during a steady rain. *Water Resources Research*, 9, 384-394.

Moron V, Robertson AW, Ward MN, Camberlin P. (2007). Spatial coherence of tropical rainfall at the regional scale. *Journal of Climate*, 20, 5244-5263.

Owor M., Taylor RG, Tindimugaya C, Mwesigwa D. (2009). Rainfall intensity and groundwater recharge, evidence from the Upper Nile Basin. *Environmental Research Letters*, 4, 1-6.

Pall P, Allen MR, Stone DA. (2006). Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under CO2 warming. *Climate Dynamics*, 28, 351-363.

Rangan H, Kull CA, Alexander L. (2010). Forest plantations, water availability, and regional climate change: controversies surrounding Acacia mearnsii plantations in the upper Palnis Hills, southern India. *Regional Environmental Change* 10, 103-117.

Rawls WJ, Brakensiek DL, Miller N. (1983). Green-Ampt infiltration parameters from soil data. *Proceedings of the American Society of Civil Engineers* 109, 62-70.

Reddy D. (2009). Personal communication. Water Technology Centre, Acharya NG Ranga Agricultural University. Hyderabad, India.

Rodell M, Velicogna I, Famiglietti JS. (2009). Satellite-based estimates of groundwater depletion in India. *Nature* 460, 999-1002.

Shah, T, Roy AD, Qureshi AS, Wang J. (2003). Sustaining Asia's groundwater boom: An overview of issues and evidence. *Natural Resources Forum*, 27, 103-141.

Shah, T. (2007). The Groundwater Economy of South Asia, An Assessment of Size, Significance and the Socio-Ecological Impacts. In, *The Agricultural Groundwater Revolution: Opportunities and Threats to Development*, Giordano M, Villholth KG. (Eds). International Water Management Institute, Battaramulla, Sri Lanka.

Singh P. (2009). Personal communication. International Crops Research Institute for the Semiarid Tropics, Hyderabad, India.

Soil Survey Staff. (1999). *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*, 2nd ed. Washington, DC: US Department of Agriculture Soil Conservation Service.

Trenberth KE, Aigu D, Rasmussen RM, Parsons DB. (2003). The changing character of precipitation. *Bulletin of the American Meteorological Society*, 84, 1205–1217.

Yang H, Reichert P, Abbaspour K, Zehnder AJB. (2003). A water resources threshold and its implications for food security. *Environmental Science and Technology*, 37, 3048-3054.

Figure Captions

Figure 1. Intensity-duration-frequency curves for 1, 2, 4, 8, and 24 hour durations

developed from hourly rainfall data (1993-2011) from Hyderabad, India

Figure 2. Annual numbers of high ($I \geq 50$ mm/day) and light intensity ($5 < I < 50$ mm/day)

rainfall days (1982-2011)

23

Tables

Table 1. Annual maximum series rainfall intensity generated from hourly rainfall data and
annual and Kharif season (June-September) total rainfall and rainy days for Hyderabad,
Andhra Pradesh, India

	Annual maximum series rainfall intensity, mm/hr					Rainfall totals, mm		Kharif rain days
	1 hour	2 hour	4 hour	8 hour	24 hour	Annual	Kharif	
1993	29.5	17.1	10.0	5.0	2.4	831	588	49
1994	34.8	23.4	14.1	8.9	6.0	848	550	62
1995	54.1	29.9	15.7	7.9	4.0	1266	747	54
1996	50.3	27.8	16.2	11.1	4.7	1063	911	64
1997	29.2	17.8	11.8	7.7	3.9	743	433	48
1998	34.1	21.2	12.0	7.9	2.8	1181	887	64
1999	30.0	16.6	8.7	4.4	1.9	580	455	63
2000	154.9	136.4	105.6	66.0	36.9	2016	1797	66
2001	37.4	20.7	10.5	6.4	2.6	688	514	53
2002	18.5	14.1	7.1	3.8	2.2	623	473	48
2003	50.6	41.2	25.4	12.8	4.3	926	789	66
2004	29.4	26.5	14.3	7.7	3.2	783	546	47
2005	46.7	32.3	18.3	9.3	4.4	1192	850	68
2006	33.8	24.6	17.2	11.9	4.6	889	636	75
2007	30.2	28.4	16.1	8.8	2.9	717	571	77
2008	44.0	25.8	15.6	9.9	7.0	1109	758	65
2009	58.7	49.3	25.0	12.7	4.6	963	834	34
2010	45.1	38.7	20.3	10.2	3.4	1179	963	50
2011	26.0	15.1	8.2	4.5	2.0	508	447	29

