Journal of Hydrology 528 (2015) 463–489

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Effect of DEM source on equivalent Horton–Strahler ratio based GIUH for catchments in two Indian river basins

Sagar Rohidas Chavan, V.V. Srinivas *

Department of Civil Engineering, Indian Institute of Science, Bangalore 560 012, India

ARTICLE INFO

Article history:
Received 5 December 2014
Received in revised form 13 June 2015
Accepted 20 June 2015
Available online 29 June 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

Keywords:
Stream network
Horton–Strahler ratios
Self-similarity
Geomorphologic instantaneous unit hydrograph
Indian river basins

SUMMARY

Horton–Strahler (H–S) concept has been extensively used for quantification of characteristics of a stream network since several decades. The quantified values are often sensitive to threshold area specified for initiation of streams to demarcate the network, and to the position of outlet of a catchment. This implies that inferences drawn based on derived characteristics for a stream network are likely to be inconsistent, which is undesirable. To address this, a strategy based on self-similarity properties of channel network was proposed recently by Moussa (2009), which involves estimation of equivalent H–S ratios using catchment shape descriptors that are independent of threshold area. This study investigates effectiveness of the strategy on 42 catchments of various sizes in two Indian river basins (Cauvery and Mahanadi). Effect of digital elevation model (DEM) source on estimates of equivalent H–S ratios and characteristics of Geomorphologic Instantaneous Unit Hydrograph (GIUH) derived based on the same are examined by considering SRTM and ASTER DEMs. Results indicate that self-similarity assumptions are valid for the Indian catchments. Comparison of equivalent GIUH derived for each of the catchments based on real channel network with that derived using different DEM sources indicated differences that could be attributed to DEM-based uncertainty associated with estimates of: (i) equivalent H–S ratios that are functions of the self-similarity properties of channel network, and (ii) equivalent length of highest order stream that depends on self-similarity properties and configuration/characteristics of stream network. This uncertainty cannot be ignored in hydrological studies.

1. Introduction

Distributed hydrological models are often used to model runoff generation mechanism in catchments. They require information on local hillslope profiles and stream network, as hillslopes control production of storm water runoff that is transported through the stream network towards the catchment outlet. Conventional practice is to assimilate information related to stream networks through qualitative classification on the basis of (i) basic patterns such as dendritic, parallel, trellis, rectangular, radial, annular, multi-basinal, contorted, or (ii) modified basic patterns such as subdendritic, pinnate, anastomotic, distributary, subparallel, fault trellis and recurved trellis (Zernitz, 1932; Howard, 1967). However, quantitative analysis of natural stream networks in hydrological systems (catchments) is quintessential for modeling their response. In this perspective, a few attempts were made to quantify stream networks. Among those, Horton (1945) was probably the first work that suggested a procedure involving ordering of streams and laws relating the number and length of streams of various orders. Later Strahler (1952, 1957, 1964) suggested modification to Horton's stream ordering procedure for avoiding some ambiguities. The resulting procedure is widely referred to as Horton–Strahler (H–S) ordering scheme. Horton's laws when implemented on a stream network quantified using H–S ordering scheme are referred to as H–S laws. The laws include (i) 'bifurcation ratio' relating stream numbers corresponding to streams of consecutive orders, (ii) 'length ratio' relating lengths of streams of successive orders, (iii) 'area ratio' relating areas drained by streams of successive orders. The ratios find use in establishing relations with the fractal nature of the channel network (e.g., Beer and Borgas, 1993; La Barbera and Rosso, 1989; Tarboton, 1996) and in modeling hydrological response from catchments using geomorphological concepts (e.g., Rodríguez-Iturbe and Valdés, 1979; Gupta et al., 1980).

The concept of H–S laws has received some criticism (e.g., Scheidegger, 1965, 1968a,b; Moussa, 2009) owing to factors such as (i) inconsistency in classifying a river network into streams of various orders with change in scale of map and support/threshold area for initiation of first order streams and (ii) sensitivity to the

* Corresponding author. Tel.: +91 80 2293 2641.
E-mail addresses: vvs@civil.iisc.ernet.in, vvsrinivas@yahoo.com (V.V. Srinivas).

http://dx.doi.org/10.1016/j.jhydrol.2015.06.049
0022-1694/

position of outlet of catchment. The factor (i) implies that estimated H–S ratios (e.g., bifurcation ratio, area ratio and length ratio) and inferences drawn for a river network based on those ratios are conditional on support area, which is undesirable (Moussa and Bocquillon, 1996; Moussa, 2008a, 2009). To address this issue, researchers are devoting their efforts to arrive at effective strategies that alleviate the effect of support area on H–S ratios. Moussa and Bocquillon (1996) studied effect of threshold area on morphometric and scaling properties of channel network in three catchments (having areas in the range 75–16,250 km^2) located in southern France, and developed a strategy based on self-similarity properties of channel network to define new catchment shape descriptors that are independent of threshold area. Those descriptors were subsequently used by Moussa (2009) to develop formulations for equivalent Horton–Strahler (H–S) ratios and GIUH that are independent of the threshold/support area chosen for extraction of stream network. Effectiveness of the equivalent H–S ratios and GIUH was demonstrated by Moussa (2009) through application to seven catchments in France whose areas ranged from 738 km^2 to 5346 km^2. There is dearth of further attempts to examine potential of the strategy elsewhere in the world. Further, there is a need to examine: (i) potential of the strategy on catchments of relatively larger size, and (ii) sensitivity of estimates of equivalent H–S ratios to source of DEM. In this perspective, investigations are carried out in this study on a large number of catchments having much wider range in their areas located in Cauvery and Mahanadi river basins, India, with the following two objectives: (1) to test methodology of Moussa (2009) on the catchments, and consequently to verify whether hypothesis of "self-similarity" is valid for channel networks in those catchments, and (2) if the hypothesis of "self-similarity" is valid, then compare (i) morphometric properties of the channel networks, and (ii) equivalent H–S ratios and equivalent GIUHs for the catchments obtained corresponding to two different DEMs (ASTER and SRTM). The developed equivalent GIUHs could prove useful to derive unit hydrographs corresponding to desired durations for target sparsely gauged/ungauged locations in the Cauvery and Mahanadi river basins. The derived unit hydrographs could be used to simulate design flood events at the target locations that find use in hydrological design and risk assessment of water resources systems (e.g., Jain et al., 2000).

The subsequent part of this paper is structured as follows. First, background information is provided on H–S laws, their scaling properties, procedure for assessment of self-similarity properties of a channel network, and estimation of equivalent H–S ratios. Following this, case study on catchments in Cauvery and Mahanadi river basins is presented. GIUHs constructed based on the conventional H–S ratios and equivalent GIUHs determined based on derived equivalent H–S ratios are compared for each of the catchments. Finally conclusions drawn based on the investigations are provided.

2. Background on Horton–Strahler laws

Horton–Strahler (HS) ordering scheme considers first-order stream as smallest channel that originates at source point of a stream. The confluence of two streams of a particular order (say w) results in a stream of subsequent order ($w+1$) downstream, while the confluence of two streams of different orders results in a stream whose order is equal to that of the highest order stream. The order of catchment Ω is considered to be the order of the stream draining its outlet. The expressions for H–S laws, namely, law of stream numbers, law of stream lengths, and law of stream areas are given by Eqs. (1)–(3) respectively. Of those, Eq. (3) that is analogous to Eq. (2) was proposed by Schumm (1956).

$$\frac{N_{w-1}}{N_w} = R_b \quad w = 1, \ldots, \Omega \tag{1}$$

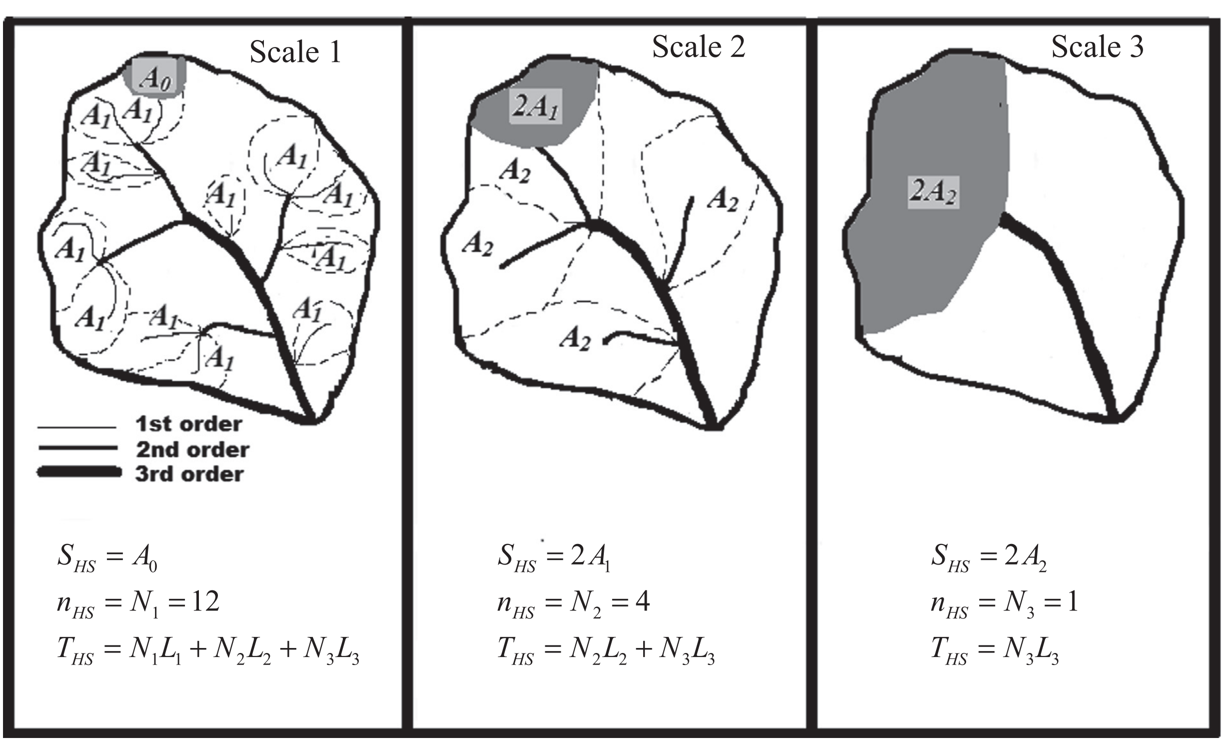

Fig. 1. Stream network demarcated in a catchment corresponding to three different Horton-Strahler scales of observation defined in terms of threshold area S_{HS} (in km^2). Analogous figure can be found in Moussa (2009, Fig. 11). n_{HS} (dimensionless value) denotes number of sources, and T_{HS} is total length of channel network (in km).

