Analysis of runoff pattern for all major basins of India derived using remote sensing data

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distribution of flotsam in debris lines or of anomalous articles, e.g. clothing mats, fishing floats, etc. Maximum inundation ranged between 140 and 800 m from the swash zone. Based on local topography, flow direction indicators and the orientation of debris lines, it was apparent that maximum landward inundation occurred by lateral flow at Pulicat, Devanaampatnam, Parangipettai and Taramgambadi. Lateral flows filled interdune-ridge valleys that were landward of shore-parallel dune-ridges at Devanaampatnam and Parangipettai. The interdune-ridge valleys at the landward ends of these two profiles were connected to tidal inlet channels. Lateral flow also filled shallow valleys in Pulicat and Tarangambadi, where breaches in shore-parallel dune-ridges allowed the tsunami to inundate back-ridge areas.

Flow features were recorded in most of the profiles that include vegetation flop-over, orientated beams, debris shields around tree trunks and sand ripples. The mean bearing of measured flow direction was observed to be 250° from true north. Data suggest an oblique angle of tsunami wave attack, particularly in profiles between 11.5 and 12° lat where the shoreline trends NNE. The tsunami wave attack was observed to be of the order of 30–40° from the shore normal in the study area.

From our surveys, we infer the following: (i) The tsunami run-up heights along the east coast of India in TN vary between 2.5 and 5.2 m. (ii) Loss of life and property was reported in the first 100 m from the shore, where several settlements were washed away. (iii) Small differences in local run-up and coastal topography resulted in large differences in tsunami inundation and associated loss of life and damage within the TN coastal areas. (iv) The combination of local high run-up, low topography and dense development apparently accounted for the large loss of life and property. The surge water elevations, together with surge water depths appear to be important parameters in tsunami hazard analysis. (v) Low valleys behind shore-parallel dune-ridges claimed several lives due to lateral flows from tidal inlets or from breaches in the dune ridge. (vi) Keeping in view the observations during our survey, a detailed study should be taken up to assess the inundation areas all along the eastern coast of India, to prepare inundation hazard maps to avoid loss of life and property.

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Analysis of runoff pattern for all major basins of India derived using remote sensing data

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An attempt has been made to quantify and analyse intra- and inter-basin runoff potential for all basins of India using multi-date remote sensing data, curve number approach and normal rainfall data of 376 stations. Analysis showed that the highest runoff depth (1812 mm) was observed in the Brahmaputra basin (including Barak and other rivers) and the lowest (210 mm) in the Luni and rivers of Saurashtra basin. The Brahmputra basin, occupying only 8% of the geographical area of the country, provided around 19% of total runoff. In almost all basins, 90% runoff occurs during the five-month period starting from June. The runoff in the Brahmaputra, Narmada and Mahanadi basins responded well to rainfall, i.e. high runoff coefficient, whereas low runoff coefficient was found in the Cauvery basin.

THE status of water availability, particularly spatial and temporal pattern at the basin level is essential for regional planning and decision on water management. Runoff is an indication of availability of water. Thus *in situ* measurement of runoff is useful, however in most cases such measurements are not possible at the desired time and location as conventional techniques of runoff measurement are expensive, time-consuming and difficult. Therefore, rainfall–runoff models are commonly used for computing runoff. The model developed by the United States Department of Agriculture (USDA) Soil Conservation Society (SCS) known as curve number (CN) is popular among all rainfall–runoff models because of its simple mathematical relationships and low data requirement[1].

