Evaluation of geomorphic control on flood hazard through Geomorphic Instantaneous Unit Hydrograph

Vikrant Jain and R. Sinha*

Engineering Geosciences Group, Department of Civil Engineering,
Indian Institute of Technology, Kanpur 208 016, India

Flood hazard in a basin depends upon the hydrological response of the upstream basin area. The upstream basin area may produce different amounts of run-off for a given rainfall based on its hydrologic response. The present communication shows the importance of drainage network characteristics in understanding the hydrologic response of a basin. The study is carried out through Geomorphic Instantaneous Unit Hydrograph analysis, wherein Horton's morphometric ratios were used to define the drainage network. A flood-prone river basin in north Bihar plains has been selected as a study area. The study shows that the length ratio (R_L) significantly influences the hydrologic response of a river basin. Hence, computation of this parameter should be included in flood analysis of any river.

HYDROLOGICAL response of a river basin is defined by the production of run-off against a given rainfall, which in turn is characterized by soil characteristics and basin geomorphology. Soil characteristics control the infiltration loss, whereas the distribution of the remaining 'rainfall excess' is governed by basin geomorphology. Alluvial plains are characterized by uniform alluvial soil of recent origin. Hence, to a large extent, the infiltration rate is considered to be a constant[1]. Run-off variability within the alluvial basins is therefore controlled by basin geomorphology, especially the drainage network of the river basins.

The concept of Geomorphic Instantaneous Unit Hydrograph (GIUH)[2] is essentially based on this fundamental idea and has provided the first analytically developed model to calculate river hydrograph from Horton's morphometric parameters. This approach has also been followed up in India and some recent works have successfully used GIUH to compute the hydrological response of ungauged basins[3–5].

In the GIUH model, uniform distribution and instantaneous imposition of unit 'rainfall excess' over the basin is assumed. Thus, GIUH is independent of rainfall characteristics and loss parameters. Further assumption is made that the incoming discharge due to this rainfall excess is filling a bucket at the outlet and the rate of filling of a bucket at the outlet of a basin will give the hydrograph. The GIUH is defined as the probability density function for the time of arrival of a randomly chosen drop to the trapping state (bucket)[2]. The bucket at the outlet will start empty and will reach a final volume equal to the total volume of rainfall excess over the basin. The total volume yielded as output up to a certain time t will be given by, volume $[V(t) = q(t)\mathrm{d}t]$. The derivative of the observed $V(t)$ gives the hydrograph of discharge $q(t)$ resulting from the rainfall input. This hydrograph $q(t)$ is the IUH of the river[2]. The general equations of GIUH are a function of Horton's numbers, i.e. bifurcation ratio (R_B), area ratio (R_A), length ratio (R_L), length of highest-order stream (L_Ω) and mean velocity of stream flow (v). Therefore, it provides a theoretical link between hydrology and geomorphology, and can be used to analyse the geomorphic control on basin hydrology.

The focus of our communication is the Baghmati river in north Bihar (Figure 1) which originates near Kathmandu in Nepal and drains the interfluve region between the Gandak and Kosi megafans in north Bihar plains. Basic hydrologic and morphometric data of the Baghmati river basin are listed in Table 1. The Baghmati river is extremely flood-prone[6] and inundates an area of about 2370 km^2 in Bihar causing vast damage to lives and property every year (Ganga Flood Control Commission, Ministry of Water Resources, Government of India, unpublished). Our earlier work involved the computation of GIUH for the Baghmati river for the upstream station (Dhengbridge)[5] using morphometric parameters (see Table 1) and its validation using observed data. Here, we