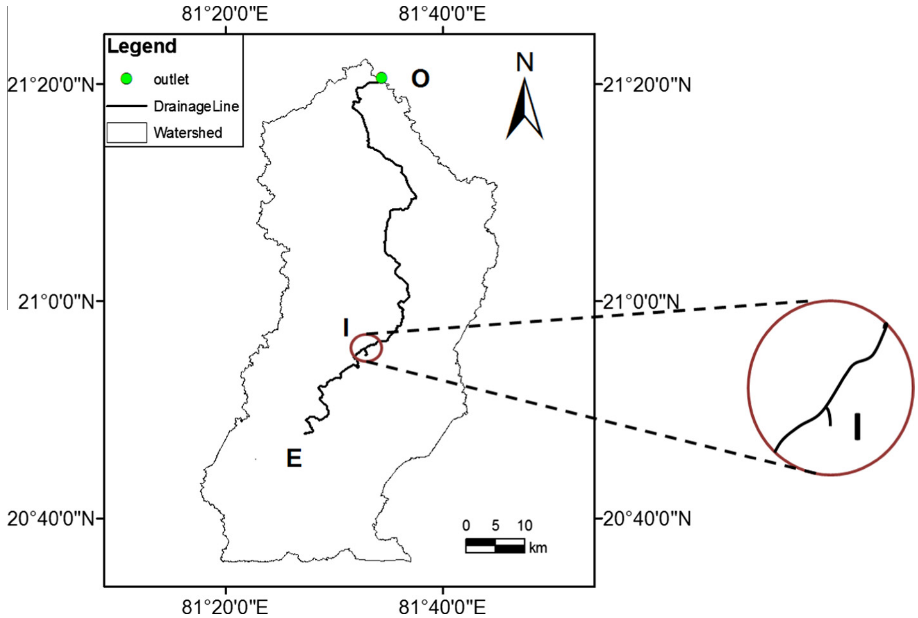

Fig. 2. A typical channel network for the case where threshold area S is equal to S_A (in km^2). First bifurcation node begins at point 'I', O is outlet for the catchment, and OE is total length of the channel network (in km). The inset figure shows magnified view of first bifurcation node.

$$\frac{L_w}{L_{w-1}} = R_l \quad w = 1, \ldots, \Omega \tag{2}$$

$$\frac{A_w}{A_{w-1}} = R_a \quad w = 1, \ldots, \Omega \tag{3}$$

where N_w (dimensionless value) denotes the number of streams of order w whose mean length is L_w (in km), and A_w (in km^2) is the mean area contributing flow to stream of order w. R_b, R_l and R_a are dimensionless ratios that are computed from slopes of the lines in plots corresponding to 'N_w versus w', 'L_w versus w', and 'A_w versus w', respectively. The plots are prepared on a semi-log paper with w on a linear scale. Parameters N^* (dimensionless value), L^* (in km), and A^* (in km^2) of a channel network are computed as,

$$N_w = N^* \times R_b^{\Omega-w} \tag{4}$$

$$L_w = L^* \times \left(\frac{1}{R_l}\right)^{\Omega-w} \tag{5}$$

$$A_w = A^* \times \left(\frac{1}{R_a}\right)^{\Omega-w} \tag{6}$$

Estimates of H–S ratios corresponding to a channel network are, in general, conditional on support/threshold area for initiation of first order streams. For an ideal Hortonian channel network (for which H–S laws are perfectly valid), $N^* = 1$, $L^* = L_\Omega$ and $A^* = S_0$, where L_Ω (in km) and S_0 (in km^2) denote the length of highest order stream and the total area of the catchment respectively.

3. Scaling properties of Horton–Strahler laws

A stream network can be demarcated in a catchment corresponding to various discrete Horton–Strahler (H–S) scales of observation that are defined in terms of threshold area S_{HS} (in km^2) considered for extraction of channel network from a DEM (Moussa, 2009). A typical example of stream network that could be demarcated in a catchment corresponding to three different Horton–Strahler scales of observation (defined in terms of threshold areas A_0, $2A_1$ and $2A_2$) are shown in Fig. 1, wherein A_0, A_1 and A_2 represent respectively area (in km^2) contributing flow to zeroth, first and second order stream defined using H–S scheme. From Fig. 1, the following equations can be derived for S_{HS}, and the corresponding number of sources n_{HS} (dimensionless value) and total length of channel network T_{HS} (in km).

$$\left.\begin{array}{l} \text{For scale} = 1, w = \text{scale} - 1 = 0, S_{HS} = A_w \\ \text{For } 2 \leqslant \text{scale} \leqslant \Omega, w = \text{scale} - 1, S_{HS} = 2A_w = 2A^* \times \left(\frac{1}{R_a}\right)^{\Omega-w} \end{array}\right\} \tag{7}$$

$$n_{HS} = N_{w+1} \quad \text{for } 1 \leqslant \text{scale} \leqslant \Omega \tag{8}$$

$$T_{HS} = \sum_{k=w+1}^{\Omega} N_k L_k \quad \text{for } 1 \leqslant \text{scale} \leqslant \Omega \tag{9}$$

Moussa (2009) showed that Eqs. (8) and (9) can be expressed as function of S_{HS} and H–S ratios based on Eqs. (4)–(6), as follows

$$n_{HS} = \frac{N^*}{R_b} \times \left(\frac{1}{2}\right)^{\frac{-\log(R_b)}{\log(R_a)}} \times \left(\frac{S_{HS}}{A^*}\right)^{\frac{-\log(R_b)}{\log(R_a)}} \tag{10}$$

$$\begin{aligned} T_{HS} &= N^* \times L^* \times \left[1 - \left(\frac{R_b}{R_l}\right)^{\Omega}\right] \Big/ \left[1 - \left(\frac{R_b}{R_l}\right)\right] \quad \text{for scale} = 1 \\ &= \frac{N^* \times L^*}{1 - \frac{R_b}{R_l}} \left[1 - \left(\frac{1}{2}\right)^{\frac{\log(R_l) - \log(R_b)}{\log(R_a)}} \times \left(\frac{S_{HS}}{A^*}\right)^{\frac{\log(R_l) - \log(R_b)}{\log(R_a)}}\right] \\ &\quad \text{for } 2 \leqslant \text{scale} \leqslant \Omega \end{aligned} \tag{11}$$

The foregoing equations provide quantitative description of a drainage basin in terms of six parameters: R_b, R_l, R_a, N^*, L^* and A^*.

4. Self-Similarity properties of channel network

Moussa and Bocquillon (1996) derived the following formulations for the number of sources n (dimensionless value) and total length of the channel network T (in km) based on the assumption of self-similarity/fractality/homogeneity.

$$n = \psi(S/S_0) \text{ and } T/\sqrt{S_0} = \phi(S/S_0) \tag{12}$$

where $\psi(\cdot)$ and $\phi(\cdot)$ denote functions of threshold area for channel initiation S (in km^2) and area of the catchment S_0 (in km^2). Assuming that n and T are continuous functions of S/S_0, Moussa (2008a, 2009) derived the following expressions.

$$n = \lambda(S/S_0)^{-\alpha} \tag{13}$$

$$T = (OE + \beta \times \sqrt{S_0})\left(\frac{S}{S_A}\right)^{-\alpha+\frac{1}{2}} - \beta \times \sqrt{S_0} \tag{14}$$

where λ is dimensionless parameter, α is scaling exponent (dimensionless value), OE (in km) is equal to T corresponding to the case where $S = S_A$ which is the threshold area (in km^2) for which the first bifurcation node just begins (which is shown as point 'I' in Fig. 2). Rearranging the terms in Eq. (14), expression for constant β (dimensionless value), which denotes 'channel network shape index', can be formulated as,

$$\beta = \frac{T - OE\left(\frac{S}{S_A}\right)^{\left(-\alpha+\frac{1}{2}\right)}}{\left[\left(\frac{S}{S_A}\right)^{\left(-\alpha+\frac{1}{2}\right)} - 1\right]\sqrt{S_0}} \tag{15}$$

If the hypothesis of homogeneity/self-similarity is valid, then β must be a constant across various scales ($0 \leqslant S \leqslant S_A$).

The foregoing equations provide quantitative description of a drainage basin in terms of five parameters: λ, α, β, OE and S_A. Finer details concerning estimation of the parameters are provided while discussing case study in the subsequent part of this paper.

5. Equivalent Horton–Strahler ratios

Comparison of Eqs. (10) and (13) corresponding to the number of sources and comparison of Eqs. (11) and (14) corresponding to the total length of channel network leads to the following expressions for equivalent H–S ratios.

$$R_{be} = \frac{2^{\alpha}}{\lambda} \tag{16}$$

$$R_{ae} = \left(\frac{2^{\alpha}}{\lambda}\right)^{\frac{1}{\alpha}} \tag{17}$$

$$R_{le} = \left(\frac{2^{\alpha}}{\lambda}\right)^{\frac{1}{2\alpha}} \tag{18}$$

where R_{ae}, R_{be} and R_{le} are dimensionless values that are equivalent to conventional H–S ratios R_a, R_b and R_l respectively.

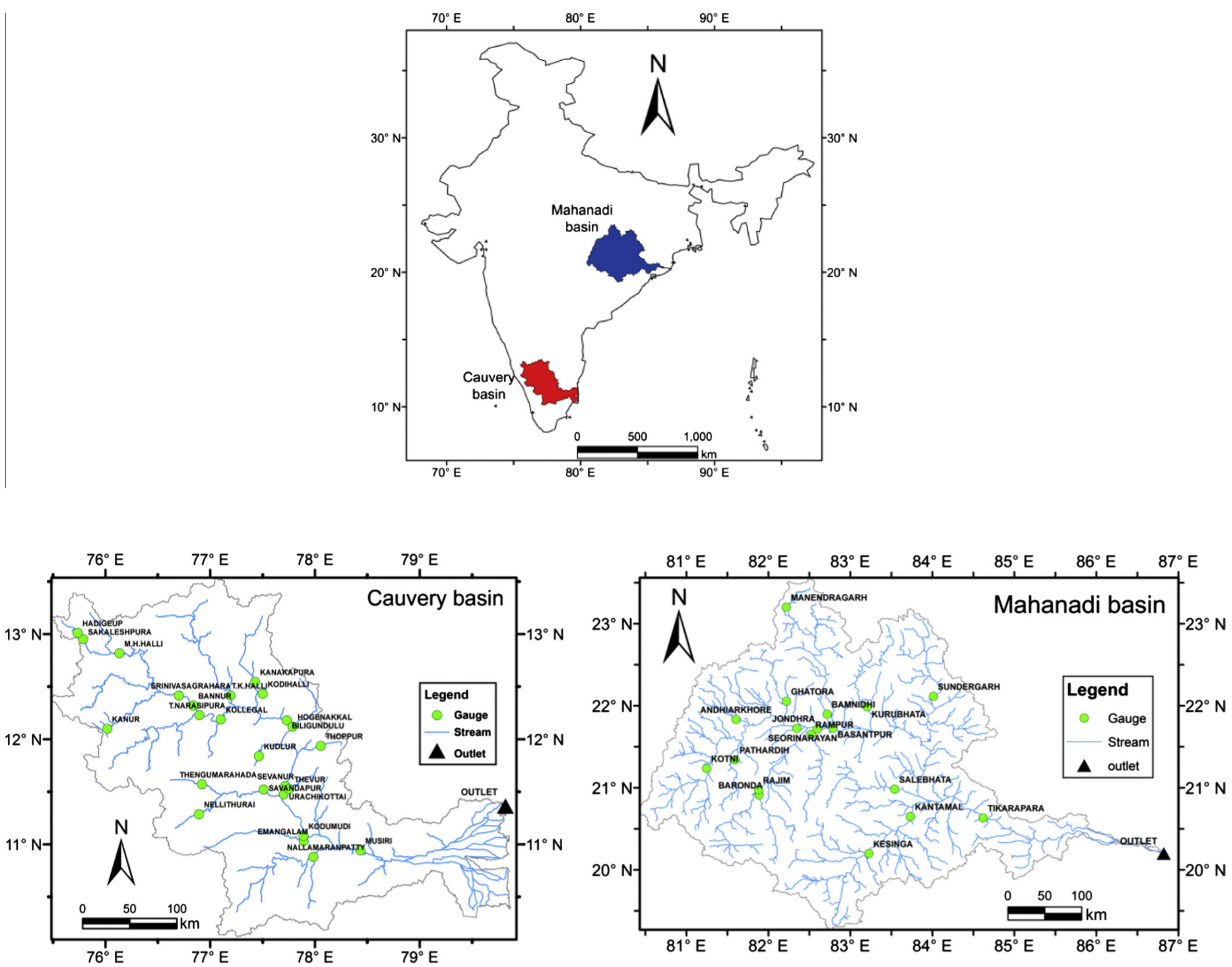

Fig. 3. Location of Mahanadi and Cauvery river basins and stream gauges considered for the study.