The CN represents the watershed coefficient, which is the combined hydrological effect of soil, land use, agricultural land treatment class, hydrological condition and antecedent soil moisture condition (AMC)[1]. Generally, the model is well suited for small watersheds of less than 4000 ha, as it requires details of soil physical properties, land use, conservation treatment and vegetation condition[2,3]. However, with increasing availability of finer spatial resolution information from space-based remote sensing data on vegetation, it is possible to use the SCS model for larger areas with better accuracy[4]. Gumbo et al.[5] found that the CN method worked well in GIS environment because of its relatively simple

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equations. One of the major inputs for rainfall–runoff modelling is land-cover. Satellite re note sensing is the best source of mapping this information[6]. Using multi-date remote sensing data, both spatial and temporal patterns of the land-cover can be derived, which can be used to generate the spatio-temporal pattern of derived parameters. The basin level runoff estimates, which are available for our country, are derived from comparatively old data. This study represents the results of spatio-temporal pattern of runoff at the basin level in India using remote sensi.ng and GIS.

Three types of data were used in this study, namely remote sensing data, thematic spatial maps and weather data. The remote sensing data were of SPOT–vegetation sensor ten-day cumulative NDVI (Normalized Difference Vegetation Index) product of 39 dates, i.e. from 1 May 2001 to 21 May 2002. NDVI is computed as: $(NIR - R)/(NIR + R)$, wherein NIR and R are reflectance in near infrared and red bands. The vegetation optical instrument on-board ʿPOT satellite of the French Space Agency, operates in four spectral bands: blue, red and near infrared (NIR), and short wave infrared (SWIR), having a spatial resolution of 1 km. The ten-day composite NDVI products are available free on the Internet. The NDVI profiles of various land-cover classes were generated using the images. The training sites for these classes were marked with the help of land use and crop region maps of survey of India (SOI; 1978). A hierarchical loʿical model for land-cover classification was prepared by studying the pattern of NDVI profile. Land-cover classification was done keeping in mind the hydrological requirement of different crop and land-cover classes. Misclassification among land-cover classifications was expected due to low resolution. However majority of misclassification would be between related hydrological land-cover classes, thereby not changing the curve number to a large extent.

Figure 1 shows the hydrological land-cover map of India. As expected, less vegetation was found in the Indus, Luni and rivers of the Saurashtra basin whereas the Ganga, Brahamputra, Narmada, Brahmini-Baitrani, Mahanadi, Subarnrekha, Godavari and Tapi basins had good vegetation cover. Moderate vegetation cover was found in the Mahi, Sabarmati, the Krishna and Cauvery basins.

The spatial maps included basin bouⁱ daries that were derived from *Irrigation Atlas* (SOI, 1971) and soil textural class (SOI, 1978). Monthly normal rainfall data for the period 1951–80 were collected from climatological tables of observation in India[7] and rainfall surfaces were generated by inverse square distance interpolation technique with cell size 1 km. After preparation of spatial database, the CN model was formulated in GIS. The CN method is based on the assumption of proportionality between ɾetention and runoff. The mathematical relation for runoff is given by:

$$Q = (P - Ia)^2/(P - Ia + S), \tag{1}$$

where Q is the actual runoff, P the precipitation, Ia the initial abstraction which includes interception, surface storage

and infiltration into soil and S the potential retention. Since $Ia = 0.2$, S (based on the analysis performed by SCS for the development of the rainfall–runoff relation for average condition[8], i.e. AMC II), AMC is determined by the sum of the last five consecutive days' rainfall. In addition, the, following relationships between initial abstraction and potential maximum retention have been developed for Indian[9] condition. Equation (1) can be written as:

$$Q = (P - 0.2S)^2/(P + 0.8S) \quad \text{for black soil,} \tag{2}$$

$$Q = (P - 0.3S)^2/(P + 0.7S) \quad \text{for other soil groups,} \tag{3}$$

where S is determined by CN, through the following relation:

$$S = 25400/CN - 254. \tag{4}$$

Each cell of 1 km^2 was assumed as a unique hydrological unit, since the hydrological land-class map generated from SPOT data had 1 km^2 resolution. The first step in the model was to derive a hydrological soil grouping (HSG), which is a qualitative term given by the SCS. It is categorized into A (lowest runoff potential), B (moderately low runoff), C (moderately high runoff), and D (highest runoff) using in-
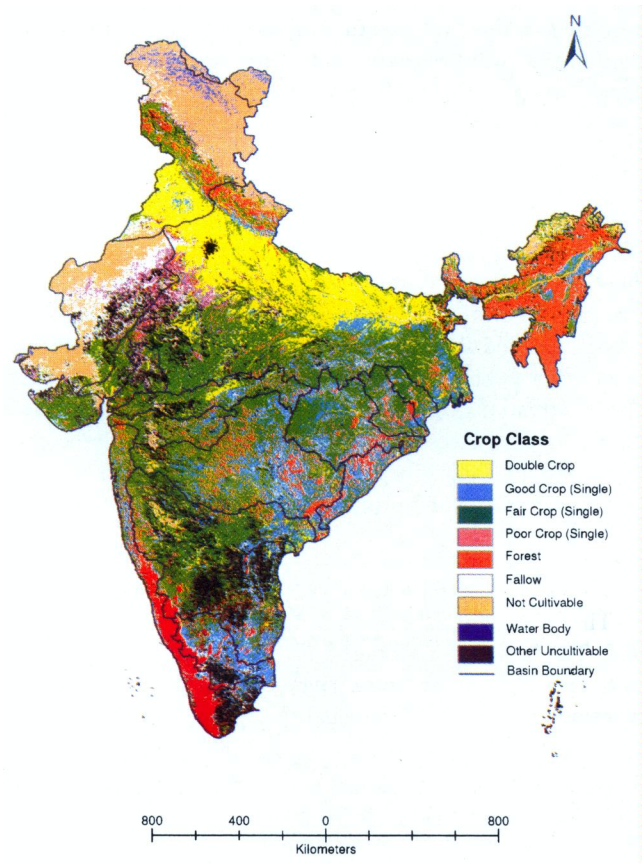

Figure 1. Hydrological land-cover classification of India generated from SPOT-vegetation multitemporal NDVI products.
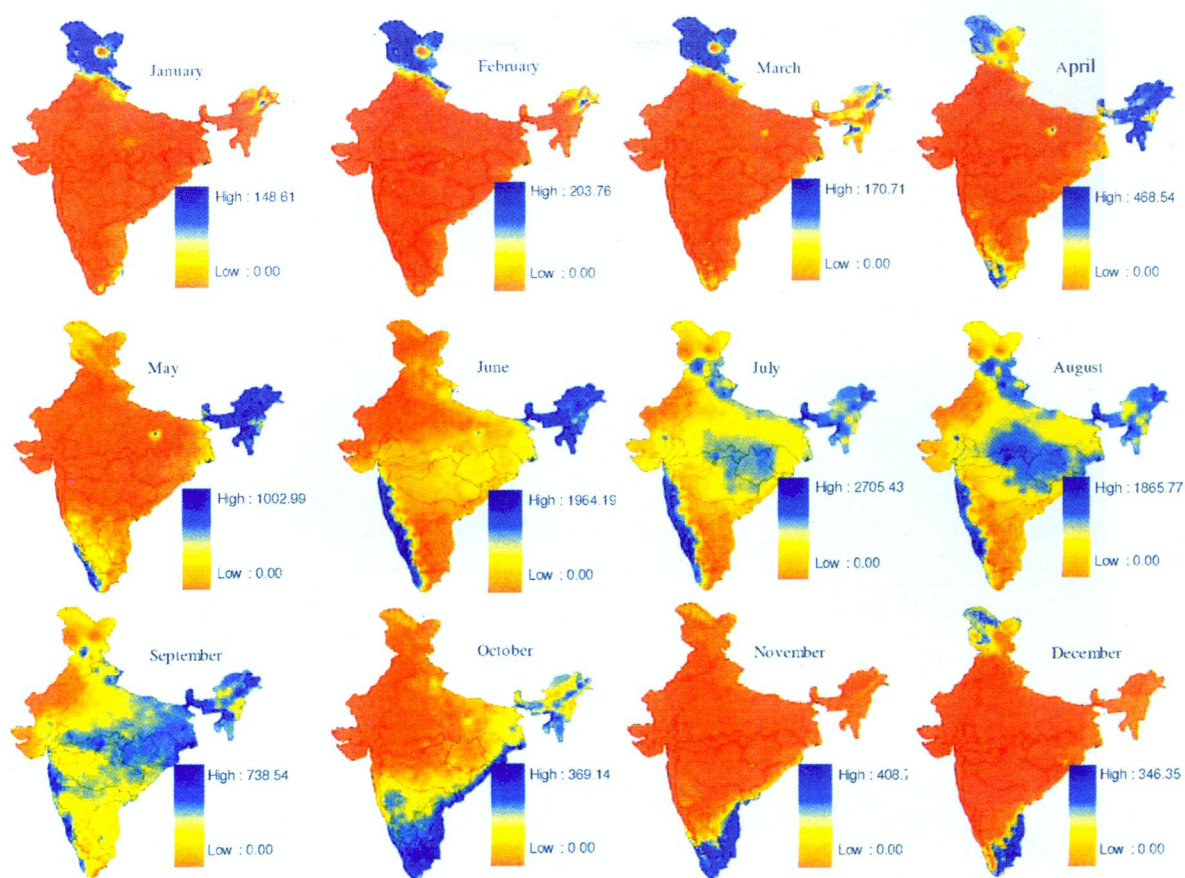
Figure 2. Spatio-temporal runoff (mm) pattern map of Indian mainland (labels are different for different months).