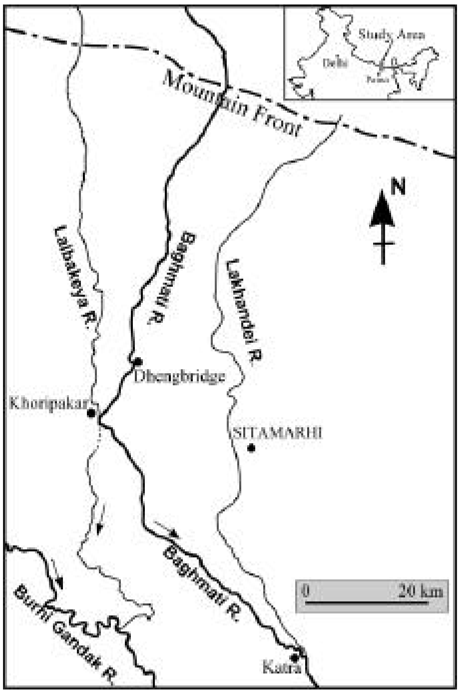

Figure 1. Baghmati river system with its main tributaries, the Lalbakeya and the Lakhandei. The Lalbakeya joins the Baghmati at Khoripakar, bifurcates downstream and flows into the Burhi Gandak river. The Lakhandei joins the Baghmati river at Katra and then the combined flow meets the Kosi river in its downstream reaches.

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*For correspondence. (e-mail: rsinha@iitk.ac.in)

Table 1. Hydrologic and morphometric characteristics of the Baghmati river

Parameter	Value	Parameter (at Dhengbridge)	Value
Basin area	8848 km^2	Average annual discharge	156 m^3/s
Average infiltration rate	0.3 cm/h	Bankfull discharge	1100 m^3/s
Average monthly discharge (non-monsoon–monsoon)	50–500 m^3/s	Mean annual flood	1473 m^3/s
GIUH for Dhengbridge			
Input parameters for GIUH	Definition		Value for Dhengbridge
Bifurcation ratio (R_B)	$R_B = N_{u-1}/N_u$; N_u = No. of streams of order u		3.53
Length ratio (R_L)	$R_L = L_u/L_{u-1}$; L_u = Length of streams of order u		3.68
Area ratio (R_A)	$R_A = A_u/A_{u-1}$; A_u = Area of streams of order u		5.41
Length of main channel (L_Ω)	Length of the 5th (highest) order stream		81 km
Average stream velocity			1.63 m/s
Peak of GIUH (q_p) = 0.0464 h^{-1}; Time to peak (t_p) for GIUH = 10 h			

Table 2. Range of morphometric values to determine the effect of geomorphometric parameters on GIUH

Morphometric ratio	Range of morphometric values		Three different values of morphometric ratios to generate different sets
	Baghmati river	Standard range	
R_B	2.77–4.81	3.0–5.0	3.0, 4.0, 5.0
R_L	1.4–5.95	1.5–3.5	1.5, 3.5, 5.5
R_A	3.33–7.85	3.0–6.0	4.0, 6.0, 8.0
L_Ω (km)	6–128	–	10, 50, 100

analyse the control of morphometric parameters on runoff generation through GIUH analysis.

Our approach has involved preparation of a detailed drainage map of the Baghmati basin using 1:50,000 scale toposheets and computation of morphometric parameters for the sub-basins following Strahler's scheme of stream-ordering[7]. In order to analyse the effect of individual morphometric parameters, viz. R_B, R_L, R_A and L_Ω on peak discharge of the GIUH, different 'sets' of morphometric values were prepared for the study. A 'set' is defined as consisting of constant values of any three morphometric parameters, whereas the fourth parameter was varied to observe the changes in peak discharge. The constant values of morphometric parameters for a 'set' were taken in accordance with the range of values observed for the Baghmati river (Table 2). In the present analysis for Baghmati river, the value of velocity was kept constant according to the assumption in the GIUH concept. The assumption of constant velocity is based on the earlier works[8,9] which have been experimentally validated by further studies[10–15].