6. Case study

6.1. Description of the investigated catchments and data

Catchments corresponding to 24 gauges in Cauvery river basin and 18 gauges in Mahanadi river basin have been considered to (i) verify hypothesis of "self-similarity" for their channel networks, and (ii) if the hypothesis of "self-similarity" is valid, then investigate the effect of DEM source on equivalent H–S ratios and the corresponding equivalent GIUH constructed for each of the catchments. The 42 gauges are part of the network of Central Water Commission (CWC), India, and their locations are shown in Fig. 3. Information pertaining to observed streamflows, stage-discharge relationships, and peak water level (stage) was collated for the gauge locations. Cauvery river basin drains about 81,155 km^2 area spread over three states (Karnataka, Tamil Nadu and Kerala) and Puducherry Union Territory. The basin is bounded in the West by Western Ghats of southern Indian peninsula, and by Nilgiri hills in the South that extend eastwards to the Eastern Ghats. On the other hand, catchment area of Mahanadi river basin is about 1,45,818 km^2 extending over five States viz. Chhattisgarh, Orissa, Madhya Pradesh, Jharkhand and Maharashtra, of which more than 99% is in Chhattisgarh and Orissa. The basin is bounded in the North by hills in Central India, in the South and East by the Eastern Ghats and in the West by Maikala hill range.

Catchment corresponding to each of the 42 gauges was delineated using ArcHYDRO tools in ArcGIS framework by processing ASTER DEM data having 30 m grid resolution and SRTM DEM data having 90 m resolution. The data corresponding to the former DEM were extracted from the web site: http://reverb.echo.nasa.gov, while those of the latter DEM were extracted from the web site: http://srtm.csi.cgiar.org/. Error in estimate of catchment area based on each DEM was quantified in terms of relative bias (R-bias) with reference to estimate of catchment area based on topographical survey that was available from CWC (2012). In general, the R-bias values (presented in Table 1) indicate that (i) DEM based estimates are marginally deviated with respect to CWC estimates for most catchments, (ii) difference in estimates based on SRTM and ASTER DEMs is marginal for most catchments, and (iii) neither of the DEMs is consistent in yielding least bias over all the catchments. The latter point can be appreciated by noting that the error is significant in the case of both the DEMs for Sevanur catchment in

Table 1
Effect of DEM source and resolution on area of delineated catchment. NA indicates that estimate of catchment area based on topographical survey is not available in the reference (CWC, 2012).

S.No.	Catchment of gauge	Catchment area (km^2)			R-bias (%)	
		SRTM (90 m)	ASTER (30 m)	CWC estimate	SRTM (90 m)	ASTER (30 m)
a. Results for catchments in Cauvery river basin						
1	Kodihalli	160.99	156.11	NA	–	–
2	Sevanur	304.02	354.53	258	17.84	37.41
3	Thoppur	329.31	328.24	362	−9.03	−9.33
4	Hadigeup	419.76	416.41	NA	–	–
5	Srinivasagraham	478.33	470.38	NA	–	–
6	Sakleshpur	589.68	580.68	617	−4.43	−5.89
7	Kudlur	720.69	711.51	709	1.65	0.35
8	Thevur	1184.27	1196.22	1248	−5.11	−4.15
9	Thengumarahada	1362.40	1351.06	1370	−0.555	−1.38
10	Nellithurai	1483.68	1467.72	1475	0.59	−0.49
11	Hogenakkal	1558.09	1544.86	1636	−4.76	−5.57
12	M. H. Halli	3006.04	2950.41	3050	−1.44	−3.27
13	Kanakpura	3294.76	3280.14	3425	−3.80	−4.23
14	Elubthimangalam	3458.92	3471.11	3386	2.15	2.51
15	Savandapur	5594.85	5519.41	5776	−3.14	−4.44
16	T. Narasipur	7053.81	7025.72	7000	0.77	0.37
17	T. K. Halli	8093.65	8055.77	7890	2.58	2.10
18	Nallamaranpatty	8660.23	8622.74	9080	−4.62	−5.04
19	Bannur	12075.8	10755.51	NA	–	–
20	Kollegal	21730.05	18481.91	21082	3.07	−12.33
21	Billigundulu	37450.44	36016.11	36682	2.09	−1.82
22	Urachikottai	44811.73	43526.04	44100	1.61	−1.30
23	Kodumudi	52673	51258.56	53233	−1.05	−3.71
24	Musiri	69267.4	68110.52	66243	4.57	2.82
b. Results for catchments in Mahanadi river basin						
1	Manendragarh	1017.17	1016.18	1100	−7.53	−7.62
2	Andhiarkhore	2133.38	2179.60	2210	−3.47	−1.38
3	Patherdih	2494.70	2481.91	2511	−0.65	−1.16
4	Ghatora	2935.10	3076.332	3035	−3.29	1.36
5	Baronda	3213.44	3205.76	3225	−0.36	−0.60
6	Rampur	3436.02	3433.51	2920	17.67	17.59
7	Salebhata	4632.10	4574.69	4650	−0.38	−1.62
8	Kurubhata	4763.69	4822.36	4625	3.00	4.27
9	Sundergarh	6061.67	5974.34	5870	3.27	1.78
10	Kotni	7063.33	7050.28	6990	1.05	0.86
11	Rajim	8494.70	8419.36	8760	−3.03	−3.89
12	Bamnidhi	9878.19	9869.70	9730	1.52	1.44
13	Kesinga	12004.34	11929.62	11960	0.37	−0.25
14	Kantamal	20237.98	20535.30	19600	3.25	4.77
15	Jondhra	29901.00	33086.59	29645	0.86	11.61
16	Seorinarayan	48265.56	47754.02	48050	0.45	−0.62
17	Basantpur	58647.15	58750.02	57780	1.50	1.68
18	Tikarapara	127415.20	127118.8	124450	2.38	2.14

Table 2
Effect of support/threshold area specified for initiation of stream network on characteristics of the network. Values in parentheses correspond to 90 m resolution SRTM DEM, while those without parentheses refer to 30 m resolution ASTER DEM. Ω, n, R_a, R_b, R_l and N^* are dimensionless.