Table 2. Parameters for Weibull CDF: $F(I) = 1 - \exp(-(I/\alpha))^\beta$, where I is rainfall intensity, and C1, C2, C3, and C4 are parameters of the IDF function: $I_t^T = C1 \frac{T^{C2}}{t^{C3}} (R_{24}^2)^{C4}$

Storm duration	Weibull CDF parameters		IDF function parameters			
	α, scale	β, shape	C1	C2	C3	C4
1 hour	49.958	1.761	6.998	0.405	0.217	0.700
2 hour	35.866	1.484	7.000	0.439	0.251	0.703
4 hour	21.460	1.269	6.998	0.439	0.287	0.712
8 hour	12.362	1.213	6.998	0.433	0.298	0.724
24 hour	5.707	1.093	6.998	0.446	0.325	0.730
			Fitted to all 5 durations			
			7.104	0.243	0.490	0.391
			Kothyari and Garde parameters			
			7.100	0.200	0.710	0.330

Accepted Manuscript
Not Copyedited

Table 3. Rainfall intensity values from Weibull cumulative distribution functions (CDFs) and from formula of K&G IDF fitted to recent rainfall data (hourly data 1993-2011) and original data (daily data 1950-1980)[1]. RMSE is calculated based on CDF intensities.

Rainfall intensity (mm/hr) from Weibull CDF; hourly data 1993-2011 for Hyderabad

t (hours)	T, return period (years)							
duration	2	5	10	15	25	50	75	100
1	40.6	65.5	80.2	88.0	97.0	108.4	114.6	118.9
2	28.0	49.4	62.9	70.2	78.8	89.9	96.1	100.3
4	16.1	31.2	41.4	47.1	53.9	62.9	68.0	71.5
8	9.1	18.3	24.6	28.1	32.4	38.0	41.3	43.5
24	4.1	8.8	12.2	14.2	16.6	19.9	21.8	23.1

Rainfall intensity (mm/hr) from K&G general formula fitted based on recent intensity data for Hyderabad[1]

t (hours)	T, return period (years)							
duration	2	5	10	15	25	50	75	100
1	51.4	64.3	76.1	84.0	95.1	112.5	124.2	133.2
2	36.6	45.8	54.2	59.8	67.7	80.1	88.4	94.8
4	26.1	32.6	38.6	42.6	48.2	57.1	63.0	67.5
8	18.6	23.2	27.5	30.3	34.3	40.6	44.8	48.1
24	10.8	13.5	16.0	17.7	20.0	23.7	26.2	28.1
							RMSE	6.27

Rainfall intensity (mm/hr) from K&G original formula fitted to earlier intensity data for southern zone of India[1]

t (hours)	T, return period (years)							
duration	2	5	10	15	25	50	75	100
1	37.7	45.2	52.0	56.4	62.4	71.7	77.8	82.4
2	23.0	27.7	31.8	34.5	38.2	43.8	47.5	50.4
4	14.1	16.9	19.4	21.1	23.3	26.8	29.1	30.8
8	8.6	10.3	11.9	12.9	14.3	16.4	17.8	18.8
24	3.9	4.7	5.4	5.9	6.5	7.5	8.1	8.6
							RMSE	26.8

[1] $I_t^T = 7.104 \frac{T^{0.243}}{t^{0.49}} (103.2)^{0.391}$: Updated; [2] $I_t^T = 7.1 \frac{T^{0.2}}{t^{0.71}} (103.2)^{0.33}$: K&G

Table 4. Differences (mm/hour) in predicted rainfall intensity values between K&G and
updated IDF curves[1]

t (hours)	T, return period (years)							
duration	2	5	10	15	25	50	75	100
1	-13.8	-19.0	-24.1	-27.6	-32.6	-40.8	-46.4	-50.8
2	-13.6	-18.1	-22.4	-25.3	-29.5	-36.3	-40.9	-44.5
4	-12.0	-15.7	-19.2	-21.5	-24.9	-30.3	-33.9	-36.7
8	-10.0	-12.9	-15.6	-17.4	-20.1	-24.2	-27.1	-29.3
24	-6.9	-8.8	-10.6	-11.8	-13.5	-16.2	-18.0	-19.4

[1] $I_t^T = 7.1 \frac{T^{0.2}}{t^{0.71}} (103.2)^{0.33}$: K&G, $I_t^T = 7.104 \frac{T^{0.243}}{t^{0.49}} (103.2)^{0.391}$: updated