To study the control of bifurcation ratio on river hydrograph, variation of peak discharge with respect to bifurcation ratio was derived for a given 'set' of other morphometric values. However, a 'set' represents only one particular morphometric condition. To analyse a general case, several 'sets' were prepared corresponding to different values of morphometric parameters within the range observed for the Baghmati river. In each set, the variation of peak discharge with respect to bifurcation ratio was noted. In the present case, three different values of each of these three morphometric parameters were taken corresponding to the range observed in the Baghmati basin, and 27 different sets were prepared (Table 3). The variation of peak discharge with bifurcation ratio was generated for each one of the 27 sets, and these variations are plotted in Figure 2*a* and *b*. Thus, each plot in Figure 2*a* and *b* shows the control of bifurcation ratio (R_B) on peak discharge under different morphometric characteristics. Similarly, plots depicting the control of R_A, R_L and L_Ω are plotted in Figure 2*c*–*g*.

Figure 2*a* and *b* shows that the trend of peak discharge variation with respect to bifurcation ratio (R_B) is ambiguous and it is also clear that, in general, the bifurcation ratio has little effect on the peak of the hydrograph. The effect of area ratio on the peak of the hydrograph is inconsistent (Figure 2*c* and *d*). At low values of area ratio ($R_A < 6$) the peak of the hydrograph decreases, but at higher values of area ratio ($R_A > 6$) the peak of the hydrograph increases with increase in area ratio. Among all the Horton's ratios, the length ratio (R_L) has the maximum effect on the peak of GIUH (Figure 2*e* and *f*). In other