Sl. No.	S (km^2)	$\frac{S}{S_0}$ ($\times 10^{-3}$)	Ω	L_Ω (km)	n	T (km)	R_a	R_b	R_l	N^*	L^* (km)	A^* (km^2)
a. Result for catchment of gauge at Patherdih in Mahanadi basin												
1	23.00	9.24	3	95.10	29	427.00	6.68	5.39	3.49	1.19	71.69	1963.57
		(9.19)	(3)	(96.27)	(30)	(407.34)	(6.74)	(5.48)	(3.51)	(1.09)	(71.01)	(2017.82)
2	22.50	9.07	3	95.10	29	432.00	6.68	5.39	3.45	1.19	71.44	1963.57
		(9.02)	(3)	(96.27)	(30)	(409.74)	(6.74)	(5.48)	(3.49)	(1.09)	(70.88)	(2017.82)
3	18.00	7.25	3	95.10	40	495.00	7.86	6.32	3.87	1.20	77.61	2017.25
		(7.22)	(3)	(96.27)	(37)	(454.42)	(7.75)	(6.08)	(3.85)	(1.18)	(75.04)	(2013.98)
4	13.50	5.44	4	50.73	49	556.00	4.29	3.84	2.02	0.78	51.51	2798.39
		(5.41)	(4)	(45.59)	(48)	(526.54)	(4.28)	(3.79)	(2.00)	(0.77)	(49.37)	(2812.67)
5	9.00	3.63	4	53.19	74	694.00	4.85	4.18	2.15	0.97	50.44	2373.68
		(3.61)	(4)	(45.59)	(67)	(629.02)	(4.79)	(4.12)	(2.07)	(0.87)	(48.34)	(2635.86)
6	8.10	3.26	4	53.19	83	733.00	4.96	4.32	2.16	0.95	50.52	2408.41
		(3.25)	(4)	(61.01)	(80)	(659.01)	(4.90)	(4.28)	(2.27)	(0.96)	(50.63)	(2315.79)
7	7.20	2.90	4	53.19	92	774.00	5.05	4.46	2.15	0.93	50.57	2438.81
		(2.89)	(4)	(61.01)	(90)	(698.01)	(5.18)	(4.51)	(2.40)	(0.95)	(55.54)	(2323.39)
8	6.30	2.54	4	83.57	105	833.00	5.03	4.51	2.42	1.08	57.21	1896.23
		(2.53)	(4)	(88.15)	(108)	(750.09)	(5.38)	(4.75)	(2.74)	(1.02)	(63.95)	(1996.18)
9	5.40	2.18	4	83.57	126	895.00	5.39	4.74	2.63	1.19	61.67	1789.37
		(2.16)	(4)	(96.27)	(125)	(819.75)	(5.59)	(4.91)	(2.81)	(1.08)	(65.19)	(1856.09)
10	4.50	1.81	4	95.10	152	988.00	5.77	5.02	2.82	1.29	64.77	1721.09
		(1.80)	(4)	(96.27)	(142)	(892.83)	(5.82)	(5.01)	(2.85)	(1.19)	(64.37)	(1789.29)
11	3.60	1.45	5	50.73	198	1110.00	3.72	3.92	2.03	0.75	51.51	2442.39
		(1.44)	(4)	(96.27)	(176)	(991.87)	(6.35)	(5.42)	(3.03)	(1.23)	(67.96)	(1796.03)
12	2.70	1.09	5	50.73	270	1295.00	4.30	4.27	2.11	0.72	54.71	2929.65
		(1.08)	(5)	(45.59)	(240)	(1136.98)	(4.46)	(3.98)	(2.04)	(0.87)	(44.62)	(2577.94)
13	1.80	0.73	5	53.19	385	1570.00	4.49	4.45	2.21	0.93	52.65	2297.85
		(0.72)	(5)	(88.15)	(366)	(1369.28)	(4.67)	(4.38)	(2.26)	(0.93)	(47.88)	(1980.06)
14	0.90	0.36	5	95.10	756	2172.00	4.99	5.00	2.73	1.46	61.75	1438.83
		(0.36)	(5)	(96.27)	(746)	(1924.78)	(5.59)	(5.02)	(2.73)	(1.32)	(59.61)	(1584.17)
b. Result for catchment of gauge at Basantpur in Mahanadi basin												
1	551.2	9.27	3	184.28	32	2264.00	6.71	5.66	2.17	1.07	205.29	55455.31
		(9.40)	(4)	(38.86)	(32)	(2201.47)	(3.56)	(3.25)	(1.05)	(0.81)	(67.19)	(66180.74)
2	495	8.32	4	10.32	35	2396.00	3.87	3.34	0.73	0.80	30.89	78592.42
		(8.44)	(4)	(38.86)	(37)	(2352.73)	(3.75)	(3.30)	(1.12)	(0.94)	(69.13)	(61303.26)
3	450	7.56	4	10.32	38	2537.00	3.92	3.42	0.72	0.78	30.76	79283.23
		(7.67)	(4)	(38.86)	(39)	(2491.24)	(3.80)	(3.35)	(1.10)	(0.93)	(68.60)	(61807.37)
4	405	6.81	4	10.32	40	2644.00	4.02	3.52	0.73	0.79	30.85	80080.78
		(6.91)	(4)	(38.86)	(42)	(2601.98)	(3.93)	(3.49)	(1.12)	(0.93)	(68.89)	(62451.48)
5	360	6.05	4	10.32	46	2813.00	4.20	3.70	0.75	0.77	31.73	80984.34
		(6.14)	(4)	(38.86)	(45)	(2732.00)	(3.99)	(3.57)	(1.12)	(0.92)	(68.80)	(63080.36)
6	315	5.30	4	10.32	49	2982.00	4.31	3.81	0.75	0.77	31.40	81298.27
		(5.37)	(4)	(38.86)	(52)	(2909.40)	(4.28)	(3.79)	(1.19)	(0.91)	(73.55)	(63629.93)
7	270	4.54	4	45.12	60	3246.00	4.56	4.01	1.25	0.90	83.60	67554.23
		(4.60)	(4)	(38.86)	(60)	(3155.23)	(4.53)	(4.01)	(1.21)	(0.90)	(75.47)	(65117.29)
8	225	3.78	4	45.12	70	3537.00	4.95	4.28	1.33	0.89	91.99	68159.44
		(3.84)	(4)	(38.86)	(72)	(3417.99)	(4.96)	(4.32)	(1.29)	(0.88)	(82.82)	(66420.80)
9	180	3.03	4	184.28	86	3965.00	4.98	4.39	1.99	1.06	200.62	51670.82
		(3.07)	(4)	(38.86)	(89)	(3820.50)	(5.27)	(4.62)	(1.31)	(0.85)	(84.82)	(68705.60)
10	135	2.27	4	184.28	116	4479.00	5.62	4.82	2.17	1.10	217.36	51670.36
		(2.30)	(4)	(254.85)	(117)	(4388.13)	(5.45)	(4.74)	(2.30)	(1.16)	(236.96)	(45302.33)
11	90	1.51	5	10.32	167	5371.00	4.29	3.74	1.09	0.74	48.53	82817.78
		(1.53)	(5)	(38.86)	(174)	(5344.47)	(4.15)	(3.66)	(1.42)	(0.89)	(92.87)	(63261.65)
12	72	1.21	5	10.32	209	5936.00	4.58	3.99	1.12	0.73	48.81	84878.55
		(1.23)	(5)	(38.86)	(209)	(5865.42)	(4.37)	(3.86)	(1.45)	(0.89)	(92.79)	(64446.83)
13	54	0.91	5	184.28	286	6832.00	4.57	4.13	2.06	0.99	223.83	51489.38
		(0.92)	(5)	(38.86)	(290)	(6714.06)	(4.86)	(4.26)	(1.57)	(0.86)	(106.17)	(65817.51)
14	36	0.61	5	184.28	442	8334.00	5.15	4.58	2.21	1.06	233.25	50211.17
		(0.61)	(5)	(182.07)	(445)	(8165.12)	(5.03)	(4.43)	(2.12)	(1.21)	(194.70)	(45001.08)
15	18	0.30	6	10.32	884	11700.00	4.54	4.08	1.37	0.67	65.68	86519.62
		(0.31)	(6)	(38.86)	(864)	(11290.19)	(4.33)	(3.90)	(1.62)	(0.88)	(105.27)	(63394.53)
16	9	0.15	6	184.28	1746	16451.00	4.76	4.39	2.16	1.06	232.14	46712.98
		(0.15)	(6)	(140.45)	(1712)	(15739.13)	(4.82)	(4.39)	(2.07)	(1.07)	(194.62)	(48257.54)
17	8.1	0.14	6	184.28	1933	17289.00	4.87	4.49	2.18	1.07	233.91	47325.98
		(0.14)	(6)	(140.45)	(1898)	(16522.38)	(4.89)	(4.42)	(2.07)	(1.16)	(185.05)	(45938.59)
18	7.2	0.12	7	10.32	2161	18246.00	4.06	3.71	1.43	0.65	73.32	87021.89
		(0.12)	(7)	(6.09)	(2125)	(17434.35)	(4.03)	(3.69)	(1.35)	(0.67)	(55.00)	(80827.79)
19	6.3	0.11	7	10.32	2438	19394.00	4.13	3.79	1.46	0.66	75.20	83964.92
		(0.11)	(7)	(6.09)	(2432)	(18518.99)	(4.13)	(3.78)	(1.37)	(0.65)	(56.54)	(82802.38)
20	5.4	0.09	7	10.32	2872	20900.00	4.10	3.90	1.48	0.68	74.08	77645.49
		(0.09)	(7)	(38.86)	(2848)	(19950.77)	(4.09)	(3.74)	(1.66)	(0.83)	(113.16)	(64079.61)

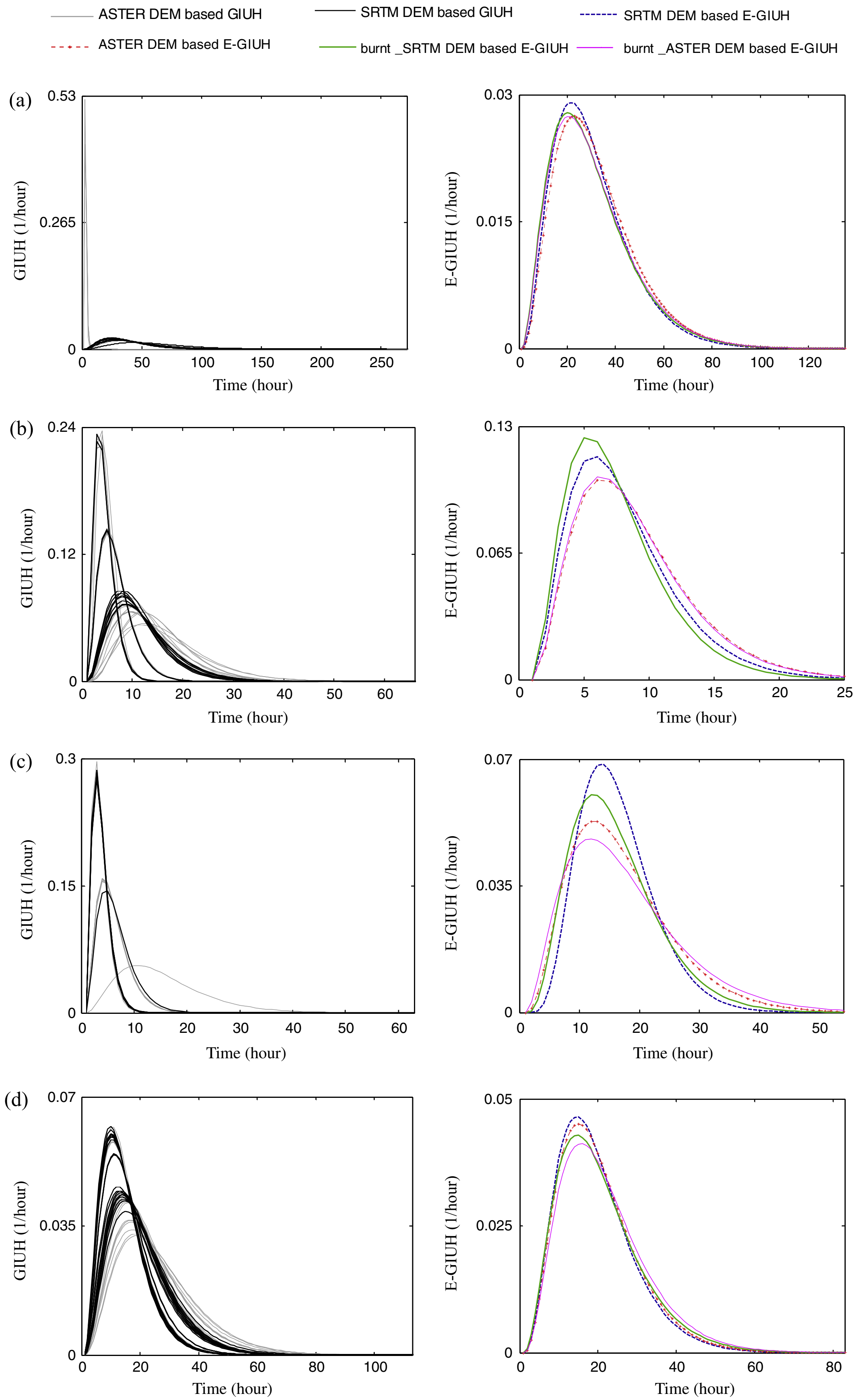

Fig. 4. GIUHs and E-GIUHs constructed for stream networks demarcated using 90 m resolution original and burnt SRTM DEM, and 30 m resolution original and burnt ASTER DEM for (a) Emangalam, and (b) Thevur catchments in Cauvery basin, and for (c) Andhiarkhore, and (d) Kantamal catchments in Mahanadi basin.

Table 3
Morphometric descriptors of stream networks in catchments of Cauvery basin derived based on 90m resolution original and burnt SRTM DEMs, and 30 m resolution original and burnt ASTER DEMs. $\lambda, \alpha, \bar{\beta}, \sigma_\beta, R_n^2, R_T^2$ are dimensionless.