Accepted Manuscript
Not Copyedited

Table 5. Green-Ampt simulated runoff (RO) and infiltration (F) for 4-hour design storms
developed from updated IDF and original IDF for the region near Hyderabad, India

Storm return period	Updated IDF		K & G IDF		% Difference[1]	
	RO, mm	F, mm	RO, mm	F, mm	RO	F
2 year	11.0	93.3	3.6	52.7	202	77
5 year	24.4	106.0	10.1	57.5	142	84
10 year	42.9	111.4	15.7	62.0	174	80

[1] % Difference: 100*[F or RO depth (Updated IDF) – F or RO depth (K&G IDF)] / F or RO depth (K&G IDF)
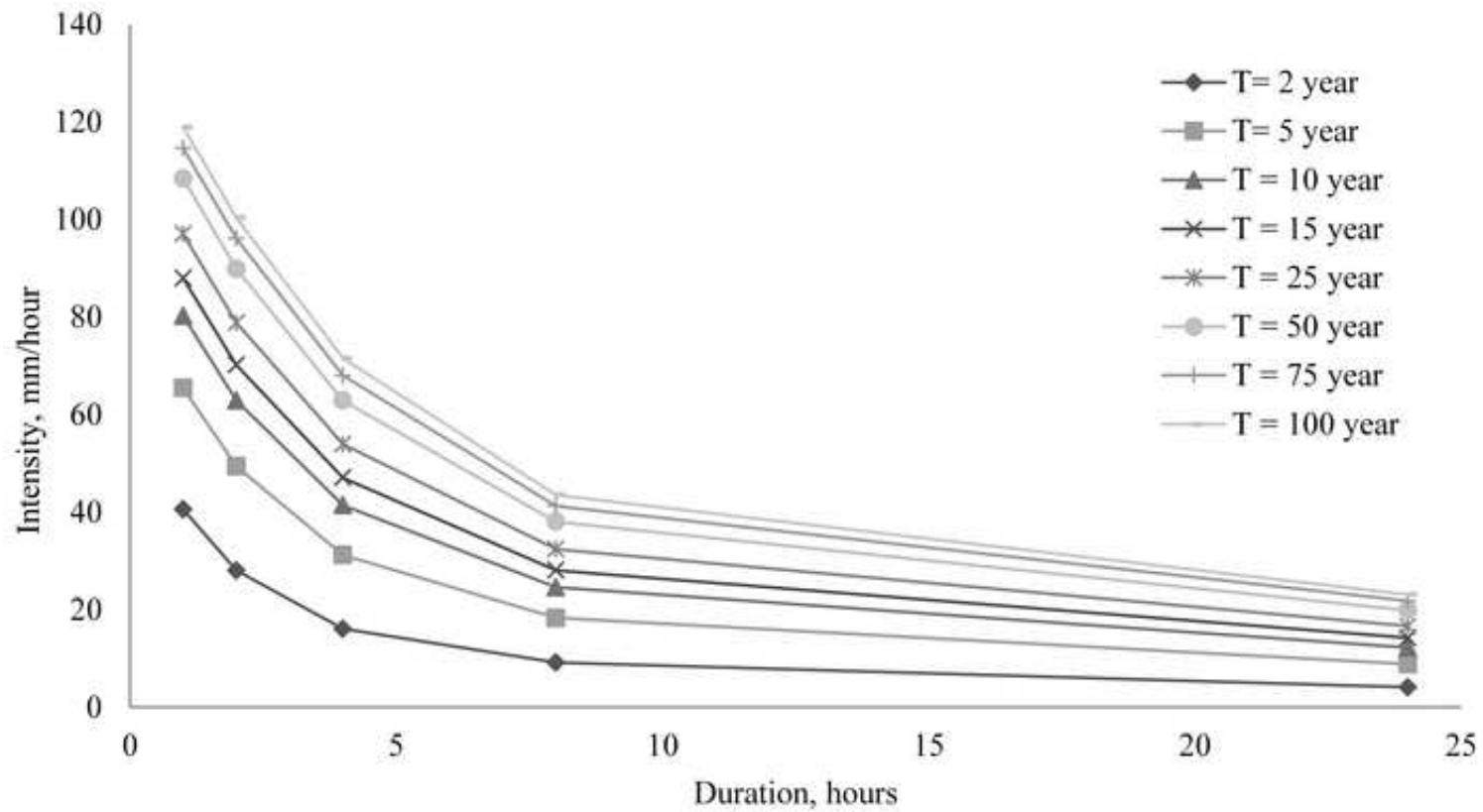
Accepted Manuscript
Not Copyedited