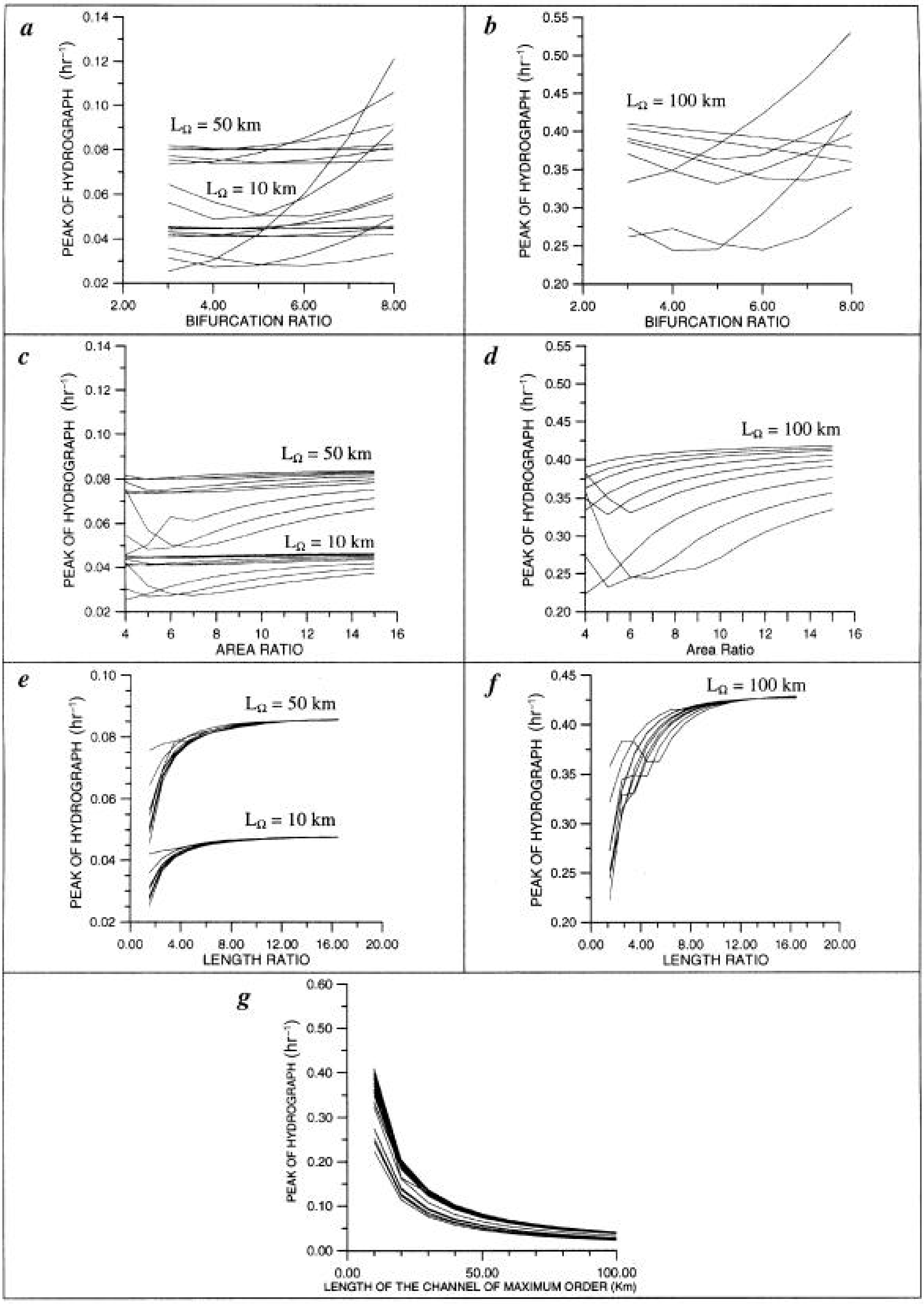

Figure 2. Relationship between peak of hydrograph and selected morphometric parameters: (***a***) and (***b***) bifurcation ratio, (***c***) and (***d***) area ratio, (***e***) and (***f***) length ratio, and (***g***) length of the channel of maximum order. Different sets of plots for individual morphometric parameters corresponding to different river lengths show the effect of basin size on morphometric–hydrological relationship.

Table 3. Different sets of constant values to study the GIUH variation with respect to an individual morphometric parameter

R_B (R_A, R_L, L_Ω)	R_L (R_B, R_A, L_Ω)	R_A (R_B, R_L, L_Ω)	R_Ω (R_B, R_L, R_A)
(4.0, 1.5, 10)	(3.0, 4.0, 10)	(3.0, 1.5, 10)	(3.0, 1.5, 4.0)
(4.0, 1.5, 50)	(3.0, 4.0, 50)	(3.0, 1.5, 50)	(3.0, 1.5, 6.0)
(4.0, 1.5, 100)	(3.0, 4.0, 100)	(3.0, 1.5, 100)	(3.0, 1.5, 8.0)
(4.0, 3.5, 10)	(3.0, 6.0, 10)	(3.1, 3.5, 10)	(3.0, 3.5, 4.0)
(4.0, 3.5, 50)	(3.0, 6.0, 50)	(3.0, 3.5, 50)	(3.0, 3.5, 6.0)
(4.0, 3.5, 100)	(3.0, 6.0, 100)	(3.0, 3.5, 100)	(3.0, 3.5, 8.0)
(4.0, 5.5, 10)	(3.0, 8.0, 10)	(3.1, 5.5, 10)	(3.0, 5.5, 4.0)
(4.0, 5.5, 50)	(3.0, 8.0, 50)	(3.0, 5.5, 50)	(3.0, 5.5, 6.0)
(4.0, 5.5, 100)	(3.0, 8.0, 100)	(3.0, 5.5, 100)	(3.0, 5.5, 8.0)
(6.0, 1.5, 10)	(4.0, 4.0, 10)	(4.0, 1.5, 10)	(4.0, 1.5, 4.0)
(6.0, 1.5, 50)	(4.0, 4.0, 50)	(4.0, 1.5, 50)	(4.0, 1.5, 6.0)
(6.0, 1.5, 100)	(4.0, 4.0, 100)	(4.0, 1.5, 100)	(4.0, 1.5, 8.0)
(6.0, 3.5, 10)	(4.0, 6.0, 10)	(4.0, 3.5, 10)	(4.0, 3.5, 4.0)
(6.0, 3.5, 50)	(4.0, 6.0, 50)	(4.0, 3.5, 50)	(4.0, 3.5, 6.0)
(6.0, 3.5, 100)	(4.0, 6.0, 100)	(4.0, 3.5, 100)	(4.0, 3.5, 8.0)
(6.0, 5.5, 10)	(4.0, 8.0, 10)	(4.0, 5.5, 10)	(4.0, 5.5, 4.0)
(6.0, 5.5, 50)	(4.0, 8.0, 50)	(4.0, 5.5, 50)	(4.0, 5.5, 6.0)
(6.0, 5.5, 100)	(4.0, 8.0, 100)	(4.0, 5.5, 100)	(5.0, 5.5, 8.0)
(8.0, 1.5, 10)	(5.0, 4.0, 10)	(5.0, 1.5, 10)	(5.0, 1.5, 4.0)
(8.0, 1.5, 50)	(5.0, 4.0, 50)	(5.0, 1.5, 50)	(5.0, 1.5, 6.0)
(8.0, 1.5, 100)	(5.0, 4.0, 100)	(5.0, 1.5, 100)	(5.0, 1.5, 8.0)
(8.0, 3.5, 10)	(5.0, 6.0, 10)	(5.1, 3.5, 10)	(5.0, 3.5, 4.0)
(8.0, 3.5, 50)	(5.0, 6.0, 50)	(5.0, 3.5, 50)	(5.0, 3.5, 6.0)
(8.0, 3.5, 100)	(5.0, 6.0, 100)	(5.0, 3.5, 100)	(5.0, 3.5, 8.0)
(8.0, 5.5, 10)	(5.0, 8.0, 10)	(5.1, 5.5, 10)	(5.0, 5.5, 4.0)
(8.0, 5.5, 50)	(5.0, 8.0, 50)	(5.0, 5.5, 50)	(5.0, 5.5, 6.0)
(8.0, 5.5, 100)	(5.0, 8.0, 100)	(5.0, 5.5, 100)	(5.0, 5.5, 8.0)