S. No.	Catchment of gauge	S_0 (km^2)	S_A (km^2)	OE (km)	OI (km)	λ	α	$\bar{\beta}$	σ_β	R_n^2	R_T^2
1	Kodihalli	160.99[a]	48.38	6.29	5.38	0.55	0.86	2.32	0.07	0.989	0.999
		(158.74)[b]	(48.11)	(7.52)	(5.38)	(0.55)	(0.86)	(2.17)	(0.08)	(0.990)	(0.999)
		[158.45][c]	[47.92]	[6.82]	[5.76]	[0.30]	[0.98]	[1.22]	[0.04]	[0.978]	[0.996]
		{156.11}[d]	{48.06}	{6.98}	{5.33}	{0.30}	{0.98}	{1.18}	{0.05}	{0.979}	{0.996}
2	Sevanur	304.02	86.76	19.28	11.42	0.18	1.07	0.03	0.06	0.985	0.997
		(260.03)	(51.59)	(18.38)	(7.27)	(0.19)	(1.04)	(0.56)	(0.17)	(0.982)	(0.996)
		[260.19]	[71.61]	[10.89]	[7.38]	[0.12]	[1.13]	[0.43]	[0.18]	[0.986]	[0.988]
		{354.53}	{81.58}	{19.42}	{9.87}	{0.17}	{1.08}	{0.36}	{0.13}	{0.997}	{0.998}
3	Thoppur	329.31	51.56	25.99	20.94	0.28	0.98	0.74	0.10	0.997	0.997
		(333.93)	(51.56)	(25.51)	(20.46)	(0.40)	(0.93)	(1.45)	(0.08)	(0.995)	(0.997)
		[339.76]	[47.64]	[28.72]	[23.12]	[0.30]	[0.98]	[0.98]	[0.08]	[0.990]	[0.995]
		{328.24}	{47.64}	{29.20}	{23.56}	{0.23}	{1.04}	{0.38}	{0.09}	{0.989}	{0.995}
4	Hadigeup	419.76	76.91	20.25	5.63	0.28	0.99	0.89	0.05	0.996	0.997
		(423.79)	(74.43)	(21.88)	(5.99)	(0.27)	(0.99)	(0.81)	(0.05)	(0.996)	(0.997)
		[422.45]	[76.11]	[21.14]	[6.23]	[0.35]	[0.96]	[1.14]	[0.04]	[0.992]	[0.996]
		{416.41}	{76.29}	{20.09}	{5.21}	{0.32}	{0.98}	{1.06}	{0.04}	{0.994}	{0.997}
5	Srinivas-Agraham	478.33	127.43	31.38	4.53	0.24	1.02	-0.12	0.01	0.990	0.999
		(484.73)	(132.51)	(28.28)	(4.64)	(0.29)	(0.97)	(0.38)	(0.01)	(0.999)	(1.000)
		[490.49]	[131.01]	[28.40]	[4.80]	[0.33]	[0.96]	[0.57]	[0.01]	[0.996]	[0.999]
		{470.38}	{125.61}	{33.31}	{5.69}	{0.21}	{1.06}	{-0.32}	{0.02}	{0.991}	{0.999}
6	Sakleshpur	589.68	76.91	31.14	16.46	0.30	0.98	1.12	0.08	0.992	0.997
		(595.07)	(74.43)	(32.69)	(16.05)	(0.29)	(0.99)	(1.00)	(0.07)	(0.993)	(0.997)
		[594.17]	[76.26]	[31.70]	[16.73]	[0.34]	[0.97]	[1.26]	[0.05]	[0.992]	[0.996]
		{580.68}	{76.30}	{30.59}	{16.06}	{0.30}	{0.99}	{1.10}	{0.07}	{0.994}	{0.997}
7	Kudlur	720.69	248.97	20.42	0.64	0.30	0.97	0.77	0.11	0.998	0.999
		(720.59)	(253.37)	(18.77)	(0.50)	(0.30)	(0.97)	(0.83)	(0.11)	(0.998)	(0.999)
		[720.83]	[249.85]	[21.20]	[0.48]	[0.26]	[1.00]	[0.61]	[0.11]	[0.998]	[0.999]
		{711.51}	{247.80}	{21.99}	{1.31}	{0.26}	{1.00}	{0.56}	{0.11}	{0.999}	{0.999}
8	Thevur	1184.27	133.88	67.18	52.24	0.62	0.86	2.85	0.16	0.994	0.996
		(1183.54)	(177.48)	(61.72)	(26.74)	(0.74)	(0.84)	(3.02)	(0.30)	(0.991)	(0.992)
		[1203.74]	[124.81]	[71.62]	[57.58]	[0.51]	[0.90]	[2.56]	[0.10]	[0.989]	[0.998]
		{1196.22}	{125.07}	{71.35}	{57.32}	{0.47}	{0.91}	{2.36}	{0.14}	{0.991}	{0.999}
9	Thengu-Marahada	1362.40	240.31	48.05	21.65	0.34	0.94	1.36	0.14	0.992	0.998
		(1362.52)	(237.78)	(48.56)	(23.62)	(0.52)	(0.88)	(2.51)	(0.10)	(0.991)	(0.996)
		[1359.71]	[239.15]	[49.87]	[24.27]	[0.48]	[0.90]	[2.34]	[0.13]	[0.986]	[0.998]
		{1351.06}	{240.38}	{52.71}	{25.48}	{0.31}	{0.96}	{1.05}	{0.14}	{0.992}	{0.999}
10	Nellithurai	1483.68	354.35	34.86	30.48	0.32	0.97	1.07	0.06	0.997	1.000
		(1493.65)	(353.55)	(28.06)	(27.93)	(0.52)	(0.90)	(2.33)	(0.02)	(0.998)	(0.999)
		[1475.75]	[351.97]	[28.59]	[28.34]	[0.52]	[0.91]	[2.24]	[0.06]	[0.998]	[0.998]
		{1467.72}	{306.96}	{34.82}	{17.52}	{0.30}	{0.96}	{1.02}	{0.02}	{0.995}	{0.999}
11	Hogenakkal	1558.09	119.68	101.15	10.02	0.38	0.94	0.95	0.04	0.998	1.000
		(1557.96)	(179.57)	(91.69)	(17.29)	(0.39)	(0.94)	(0.85)	(0.07)	(0.997)	(1.000)
		[1567.87]	[193.04]	[91.32]	[51.16]	[0.24]	[1.02]	[-0.29]	[0.03]	[0.996]	[1.000]
		{1544.86}	{117.96}	{105.17}	{10.65}	{0.24}	{1.02}	{0.08}	{0.07}	{0.997}	{1.000}
12	M. H. Halli	3006.04	1379.96	19.08	9.85	0.29	0.99	0.93	0.06	0.997	0.999
		(3030.56)	(1274.11)	(24.99)	(8.45)	(0.50)	(0.91)	(1.74)	(0.05)	(0.996)	(0.996)
		[3035.20]	[1328.52]	[25.91]	[8.82]	[0.44]	[0.93]	[1.45]	[0.04]	[0.997]	[0.998]
		{2950.41}	{1351.89}	{20.74}	{9.21}	{0.30}	{0.99}	{0.92}	{0.05}	{0.999}	{0.999}
13	Kanakpura	3294.76	873.07	69.04	7.79	0.32	0.97	0.51	0.03	1.000	0.999
		(3299.91)	(532.78)	(88.69)	(7.19)	(0.35)	(0.96)	(0.98)	(0.10)	(0.999)	(0.999)
		[3312.84]	[499.13]	[91.87]	[7.31]	[0.33]	[0.97]	[0.93]	[0.07]	[0.999]	[0.999]
		{3280.14}	{871.44}	{69.29}	{7.25}	{0.28}	{1.00}	{0.39}	{0.03}	{0.999}	{0.999}
14	Elubthi-Mangalam	3458.92	406.02	129.40	45.81	0.30	0.98	0.32	0.04	0.986	0.999
		(3454.88)	(491.25)	(111.97)	(40.46)	(0.80)	(0.82)	(3.48)	(0.33)	(0.993)	(0.996)
		[3474.27]	[451.56]	[115.15]	[41.62]	[0.83]	[0.82]	[3.92]	[0.52]	[0.995]	[0.990]
		{3471.11}	{452.99}	{129.11}	{88.14}	{0.31}	{0.98}	{0.39}	{0.05}	{0.999}	{0.999}
15	Savandapur	5594.85	1734.63	91.79	63.47	0.37	0.95	0.68	0.03	0.999	0.999
		(5625.93)	(1733.70)	(84.93)	(61.06)	(0.47)	(0.93)	(1.10)	(0.17)	(0.999)	(0.997)
		[5610.86]	[1726.95]	[85.01]	[62.90]	[0.47]	[0.93]	[1.12]	[0.20]	[1.000]	[0.996]
		{5519.41}	{1724.93}	{92.62}	{67.05}	{0.38}	{0.96}	{0.75}	{0.03}	{0.999}	{1.000}
16	T. Narasipur	7053.81	1292.89	150.66	63.68	0.44	0.93	0.93	0.07	0.996	1.000
		(7068.43)	(1291.07)	(144.41)	(57.75)	(0.50)	(0.92)	(1.12)	(0.21)	(0.995)	(0.999)
		[7069.88]	[1294.90]	[149.85]	[59.46]	[0.47]	[0.93]	[0.89]	[0.22]	[0.997]	[0.999]
		{7025.72}	{1312.71}	{135.09}	{57.56}	{0.45}	{0.93}	{1.14}	{0.09}	{0.995}	{1.000}
17	T. K. Halli	8093.65	1265.57	134.80	130.74	0.31	0.97	0.87	0.07	0.999	0.999
		(8115.03)	(1215.45)	(123.43)	(113.29)	(0.34)	(0.97)	(1.02)	(0.03)	(0.999)	(0.999)
		[8126.50]	[1193.93]	[129.16]	[117.93]	[0.31]	[0.99]	[0.81]	[0.07]	[0.997]	[0.998]
		{8055.77}	{1261.68}	{133.99}	{130.29}	{0.32}	{0.98}	{0.99}	{0.05}	{0.998}	{1.000}

Table 3 (*continued*)