formation on soil texture. Ideally, a hydrological soil grouping was to be derived on the basis soil type, infiltration, soil depth and permeability. Since most of these parameters are soil texture-dependent, HSG was done on the basis of soil textural map and tentative map of hydrological soil groups. The raster theme of HSG was integrated with the land-cover theme to generate the hydrological soil cover complex (HSCC). This HSCC map was used for assigning the CN (CN ranges from 0 to 100, i.e. no runoff to runoff equating rainfall). The average CN of the Indian mainland was estimated by taking the mean CNs of all basins, and it was found to be 76.

This indicated considerable amount of runoff from rainfall. The basin wise average CN was found to be the lowest (68) for the Brahmputra river, the reason being good vegetation. But runoff potential was high in the Brahmputra basin because of AMC III condition during most of the months. As assigned CNs were based on average AMC II condition, CNs were later modified for AMC I (rainfall < 35 mm), and AMC III (rainfall > 52.5 mm) conditions. High CNs in the Mahi (81) and the Narmada (82) basins were due to dominant HSG-D. CN for the remaining basins ranges between 72 and 78.

After assigning CN, potential retention and runoff were calculated using eqs (2)–(4). Thus, the CN model was applied to the Indian mainland, including snow-fed river system as well as rivers in the arid area of Rajasthan desert. The resulting spatial runoff pattern for each month is shown in Figure 2. It was observed that only the Indus basin generated considerable amount of runoff from January to March, because the basin received rainfall between 75 and 100 mm during that period. From March to May, the Brahmputra basin and coastal rivers of the western and southern regions (south part) generated considerable amount of runoff because of early occurrence of rainfall in these regions. During June to October, in most of the basins, around 90% of annual runoff occurred except in the Cauvery, Indus and Brahmputra basins. The runoff pattern from June to September typically matched with the advancement of the monsoon system. However, the gap between rainfall and runoff was significant during different time periods and also widely different for different basins. This gap was wide for the Cauvery, and Indus and narrow in the Brahmputra, Narmada and Mahanadi basins. The temporal variation in the gap between rainfall and runoff was due to the fact that, the ratio between rainfall and runoff was low during low rainfall