Table 6. Estimated changes in proportion of annual rainfall contributing to groundwater recharge between precipitation character described by K&G IDF and by Updated IDF. Storm-based rainfall is for a 4-hour, 2-year design storm developed from each of the IDF relationships
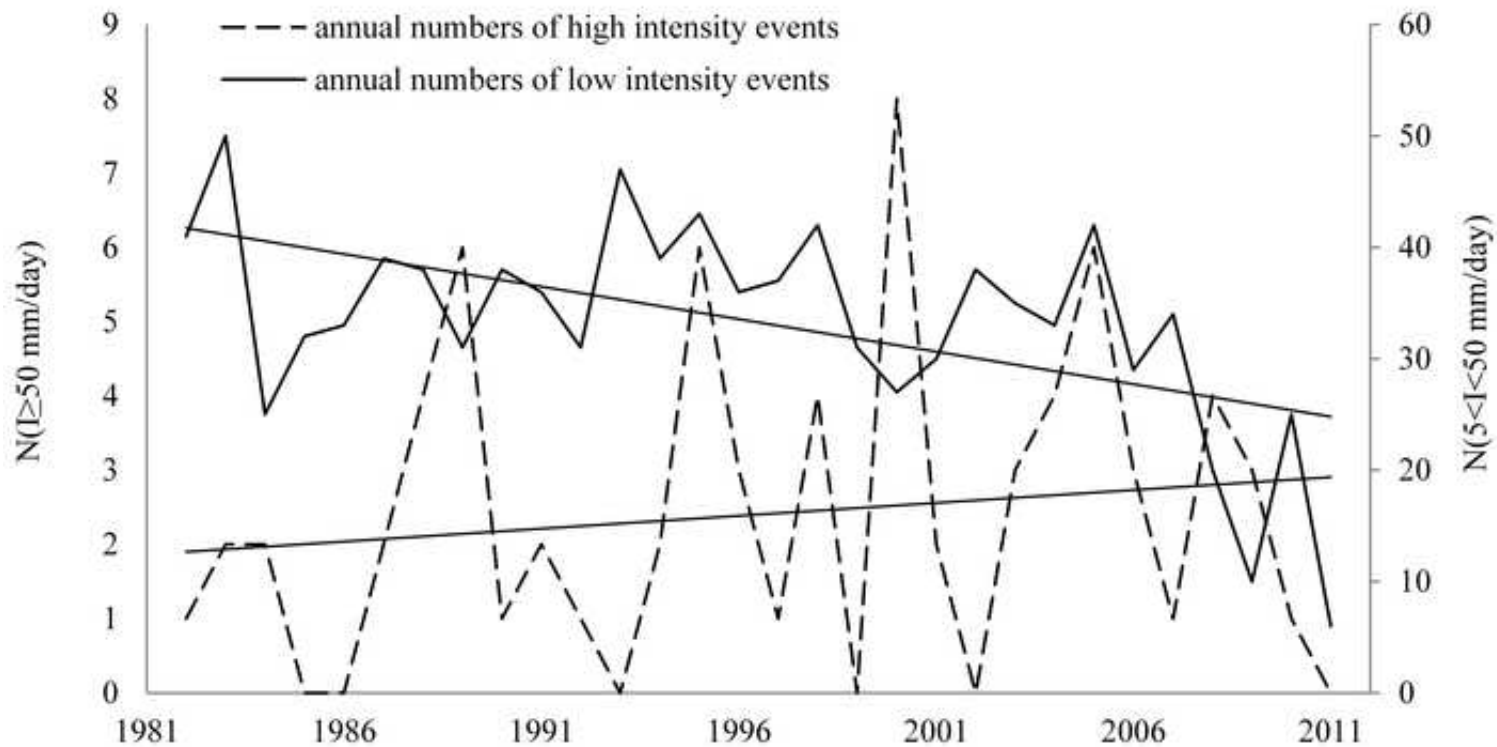
Rainfall IDF	Storm-based Rainfall, mm	Annual Rainfall, mm	Recharge as % rainfall	Est. annual recharge, mm	% Difference[1]
Updated	105.9	880	9.8	86.6	-4.4
K&G	56.3	880	10.3	90.5	

[1] % Difference: 100*[recharge as % rainfall (Updated IDF) – recharge as % rainfall (K&G IDF)] / recharge as % rainfall (K&G IDF)

Figure1

Figure2