S. No.	Catchment of gauge	S_0 (km^2)	S_A (km^2)	OE (km)	OI (km)	λ	α	$\bar{\beta}$	σ_β	R_n^2	R_T^2
18	Nalla-Maranpatty	8660.23	2250.52	102.32	0.59	0.22	1.02	0.36	0.06	0.997	1.000
		(8695.45)	(2255.35)	(99.51)	(0.86)	(0.41)	(0.94)	(1.13)	(0.16)	(0.997)	(0.993)
		[8681.56]	[2224.59]	[102.38]	[0.91]	[0.37]	[0.97]	[0.85]	[0.16]	[0.996]	[0.994]
		{8622.74}	{2221.75}	{108.87}	{1.49}	{0.24}	{1.02}	{0.41}	{0.06}	{0.998}	{1.000}
19	Bannur	12075.8	3250.56	143.20	55.76	0.38	0.94	0.90	0.02	0.996	1.000
		(12147.03)	(3245.49)	(134.54)	(51.21)	(0.39)	(0.95)	(0.80)	(0.03)	(0.997)	(0.999)
		[12118.45]	[3314.59]	[130.28]	[52.95]	[0.38]	[0.96]	[0.75]	[0.06]	[0.997]	[0.998]
		{10755.51}	{2756.18}	{173.21}	{57.65}	{0.34}	{0.98}	{0.32}	{0.03}	{0.995}	{0.999}
20	Kollegal	21730.05	7101.31	103.65	33.43	0.32	0.97	1.02	0.04	0.997	0.999
		(21844.29)	(7094.07)	(97.54)	(33.63)	(0.33)	(0.98)	(0.96)	(0.04)	(0.993)	(0.997)
		[21855.04]	[7067.50]	[101.38]	[35.11]	[0.29]	[1.00]	[0.75]	[0.03]	[0.992]	[0.998]
		{18481.91}	{7085.37}	{107.53}	{35.38}	{0.31}	{0.98}	{0.73}	{0.04}	{0.995}	{0.998}
21	Billigundulu	37450.44	8709.31	189.57	67.87	0.30	0.99	0.92	0.10	0.999	1.000
		(37656.40)	(8798.07)	(179.90)	(63.98)	(0.31)	(0.99)	(0.94)	(0.05)	(0.998)	(0.999)
		[37618.10]	[8780.30]	[185.92]	[65.76]	[0.29]	[1.00]	[0.80]	[0.04]	[0.999]	[0.999]
		{36016.11}	{8661.88}	{191.54}	{67.60}	{0.29}	{1.00}	{0.81}	{0.07}	{0.999}	{1.000}
22	Urachikottai	44811.73	8709.31	292.45	170.75	0.27	1.00	0.40	0.02	0.999	1.000
		(44976.83)	(8798.07)	(288.04)	(171.83)	(0.35)	(0.97)	(0.86)	(0.01)	(1.000)	(1.000)
		[44956.56]	[8780.29]	[296.76]	[175.71]	[0.39]	[0.96]	[1.08]	[0.07]	[1.000]	[1.000]
		{43526.04}	{8684.80}	{297.87}	{173.94}	{0.21}	{1.00}	{0.22}	{0.21}	{0.940}	{0.945}
23	Kodumudi	52673	8709.31	349.97	228.30	0.21	1.03	0.33	0.17	0.999	0.998
		(52944.05)	(8798.07)	(344.74)	(228.53)	(0.18)	(1.07)	(0.005)	(0.12)	(0.998)	(0.996)
		[52908.97]	[8780.29]	[355.21]	[234.16]	[0.16]	[1.09]	[-0.14]	[0.12]	[0.998]	[0.995]
		{51258.56}	{8701.26}	{356.60}	{232.67}	{0.19}	{1.05}	{0.09}	{0.12}	{0.999}	{0.998}
24	Musiri	69267.4	9057.35	425.75	29.40	0.27	1.00	0.92	0.24	0.999	0.999
		(68957.60)	(9044.51)	(413.82)	(27.98)	(0.23)	(1.03)	(0.52)	(0.19)	(0.998)	(0.997)
		[70209.17]	[9003.29]	[426.55]	[28.63]	[0.22]	[1.04]	[0.45]	[0.17]	[0.998]	[0.997]
		{68110.52}	{8999.52}	{432.53}	{30.84}	{0.25}	{1.01}	{0.73}	{0.20}	{0.998}	{0.999}

[a] Estimate corresponding to original SRTM DEM.
[b] Value in () corresponds to burnt SRTM DEM.
[c] Value in [ ] corresponds to burnt ASTER DEM.
[d] Value in {} corresponds to original ASTER DEM.

Table 4
Morphometric descriptors of stream networks in catchments of Mahanadi basin derived based on 90 m resolution original and burnt SRTM DEMs, and 30 m resolution original and burnt ASTER DEMs. $\lambda, \alpha, \bar{\beta}, \sigma_\beta, R_n^2, R_T^2$ are dimensionless.

S.No.	Catchment of gauge	S_0 (km^2)	S_A (km^2)	OE (km)	OI (km)	λ	α	$\bar{\beta}$	σ_β	R_n^2	R_T^2
1	Manendragarh	1017.17[a]	166.10	57.03	1.20	0.24	1.01	0.16	0.13	0.996	1.000
		(1007.76)[b]	(159.33)	(58.91)	(0.98)	(0.31)	(0.97)	(0.42)	(0.09)	(0.992)	(0.998)
		[1005.35][c]	[164.24]	[56.57]	[1.03]	[0.21]	[1.04]	[-0.06]	[0.11]	[0.983]	[0.998]
		{1016.18}[d]	{166.88}	{55.79}	{0.98}	{0.23}	{1.01}	{0.16}	{0.12}	{0.990}	{0.999}
2	Andhiarkhore	2133.38	928.33	17.43	7.93	0.08	1.23	0.20	0.02	0.972	0.996
		(2132.03)	(830.71)	(18.14)	(9.17)	(0.18)	(1.08)	(0.78)	(0.05)	(0.994)	(0.997)
		[2168.28]	[849.92]	[18.22]	[9.49]	[0.68]	[0.81]	[4.31]	[0.01]	[0.982]	[0.999]
		{2179.60}	{849.19}	{16.22}	{7.38}	{0.27}	{0.99}	{1.42}	{0.13}	{0.998}	{0.997}
3	Pathardih	2494.70	247.24	98.96	44.51	0.27	1.00	0.58	0.10	0.999	1.000
		(2478.84)	(229.43)	(96.56)	(42.65)	(0.32)	(0.96)	(1.17)	(0.19)	(0.997)	(0.998)
		[2479.12]	[226.09]	[99.64]	[44.87]	[0.30]	[0.98]	[1.17]	[0.11]	[0.996]	[1.000]
		{2481.91}	{237.62}	{93.02}	{69.18}	{0.25}	{1.01}	{0.86}	{0.11}	{0.999}	{0.999}
4	Ghatora	2935.10	991.08	67.44	0.13	0.34	0.97	0.40	0.06	0.998	0.998
		(2847.08)	(982.92)	(76.73)	(0.92)	(0.31)	(0.98)	(0.10)	(0.02)	(0.998)	(0.999)
		[3115.50]	[977.34]	[73.04]	[1.04]	[0.28]	[0.99]	[0.24]	[0.02]	[0.999]	[1.000]
		{3076.33}	{955.00}	{76.10}	{0.14}	{0.29}	{0.99}	{0.22}	{0.03}	{0.999}	{0.999}
5	Baronda	3213.44	1329.76	56.90	38.02	0.26	1.00	0.19	0.03	0.996	0.999
		(3167.16)	(1337.54)	(49.65)	(28.32)	(0.31)	(0.98)	(0.47)	(0.03)	(0.996)	(0.999)
		[3192.14]	[1339.45]	[51.28]	[29.66]	[0.32]	[0.97]	[0.54]	[0.03]	[0.998]	[0.999]
		{3205.76}	{1337.40}	{61.30}	{41.65}	{0.31}	{0.98}	{0.31}	{0.03}	{0.998}	{0.999}
6	Rampur	3436.02	452.31	132.07	59.04	0.32	0.97	0.04	0.10	0.998	0.999
		(3405.07)	(432.51)	(129.45)	(53.87)	(0.36)	(0.96)	(0.33)	(0.09)	(0.998)	(1.000)
		[3404.12]	[437.41]	[134.08]	[56.97]	[0.31]	[0.98]	[0.12]	[0.05]	[0.998]	[0.999]
		{3433.51}	{426.32}	{137.41}	{55.26}	{0.30}	{0.99}	{-0.05}	{0.08}	{0.998}	{0.999}
7	Salebhata	4632.10	1071.73	90.28	85.53	0.30	0.98	0.47	0.03	1.000	1.000
		(4545.48)	(1033.48)	(93.37)	(85.00)	(0.34)	(0.97)	(0.61)	(0.02)	(1.000)	(1.000)
		[4528.96]	[1060.44]	[90.32]	[89.00]	[0.29]	[0.99]	[0.48]	[0.03]	[1.000]	[1.000]
		{4574.69}	{1062.70}	{92.83}	{92.82}	{0.25}	{1.01}	{0.24}	{0.03}	{0.999}	{1.000}

(*continued on next page*)

Table 4 (*continued*)