Velocity for all the combinations is taken as 5.87 km/h.

words, higher values of R_L would make the condition favourable for flooding in the downstream region. The R_L value does not depend upon the size of the river basin, but is characterized by the basin shape[16]. Its normal variation of 1.5–3.5 remains the same in different large as well as small basins[16]. However, lower values of R_L ratio suggest a more circular type of river basin, while basins with higher R_L ratio will be characterized by longitudinal shape. Thus, higher value of R_L implies that the river basin/sub-basin shape supports larger length of higher-order streams and/or smaller length of lower-order streams. This would mean that the discharge would reach early to the higher-order stream, causing early accumulation of water in the downstream reaches and hence flooding. Further, Figure 2*f* shows that run-off may increase up to 100% at downstream reaches due to increase in R_L. However, sensitivity of run-off to the range of R_L values changes with basin scale. In the smaller river systems ($L_\Omega \cong 10$ km), the flood hydrograph will be sensitive for a small R_L range of 2.0 to 4.0. In case of the middle-scale river system ($L_\Omega \cong 50$ km), R_L variation in the range of 2.0–7.0 will affect the flood hydrograph. In the case of still larger river systems ($L_\Omega \cong 100$ km), R_L value up to 9.0 will affect the hydrological response of the basin.

Figure 2*g* shows that the length of the highest-order channel causes maximum effect on the peak of the GIUH. Smaller length of highest-order stream (main channel) will produce higher run-off at the outlet of the river basin. However, its effect on discharge, which is the product of peak of the hydrograph rainfall depth and basin area, will be scale-dependent, and for small sub-basins (having small area) its effect on discharge will be limited. It can be summarized from Figure 2*g* that two basins with similar basin area but different length of highest-order streams will produce different run-off at the basin outlet. Also, any decrease in the main channel length of a river basin due to channelization or natural processes will increase the flood hazard significantly at downstream regions.

Further, the scale of basin not only determines the length of the highest-order stream but also channel slope. The smaller river basins are generally characterized by steeper channel slope compared to larger basins. Therefore, the effect of slope on the river hydrograph is also discussed. The basin slope may affect the GIUH through change in velocity. However, as mentioned earlier, the velocity in a river basin at any particular time remains constant from upstream to downstream[8–15]. Therefore, the effect of velocity on the GIUH needs to be considered only for computing the hydrological response of a river basin for different time periods or for comparison of hydrological response of two river basins. The effect of velocity on the Baghmati river basin at temporal scale shows that higher velocity causes significant increase in hydrograph peak and decrease in time to peak[5].

