Rainfall Intensity-Duration-Frequency Relationships for Andhra Pradesh, India: Changing Rainfall Patterns and Implications for Runoff and Groundwater Recharge

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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 attributable to changes in rainfall characteristics are discussed. Two data sets were used from gage 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-h durations. The updated IDF relationships showed a significant change in rainfall characteristics compared with older relationships for the region surrounding Hyderabad, India; they showed greater rainfall 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. **DOI:** 10.1061/(ASCE)HE.1943-5584.0000625.

CE Database subject headings: Rainfall intensity; India; Groundwater; Runoff; Floods.

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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).

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There is mounting evidence from global and regional studies that precipitation patterns are shifting toward more common higher intensity storms and fewer light and moderate events (Kunkel et al. 1999; Easterling et al. 2000; Trenberth et al. 2003; Goswami et al. 2006; Joshi and Rajeevan 2006; Douglas and Fairbank 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. 2009). 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°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% per °C. However, this differs from the accepted 1–2% per °C increase in total annual precipitation depths [Intergovernmental Panel on Climate Change (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

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from 1,803 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 owing to the large variability in daily data. The regional analysis, however, having much larger sample size resulting from 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 because 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 [Central Groundwater Board (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).

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 (1996–2005), suggesting an annual decline of approximately 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 approximately 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 in the present work 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 the following:

- Develop updated IDF relationships for Hyderabad, Andhra Pradesh, India;
- Use updated IDF relationships to evaluate recent changes in precipitation intensity; and
- 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 primary steps. First, rainfall intensity data are organized into an annual maximum series. This is done for each duration of interest (1, 4, or 8 h) 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, or 10 year) 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 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):

$$I_t^T = \mathrm{A1}\frac{T^{\mathrm{A2}}}{t^{\mathrm{A3}}} \tag{1}$$

where I_t^T = rainfall intensity of a combination of T (frequency or return period, years) and t (duration, h) 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 Eq. (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 following equation:

$$I_t^T = \mathrm{C1}\frac{T^{\mathrm{C2}}}{t^{\mathrm{C3}}}(R_{\mathrm{char}})^{\mathrm{C4}}$$

where I_t^T = rainfall intensity of a combination of T (frequency or return period, years) and t (duration, h); R_{char} = 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-h duration, 2-year return period rainfall depth (R_{24}^2). The four options for R_{char} were each used to fit $I_t^T = \mathrm{C1}(T^{\mathrm{C2}}/t^{\mathrm{C3}})(R_{\mathrm{char}})^{\mathrm{C4}}$ 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 following form (Kothyari and Garde 1992):

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$$I_t^T = \mathrm{C1}\frac{T^{\mathrm{C2}}}{t^{\mathrm{C3}}}(R_{24}^2)^{\mathrm{C4}} \quad (2)$$

Methods for Rainfall IDF Development for Hyderabad

Two rainfall data sets (Piara Singh, personal communication, 2009) 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. Subdaily rainfall records are important in rainfall IDF analyses for accurate determination of short duration (2, 4, or 8 h) storm intensities, and hourly rainfall records for India are sparse and are generally only available since the early 1990s (Jain et al. 2007). Therefore, the hourly data set used was shorter than the daily data set. 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 in this study 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 lognormal 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 h. The two-parameter Weibull probability density and cumulative distribution functions are

$$f(I) = \alpha\beta^{-\alpha}I^{\alpha-1}e^{-(I/\beta)^{\alpha}} \quad (3)$$

and

$$F(I) = 1 - e^{-(\frac{I}{\alpha})^{\beta}} \quad (4)$$

respectively, where f = probability; F = cumulative probability; I = rainfall intensity; α = Weibull scale parameter; and β = 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 Eq. (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 (P. Singh, personal communication, 2012) rainfall records. The coefficients of Eq. (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 Eq. (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 a single recording station can add to the available evidence for changing rainfall characteristics. Using the daily rainfall data set 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-h 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 runoff for 4-h design storms in an agricultural area near Hyderabad; a 20-min time step was used. Green-Ampt infiltration is represented by

$$F = K_{se}(t - t_p + t'_p) + \psi_f M \ln\left(1 + \frac{F}{\psi_f M}\right) \quad (5)$$