Table 1. Comparison of estimated and reported runoff in major basins

Basin	Estimated in present study		Reported by Chaturvedi[10]	
	Runoff (M ha m)	Rainfall (mm)	Runoff (M ha m)	Rainfall (mm)
Indus	18.50 (7.59)	1114.44	7.69 (4.07)	560
Ganga	58.93 (24.16)	1116.51	55.01 (29.14)	1160
Brahmaputra, Barak and others	48.83 (20.02)	2551.77	59.70 (31.63)	1220
Luni and rivers of Saurashtra	6.76 (2.77)	496.42	1.23 (0.65)	380
Sabarmati	1.12 (0.46)	799.65	0.37 (0.20)	760
Mahi	2.07 (0.85)	873.36	1.18 (0.63)	830
Narmada	8.32 (3.41)	1128.86	4.01 (2.12)	1210
Brahmani-Baitrani and Subarnrekha	7.06 (2.89)	1415.54	4.39 (2.30)	1470
Mahanadi	13.58 (5.57)	1387.33	7.07 (3.75)	1460
Godavari	20.57 (8.43)	1096.70	11.54 (6.11)	1100
Tapi	3.05 (1.25)	820.09	1.97 (1.04)	780
Krishna	17.90 (7.34)	1129.10	5.78 (3.06)	810
Cauvery	5.16 (2.12)	1249.28	1.86 (0.99)	990
Minor rivers*	32.05 (13.14)	1217.77	26.99 (14.3)	1110
Sum/average	243.90	1231.35	188.75	1032

Figures in parentheses are percentage of total.
*West-flowing rivers between Tapi and Kanyakumari and east-flowing rivers between Cauvery and Kanyakumari. Rivers between Mahanadi and Godavari and those between Krishna and Cauvery, including Pennar.
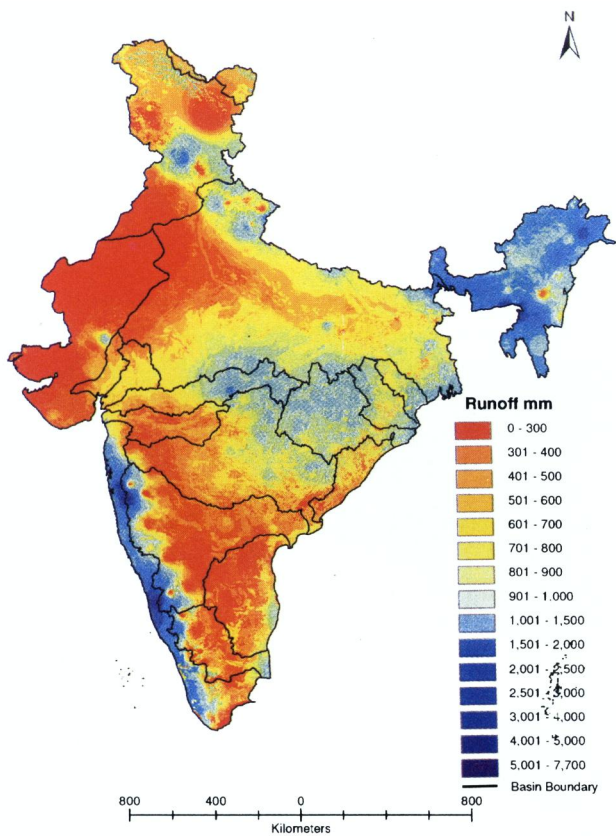

Figure 3. Annual runoff pattern map of India.

months. This is because during low rainfall period, water is generally retained by the soil and runoff occurs only when retention capacity is filled.

Though the highest runoff depth occurs in July, i.e. above 2500 mm, in majority of the Indian regions, uniform runoff was observed in September, though peak runoff was almost reduced by two-thirds (Figure 2). The runoff in the northern and central parts of India became low from October onwards, whereas it was significant in the Southern basins like Cauvery from October to December. This could be attributed to the retreating southwest monsoon and the northeast monsoon. The Rajasthan, Saurashtra and Kutch regions had low runoff throughout the year. Thus the spatial variability of runoff was high during five months, i.e. June to September. During other months, there was low spatial variability of runoff, because most of the basins had low rainfall.