Influence of R_L on hydrological response is further analysed on the tributaries of the Baghmati river. The Baghmati river has two major tributaries, i.e. the Lalbakeya river and the Lakhandei river (Figure 1). Both of these tributaries originate in the same mountain range, i.e. Siwaliks and drain a comparable catchment area of 896 and 1061 km^2 respectively. However, the confluence of these rivers with the main Baghmati river is characterized by marked differences. The area around Lalbakeya–Baghmati confluence (Khoripakar) (Figure1) is not affected by flood, while the area around Lakhandei–Baghmati confluence (Katra) is severely affected by flood, with an inundation period of 2–3 months. It is suggested that this variation in hydrological response is due to differences in morphometric values of the sub-basins.

The Lalbakeya river is characterized by relatively lower length ratio ($R_L = 2.73$), while the Lakhandei river shows much higher length ratio (R_L) value of 9.29. Based on the GIUH analysis, it is interpreted that higher R_L value of the Lakhandei sub-basin is responsible for flooding around Katra, while reverse is the case for the Lalbakeya river sub-basin. Hence, the GIUH analysis will be helpful in finding the relative hydrologic response of the sub-basin, and these results can be used in flood-management planning.

Conventional flood-management programmes such as embankment construction have mainly concentrated on the main channel and have provided limited relief in most flood-prone areas across the country. The main emphasis should now shift to management of the upstream area, where run-off generation and distribution take place. Recently, the basin-scale approach towards flood management has been strongly advocated[17]. Geomorphic characteristics of a river basin play a key role in controlling the basin hydrology.

The present investigation highlights the importance of morphometric studies in flood analysis. Effect of the geomorphometric parameters on the GIUH suggests that the length of channel of maximum order (L_Ω) and length ratio (R_L) have maximum control on the hydrological response of a river basin. The results of this communication are based on a wide range of morphometric parameters (Table 3) covering all natural river systems, and therefore, the conceptual understanding of geomorphic control on flood hazard is applicable to other river basins as well. In general, the tributaries with smaller length of channel of maximum order (L_Ω) and higher length ratio (R_L) would be characterized by higher peak of hydrograph. The outlets of these tributaries would therefore be potential flood-prone areas in a river basin. It is strongly recommended that the upstream flood-control efforts should be concentrated in such regions to reduce flood hazard.

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Equatorial East Indian Ocean sea surface temperature: A new predictor for seasonal and annual rainfall

P. Rahul Chand Reddy and P. S. Salvekar*

Indian Institute of Tropical Meteorology, Pune 411 008, India

Here we examine the relationship of both the all India annual rainfall (AIAR) and the Indian southwest monsoon rainfall (ISWMR) with global sea ice sea surface temperature of the equatorial (EQ) East Indian Ocean along the grid 5S–5N, 85E–95E. A strong positive correlation (99%) exists between the April SST (sea surface temperature) in the region EQ–5N, 85E–95E and the AIAR, while a negative correlation (95%) exists between June SST in the region 5S–EQ, 85E–95E and the ISWMR. The SSTs in the grid could be used to predict the AIAR and the ISWMR prior to 8 and 3 months respectively.

THE Asian monsoon circulation influences most of the tropics and subtropics of the eastern hemisphere and more than 60% of the earth's population. Accurate long-lead prediction of monsoon rainfall can improve planning to mitigate the adverse impacts of monsoon variability and to take advantage of beneficial conditions[1]. The southwest (summer) and the northeast (winter) monsoons influence weather and climate between 30N and 30S over the African, Indian and Asian land masses[2]. As a first approximation, it can be said that the distribution of SST

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*For correspondence. (e-mail: pss@tropmet.res.in)