where F = cumulative infiltration; K_{se} = effective hydraulic conductivity; t = time beginning at onset of rainfall; t_p = time to ponding ($t_p = F_p/i$); F_p = cumulative infiltration at the time of ponding [$F_p = (\Psi_f M)/(i/K_{se} - 1)$]; i = rainfall intensity; t'_p = time to infiltrate F_p if ponding started from the beginning of the rainfall event; Ψ_f = wetting front suction; $M = \ominus_s$; and $\ominus_i$, $\ominus_s$, and $\ominus_i$ 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; D. Reddy, personal communication, 2009). There were typically samples from four soil layers at each location. Values of K_s ranged from 0.131 to 165 mm/h 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/h. 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 $K_{se} = 0.5K_s$; this approximation was used in this study in the absence of field measurements of K_{se}. The measured values of K_s and particle size (D. Reddy, personal communication, 2009) showed that most soils (20 of 37 samples) in the watershed were a sandy loam (Soil Survey Staff 1999). This texture was used to estimate the remaining Green-Ampt parameters: wetting front

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suction, saturated soil water content, and initial soil water content (Ψ_f, $\ominus_s$, and $\ominus_i$, 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/h; $\Psi_f = 11.04$ cm;$\ominus_s = 0.45$ cm/cm; and $\ominus_i = 0.12$ 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.

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 Fig. 1. The CDF parameters and the coefficients used in the parametric IDF form of Eq. (2) are shown in Table 2.

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

Using the coefficients in Table 2, RMSE of rainfall intensities between updated and K&G IDF relationships is 26.8 mm/h. Mean difference (intensities from original K&G IDF minus intensities from updated IDF following Eq. (2) form) is −23.5 mm/h (Table 4), and the percentage difference from K&G IDF is greater than 100% for most return periods for storms of 4-h 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 1. Annual Maximum Series Rainfall Intensity Generated from Hourly Rainfall Data, Annual and Kharif Season (June–September) Total Rainfall, and Rainy Days for Hyderabad, Andhra Pradesh, India

	Annual maximum series rainfall intensity (mm/h)					Rainfall totals (mm)		Kharif rain days
	1 h	2 h	4 h	8 h	24 h	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	1,266	747	54
1996	50.3	27.8	16.2	11.1	4.7	1,063	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	1,181	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	2,016	1,797	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	1,192	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	1,109	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	1,179	963	50
2011	26.0	15.1	8.2	4.5	2.0	508	447	29

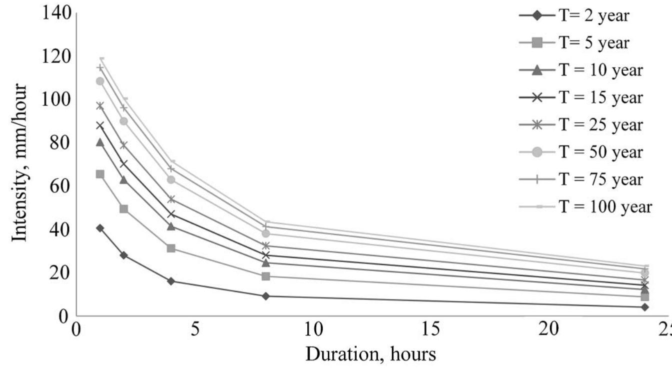

Fig. 1. Intensity-duration-frequency curves for 1-, 2-, 4-, 8-, and 2-h durations developed from hourly rainfall data (1993–2011) from Hyderabad, India

Table 2. Parameters for Weibull CDF

Storm duration (h)	Weibull CDF parameters		IDF function parameters			
	α, scale	β, shape	C1	C2	C3	C4
1	49.958	1.761	6.998	0.405	0.217	0.700
2	35.866	1.484	7.000	0.439	0.251	0.703
4	21.460	1.269	6.998	0.439	0.287	0.712
8	12.362	1.213	6.998	0.433	0.298	0.724
24	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

Note: $F(I) = 1 - \exp[-(I/\alpha)]^{\beta}$, where I = rainfall intensity; and C1, C2, C3, and C4 are parameters of the IDF function: $I_t^T = \mathrm{C1}(T^{\mathrm{C2}}/t^{\mathrm{C3}})(R_{24}^2)^{\mathrm{C4}}$.

Trends in Rainfall Intensity

Analyzing the daily rainfall data from Hyderabad (1982–2011), noticeable trends of increasing annual numbers of high intensity rainfall events ($I \geq 50$ mm/day) and decreasing numbers of low and moderate intensity events ($5 < I < 50$ mm/day) were observed (Fig. 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 nonparametric Mann-Kendall test of trend significance showed a highly significant ($\alpha = 0.05$) 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.