S.No.	Catchment of gauge	S_0 (km^2)	S_A (km^2)	OE (km)	OI (km)	λ	α	$\bar{\beta}$	σ_β	R_n^2	R_T^2
8	Kurubhata	4763.69	906.38	132.38	11.95	0.28	0.99	−0.17	0.09	0.995	0.998
		(4700.30)	(909.57)	(123.22)	(10.55)	(0.36)	(0.96)	(0.34)	(0.09)	(0.998)	(0.999)
		[4768.72]	[937.58]	[127.44]	[11.73]	[0.31]	[0.98]	[0.09]	[0.09]	[0.999]	[0.999]
		{4822.36}	{943.15}	{130.12}	{11.56}	{0.29}	{0.99}	{-0.05}	{0.12}	{0.998}	{0.998}
9	Sundergarh	6061.67	1294.40	100.45	82.58	0.27	1.00	0.44	0.12	0.998	0.999
		(6187.98)	(1108.19)	(97.17)	(73.95)	(0.35)	(0.96)	(1.09)	(0.12)	(0.998)	(0.999)
		[5880.98]	[1302.78]	[92.84]	[76.14]	[0.31]	[0.98]	[0.76]	[0.10]	[0.999]	[0.999]
		{5974.34}	{1302.36}	{102.62}	{86.02}	{0.27}	{1.00}	{0.44}	{0.10}	{0.998}	{0.999}
10	Kotni	7063.33	2060.43	70.50	14.35	0.23	1.02	0.53	0.10	0.999	1.000
		(7017.68)	(2042.25)	(71.89)	(18.58)	(0.27)	(1.00)	(0.67)	(0.11)	(0.999)	(1.000)
		[6999.02]	[2033.01]	[75.60]	[20.41]	[0.24]	[1.01]	[0.53]	[0.09]	[0.999]	[1.000]
		{7050.28}	{2044.78}	{72.78}	{14.26}	{0.22}	{1.03}	{0.49}	{0.10}	{0.998}	{1.000}
11	Rajim	8494.70	3229.62	68.34	1.27	0.27	0.99	0.60	0.05	0.999	1.000
		(8414.05)	(3208.35)	(64.84)	(1.62)	(0.35)	(0.96)	(0.98)	(0.05)	(0.998)	(0.999)
		[8405.76]	[3197.06]	[65.05]	[1.78]	[0.32]	[0.97]	[0.91]	[0.03]	[0.999]	[1.000]
		{8419.36}	{3213.78}	{69.72}	{1.14}	{0.28}	{1.00}	{0.61}	{0.05}	{0.999}	{1.000}
12	Bamnidhi	9878.19	2169.23	185.46	143.11	0.32	0.97	0.08	0.05	0.999	1.000
		(9795.64)	(1976.67)	(182.97)	(142.02)	(0.41)	(0.94)	(0.58)	(0.04)	(0.999)	(1.000)
		[9719.87]	[1968.17]	[188.80]	[145.76]	[0.34]	[0.97]	[0.28]	[0.08]	[0.998]	[0.999]
		{9869.70}	{2026.38}	{188.02}	{145.81}	{0.29}	{0.99}	{0.01}	{0.05}	{0.999}	{0.999}
13	Kesinga	12004.34	2798.26	59.92	2.65	0.31	0.98	1.44	0.08	0.999	1.000
		(11840.51)	(2505.74)	(70.35)	(4.90)	(0.38)	(0.95)	(1.88)	(0.09)	(1.000)	(0.999)
		[11581.76]	[2524.75]	[64.86]	[4.55]	[0.32]	[0.98]	[1.70]	[0.11]	[1.000]	[0.999]
		{11929.62}	{2767.73}	{54.31}	{2.15}	{0.27}	{1.00}	{1.41}	{0.09}	{1.000}	{1.000}
14	Kantamal	20237.98	2801.80	149.55	92.17	0.23	1.02	1.11	0.25	1.000	1.000
		(20237.96)	(2514.60)	(154.41)	(88.92)	(0.35)	(0.96)	(2.03)	(0.19)	(1.000)	(0.999)
		[20143.81]	[2554.89]	[152.79]	[95.00]	[0.29]	[0.99]	[1.81]	[0.24]	[1.000]	[0.999]
		{20535.30}	{2813.78}	{151.71}	{97.91}	{0.22}	{1.02}	{1.11}	{0.21}	{0.999}	{1.000}
15	Jondhra	29901.00	4136.71	244.50	121.50	0.31	0.98	1.27	0.16	1.000	1.000
		(29693.09)	(4139.20)	(236.87)	(114.22)	(0.36)	(0.96)	(1.65)	(0.20)	(1.000)	(1.000)
		[29595.69]	[4105.70]	[251.06]	[122.35]	[0.30]	[0.99]	[1.29]	[0.21]	[1.000]	[1.000]
		{33086.59}	{8008.74}	{182.41}	{114.21}	{0.28}	{0.99}	{0.96}	{0.10}	{0.999}	{1.000}
16	Seorinarayan	48265.56	13151.83	154.04	14.22	0.27	0.99	1.10	0.10	0.999	1.000
		(47771.31)	(13112.36)	(142.65)	(12.45)	(0.32)	(0.98)	(1.32)	(0.09)	(0.999)	(1.000)
		[47736.75]	[13099.91]	[152.26]	[13.73]	[0.28]	[1.00]	[1.15]	[0.10]	[1.000]	[1.000]
		{47754.02}	{9278.90}	{197.26}	{13.84}	{0.26}	{1.00}	{1.21}	{0.14}	{1.000}	{1.000}
17	Basantpur	58647.15	13151.88	177.40	37.60	0.32	0.97	1.49	0.12	1.000	1.000
		(58672.96)	(13112.36)	(165.21)	(34.95)	(0.37)	(0.97)	(1.74)	(0.13)	(1.000)	(1.000)
		[58729.41]	[13099.91]	[174.37]	[35.86]	[0.33]	[0.97]	[1.60]	[0.12]	[1.000]	[1.000]
		{58750.02}	{9942.14}	{227.72}	{10.09}	{0.30}	{0.98}	{1.55}	{0.17}	{1.000}	{1.000}
18	Tikarapara	127415.24	22891.83	451.25	97.86	0.48	0.91	2.11	0.09	0.994	1.000
		(125778.63)	(22745.31)	(409.80)	(89.67)	(0.41)	(0.96)	(1.58)	(0.06)	(0.997)	(1.000)
		[125272.78]	[22742.81]	[426.30]	[90.17]	[0.45]	[0.93]	[1.89]	[0.13]	[0.998]	[0.999]
		{127118.80}	{22872.46}	{448.60}	{94.72}	{0.41}	{0.93}	{1.67}	{0.08}	{0.995}	{1.000}

[a] Estimate corresponding to original SRTM DEM.
[b] Value in () corresponds to burnt SRTM DEM.
[c] Value in [ ] corresponds to burnt ASTER DEM.
[d] Value in {} corresponds to original ASTER DEM.

Cauvery basin and Rampur catchment in Mahanadi basin. Further, the error is large in the case of ASTER DEM for Kollegal catchment in Cauvery basin and Jondhra catchment in Mahanadi basin. Overall the observations indicate that source of DEM has an effect in the analysis for a catchment. Therefore finer resolution DEM need not be the default choice for application.

6.2. Computation of Horton–Strahler ratios

A set of stream networks was demarcated in each of the 42 catchments delineated based on a DEM (SRTM, ASTER), with each network corresponding to a value specified for threshold area S for channel initiation. Each of the stream networks was then ordered using H–S ordering scheme and H–S ratios (R_a, R_b and R_l) were computed using the procedure described in the Section 2. For brevity, H–S ratios computed for two typical catchments in Mahanadi basin based on both the DEMs are shown in Table 2 for various values specified for S. The corresponding estimates for the ratio S/S_0, order of catchment (Ω), length of highest order stream (L_Ω), number of sources (n), total length of the channel network (T), and N^*, L^* and A^* that were determined based on Eqs. (4)–(6) are also presented alongside H–S ratios. Similar information was documented for all other catchments considered in the study by repeating analysis with SRTM and ASTER DEMs. Estimates of the ratios were found to be sensitive to value specified for S. Variability in estimate of R_l with S was more pronounced, especially in situations where catchment outlet is situated just downstream of the location of confluence of two major streams. This makes the length of highest order stream unrealistically short for certain values of S, as can be seen from L_Ω value for the catchment of Basantpur gauge (Table 2b). Therefore, it can be expected that results obtained from applications of H–S ratios and other characteristics derived based

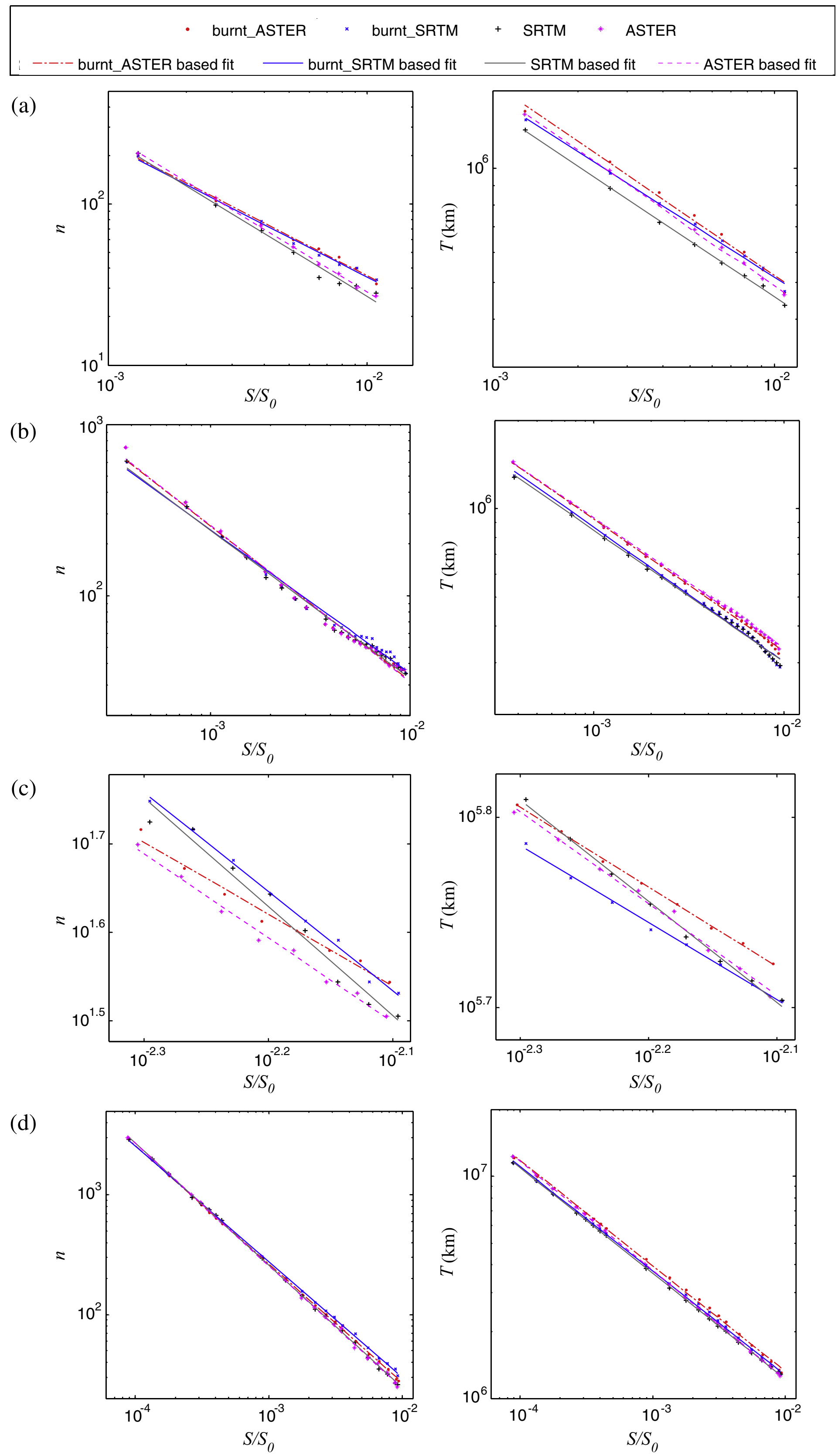

Fig. 5. Plots prepared to discern relationship between n (dimensionless) and (S/S_0) (dimensionless), and T (in km) and (S/S_0) for (a) Emangalam, and (b) Thevur catchments in Cauvery basin, and for (c) Andhiarkhore, and (d) Kantamal catchments in Mahanadi basin.