The monthly runoff was summed up to obtain annual runoff depth and statistics for each basin was calculated. The spatial variation of annual runoff showed high runoff (2000–7700 mm) in the western coast, the northeastern region and parts of Himachal Pradesh and Uttranchal due to high annual rainfall in these regions (2500–8200 mm; Figure 3). Low to very low runoff depth of the order 0–400 mm was observed in the regions of Rajasthan, Kutch and Saurashtra and also parts of Punjab and Haryana, caused by low to very low rainfall (300–600 mm). Medium to high runoff 1000–2000 mm was found in the Eastern Ghats and the central parts of India, including Madhya Pradesh and parts of Maharashtra. The average annual runoff depth over India was found to be 765 mm, which was around 60% of the total rainfall in India, i.e. 1230 mm. Though the runoff pattern mostly followed the rainfall pattern, there were deviations, that could be attributed to variation in textural classes and hydrological landcover classification generated using remote sensing data.

The comparison of estimated and reported runoff showed that the former was higher in all basins compared to the latter (Table 1). This could be due to high climatic rainfall values in the Indus, Brahmputra, Luni and rivers of Saurashtra, Krishna, and Cauvery basins, than the values reported by Chaturvedi[10]. The Indus, Ganga and Godavari basins together represented 40% of the total runoff, serving about 48% of the geographical area of the country. The basins of Brahmaputra, and Rajasthan and Saurashtra, which occupied equal geographical area (approximately 9%) had 20% and a meagre 2.77% of total runoff respectively. The estimated runoff of the Sabarmati, Mahi, and Tapi basins was similar to reported values. RMSE between reported and estimated runoff of all basins combined was about 6.63. The total annual runoff of the Indian mainland was 243.68 M ha-m. This spatial and temporal pattern of runoff estimated using remote sensing data indicated the time and location of excess and deficit water, which could be used for proper water allocation. There is further need to improve this method by integrating digital elevation model with runoff routine module and also incorporating the snowmelt runoff module.

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Role of microbial community in stalactite formation, Sahastradhara caves, Dehradun, India

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Speleothems found in three caves in Sahastradhara, Dehradun, India were studied to understand if geomicrobiological processes were involved in mineral formation. Mineralogical studies (XRD and SEM–EDAX) of the stalactite samples revealed that calcite is the dominant mineral. An abundant microbial community (9×10^5 cells, g sed^{-1}) was detected by direct microscopic observation after DAPI staining. Application of fluorescence *in situ* hybridization techniques (FISH), based on the presence of rRNA, demonstrates the presence of a large number of active microbial cells (around 55% of the total cell number). The microbial community is dominated by Eubacteria, mainly sulphate-reducing bacteria (representing 10% of the total microbial community), but Archaea are also present. A significant fraction of these cells are active, indicating the high probability of their participation in biomineralization processes involved in the stalactite formation. This conclusion is at variance with the established classical model for stalactite formation based entirely on inorganic processes associated with carbonate solubility.

MICROORGANISMS have been shown to be important active and passive promoters of redox reactions influencing geological processes. Extensive documentation of microbial precipitation of calcium carbonate exists in the non-cave, carbonate literature[1]. Studies of microorganisms in caves have been predominantly descriptive with only a few experimental studies reported, but the past decade has produced extensive research into microbial interactions with minerals within cave environments. Bacteria and fungi can induce the precipitation of calcium carbonate extracellularly through a number of processes that include photosynthesis, ammonification, denitrification, sulphate reduction, and anaerobic sulphide oxidation[2,3]. Additionally, the activity of sulphate-reducing bacteria has been shown to mediate the precipitation of dolomite[4,5]. A large variety of heterotrophic microbial communities in stalactites are well documented in cave ecosystems[6] and the involvement of fungi, algae and bacteria is implicated in the precipitation of carbonate dripstone in caves[7,8]. The present investigation aimed to estimate the microbial community composition using the rRNA technique and its probable role in the formation of stalactites from Sahastradhara.

The study area is situated in the Dehradun Valley, a crescent-shaped intermontane valley formed within the