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Table 3. Rainfall Intensity Values (mm/h) from Weibull CDFs and from Updated Formula of K&G IDF Fitted to Recent Rainfall Data (Hourly Data 1993–2011) and from Original K&G IDF Formula (Daily Data 1950–1980)

Source of IDF relationship	t Duration (h)	T, return period (years) 2	5	10	15	25	50	75	100
Weibull CDF fitted to hourly data 1993–2011 for Hyderabad	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
K&G updated formula fitted to hourly data 1993–2011 for Hyderabad[a]	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	6.3
K&G original formula fitted to historical data for southern India[b]	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	29.0

Note: RMSE, calculated for the updated and original K&G relationships, are based on CDF intensities.
[a] $I_t^T = 7.104(T^{0.243}/t^{0.49})(103.2)^{0.391}$: updated.
[b] $I_t^T = 7.1(T^{0.2}/t^{0.71})(103.2)^{0.33}$: K&G original.

Table 4. Differences (mm/h) in Predicted Rainfall Intensity Values between K&G and Updated IDF Curves

t (h) Duration	T, return period (years) 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

Note: $I_t^T = 7.1(T^{0.2}/t^{0.71})(103.2)^{0.33}$: K&G; $I_t^T = 7.104(T^{0.243}/t^{0.49})(103.2)^{0.391}$: updated.

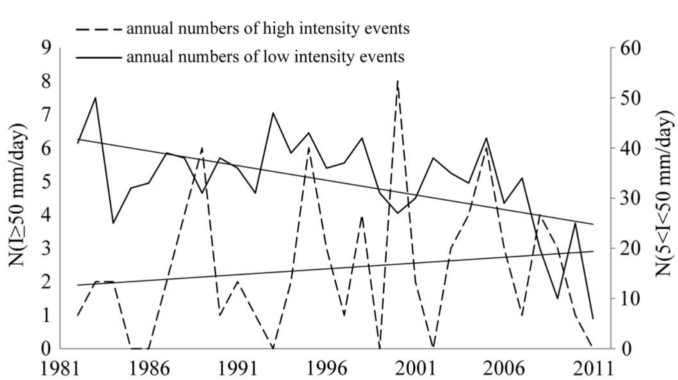

Fig. 2. Annual numbers of high ($I \geq 50$ mm/day) and light intensity ($5 < I < 50$ mm/day) rainfall days (1982–2011)

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-h 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, approximately 70% of rainfall infiltrates soils and 11% of rainfall infiltration becomes groundwater recharge in the region near Hyderabad (CGWB 2011). 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-h, 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 percentage of rainfall depth for the design storms (Table 6) is 4% lower based on the updated IDF design storm compared with 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).

Table 5. Green-Ampt RO and Infiltration (F) for 4-h Design Storms Developed from Updated IDF and Original IDF for the Region near Hyderabad, India

Storm return period	Updated IDF RO (mm)	Updated IDF F (mm)	K&GIDF RO (mm)	K&GIDF F (mm)	Difference[a] (%) RO	Difference[a] (%) 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

[a] % Difference: $100 * [F$ or RO depth (updated IDF) $- F$ or RO depth (K & G IDF)$]/F$ or RO depth (K & G IDF).

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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

Rainfall IDF	Storm-based rainfall (mm)	Annual rainfall (mm)	Recharge as % rainfall	Estimated annual recharge (mm)	Difference[a] (%)
Updated	105.9	880	9.8	86.6	−4.4
K&G	56.3	880	10.3	90.5	

Note: Storm-based rainfall is for a 4-h, 2-year design storm developed from each of the IDF relationships.
[a]% Difference: 100 ∗ [recharge as % rainfall (Updated IDF) − recharge as % rainfall (K & G IDF)]/recharge as % rainfall (K & G IDF).

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 2011) 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.

Discussion: Precipitation Characterization and Groundwater in India

A change in rainfall intensity characteristics generally has important impacts on the hydrology of a region. In semiarid 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 primarily 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. Because of 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 in this study 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 semiarid 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 of Kothyari and Garde (1992) with updated parameters based on 1993–2011 rainfall data, including the 2-year, 24-h rainfall of 103.2 mm, is $I_t^T = 7.11(T^{0.243}/t^{0.49})(103.2)^{0.391}$. These updated IDF curves show noticeably greater rainfall intensity patterns—on average 24 mm/h or 114% greater for 1- to 24-h durations—compared to the previously available rainfall characterization (Kothyari and Garde 1992) for the southern region of India, $I_t^T = 7.11(T^{0.2}/t^{0.71})(103.2)^{0.33}$.

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 with 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. 2007; 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.

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