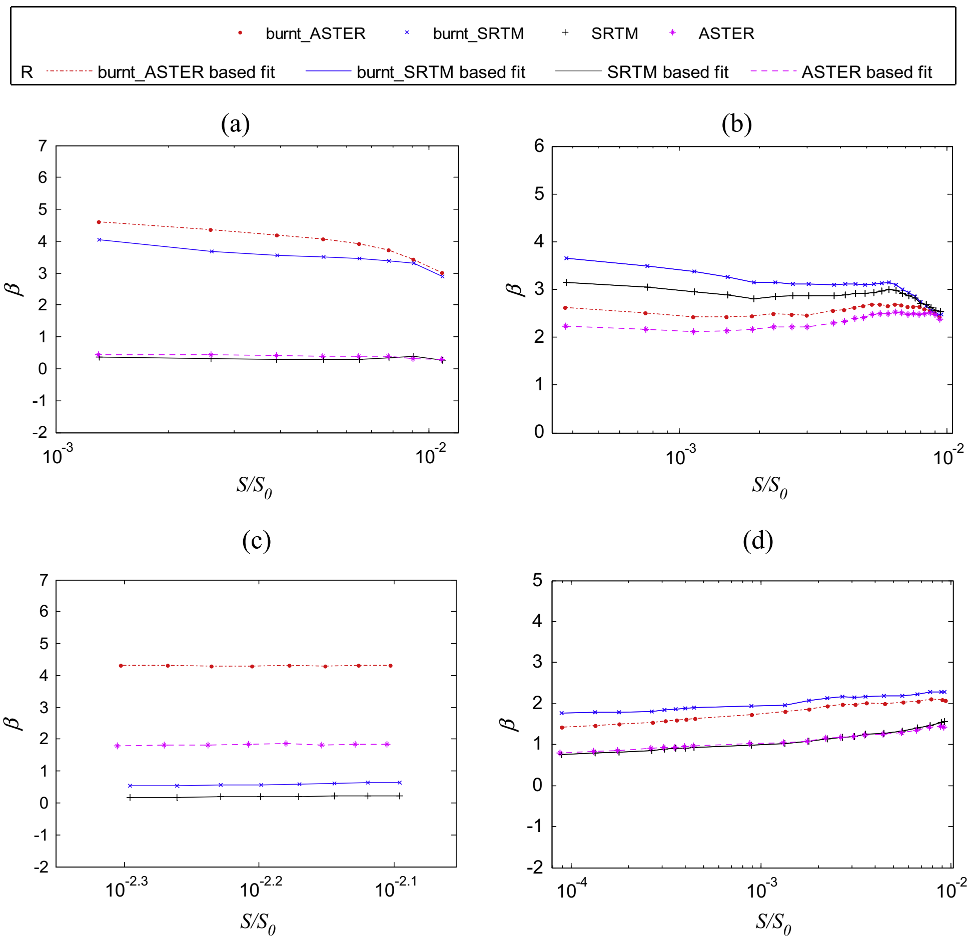

Fig. 6. Plots prepared to verify variation in β (dimensionless) value with respect to (S/S_0) (dimensionless) for (a) Emangalam, and (b) Thevur catchments in Cauvery basin, and for (c) Andhiarkhore, and (d) Kantamal catchments in Mahanadi basin.

on a stream network demarcated using H–S concept are conditional on value chosen for S, which is undesirable.

6.3. Derivation of GIUH

A typical application of H–S ratios is in construction of Geomorphological Instantaneous Unit Hydrograph (GIUH, Eq. (19)) (Rodríguez-Iturbe and Valdés, 1979; Rosso, 1984; Rodríguez-Iturbe and Rinaldo, 1997) for determining hydrological response of a catchment. In this study, GIUH based on Nash model (Rosso, 1984) is considered. It assumes that a catchment can be represented by a series of m identical linear reservoirs, each having storage constant k (in hours). The GIUH (in h^{-1}) is represented by the following equation.

$$\left.\begin{array}{l} GIUH(t) = \left(\frac{t}{k}\right)^{m-1} \frac{e^{\left(\frac{-t}{k}\right)}}{k\Gamma(m)} \\ \text{where} \\ m = 3.29\left(\frac{R_b}{R_a}\right)^{0.78} R_l^{0.07} \\ k = 0.70\left(\frac{R_a}{R_b R_l}\right)^{0.48} \frac{L_\Omega}{v} \end{array}\right\} \quad (19)$$

For each of the catchments, GIUHs were constructed corresponding to the set of demarcated stream networks (each network depicting a threshold area), by using estimates of the corresponding H–S ratios and L_Ω, and considering v to be the average velocity of flow (in km/h) corresponding to peak water level (stage) recorded at the respective gauge location. Results indicated that characteristics of GIUH (e.g., time to peak flow, peak flow, base time) are sensitive to estimates of H–S ratios that are in turn dependent on threshold area. For brevity, GIUHs constructed for stream networks demarcated based on SRTM and ASTER DEMs using various values for threshold area in the case of two catchments each in Cauvery and Mahanadi basins are shown in Fig. 4.

As there is no universally established procedure to arrive at optimal value for threshold area, there is a high probability for inconsistency in characteristics of GIUHs derived for a catchment by practicing hydrologists. This justifies the need to look for an effective strategy to determine H–S ratios that are independent of threshold area. These findings are in agreement with those noted by Moussa and Bocquillon (1996) and Moussa (2008b, 2009) for French catchments.

6.4. Determination of the equivalent Horton–Strahler ratios

To arrive at equivalent H–S ratios that are independent of threshold area, investigations were carried out to examine self-similarity properties of the set of stream networks (each network depicting a threshold area S) demarcated corresponding to each of the 42 catchments based on SRTM and ASTER DEMs. For this purpose, information extracted in Section 6.2 on n and T corresponding to various values for S was utilized. In addition, information was extracted for each of the 42 catchments on threshold area S_A (for which formation of the first bifurcation node just begins) and the corresponding value for the total length of the channel network OE for use in Eq. (14). Length from catchment outlet to the

Table 5
Equivalent H–S ratios and length for catchments in Cauvery basin derived based on 90m resolution original and burnt SRTM DEMs, and 30 m resolution original and burnt ASTER DEMs. R_{ae}, R_{be} and R_{le} are dimensionless.

S. No.	Catchment	R_{ae}	R_{be}	R_{le}	L_e (km)
1	Kodihalli	4.01[a]	3.31	2.00	11.75
		(3.99)[b]	(3.30)	(2.00)	(11.49)
		[6.78][c]	[6.50]	[2.60]	[13.41]
		{6.78}[d]	{6.55}	{2.60}	{13.38}
2	Sevanur	10.18	11.95	3.19	17.90
		(10.01)	(10.99)	(3.16)	(19.45)
		[12.69]	[17.85]	[3.56]	[20.36]
		{10.35}	{12.61}	{3.22}	{21.58}
3	Thoppur	7.27	7.03	2.70	18.47
		(5.35)	(4.73)	(2.31)	(18.26)
		[6.71]	[6.48]	[2.59]	[19.51]
		{8.41}	{9.10}	{2.90}	{18.84}
4	Hadigeup	7.31	7.22	2.70	19.73
		(7.39)	(7.28)	(2.72)	(19.48)
		[6.00]	[5.60]	[2.45]	[18.91]
		{6.33}	{6.06}	{2.52}	{18.84}
5	Srinivasagraham	8.16	8.42	2.86	19.87
		(7.20)	(6.77)	(2.68)	(21.94)
		[6.34]	[5.94]	[2.52]	[21.85]
		{8.60}	{9.69}	{2.93}	{19.81}
6	Sakleshpur	6.93	6.69	2.63	24.14
		(7.08)	(6.88)	(2.66)	(23.55)
		[6.06]	[5.70]	[2.46]	[22.87]
		{6.66}	{6.50}	{2.58}	{22.97}
7	Kudlur	6.88	6.50	2.62	26.54
		(6.81)	(6.44)	(2.61)	(26.52)
		[7.58]	[7.59]	[2.75]	[27.41]
		{7.52}	{7.57}	{2.74}	{27.08}
8	Thevur	3.50	2.94	1.87	33.46
		(2.88)	(2.43)	(1.70)	(29.70)
		[4.22]	[3.64]	[2.05]	[38.24]
		{4.61}	{4.04}	{2.15}	{39.81}
9	Thengumarhada	6.21	5.56	2.49	41.55
		(4.18)	(3.53)	(2.04)	(40.35)
		[4.54]	[3.90]	[2.13]	[42.90]
		{6.70}	{6.24}	{2.59}	{41.96}
10	Nellithurai	6.48	6.08	2.55	39.19
		(4.14)	(3.58)	(2.03)	(38.41)
		[4.11]	[3.60]	[2.03]	[37.45]
		{6.97}	{6.45}	{2.64}	{37.83}
11	Hogenakkal	5.61	5.08	2.37	37.54
		(5.52)	(4.95)	(2.35)	(39.88)
		[8.22]	[8.65]	[2.87]	[37.42]
		{7.95}	{8.28}	{2.82}	{38.43}
12	M. H. Halli	7.08	6.91	2.66	54.73
		(4.30)	(3.76)	(2.07)	(51.89)
		[4.83]	[4.33]	[2.20]	[53.35]
		{6.77}	{6.61}	{2.60}	{53.12}
13	Kanakpura	6.56	6.23	2.56	54.25
		(6.05)	(5.60)	(2.46)	(58.54)
		[6.20]	[5.90]	[2.49]	[58.59]
		{7.08}	{7.02}	{2.66}	{55.05}
14	Emangalam	6.87	6.55	2.62	57.75
		(2.62)	(2.21)	(1.62)	(49.12)
		[2.52]	[2.13]	[1.59]	[49.72]
		{6.54}	{6.29}	{2.56}	{59.97}
15	Savandapur	5.72	5.26	2.39	73.89
		(4.54)	(4.05)	(2.13)	(68.26)
		[4.54]	[4.10]	[2.13]	[69.41]
		{5.54}	{5.15}	{2.35}	{75.48}
16	T. Narasipura	4.80	4.28	2.19	78.55
		(4.24)	(3.76)	(2.06)	(72.63)
		[4.52]	[4.09]	[2.13]	[73.51]
		{4.72}	{4.25}	{2.17}	{79.11}

Table 5 (*continued*)

S. No.	Catchment	R_{ae}	R_{be}	R_{le}	L_e (km)
17	T. K. Halli	6.61	6.29	2.57	91.95
		(6.13)	(5.77)	(2.48)	(85.63)
		[6.47]	[6.33]	[2.54]	[83.94]
		{6.38}	{6.13}	{2.53}	{94.08}
18	Nallamaranpatty	8.83	9.22	2.97	98.55
		(5.14)	(4.64)	(2.27)	(87.84)
		[5.65]	[5.32]	[2.38]	[86.46]
		{8.25}	{8.63}	{2.87}	{101.33}
19	Bannur	5.60	5.01	2.37	113.00
		(5.44)	(5.03)	(2.33)	(103.37)
		[5.48]	[5.11]	[2.34]	[101.17]
		{6.08}	{5.88}	{2.47}	{106.20}
20	Kollegal	6.38	6.06	2.53	151.31
		(6.25)	(6.06)	(2.50)	(141.31)
		[6.89]	[6.92]	[2.62]	[138.83]
		{6.50}	{6.27}	{2.55}	{136.82}
21	Biligundulu	6.89	6.70	2.62	200.25
		(6.55)	(6.40)	(2.56)	(191.23)
		[6.81]	[6.80]	[2.61]	[187.01]
		{6.92}	{6.91}	{2.63}	{195.05}
22	Urachikottai	7.55	7.51	2.75	204.56
		(5.96)	(5.68)	(2.44)	(207.50)
		[5.28]	[4.97]	[2.30]	[207.61]
		{9.51}	{9.41}	{3.08}	{224.91}
23	Kudumudi	8.87	9.54	2.98	248.06
		(9.87)	(11.64)	(3.14)	(223.94)
		[10.62]	[13.16]	[3.26]	[225.73]
		{9.49}	{10.67}	{3.08}	{237.68}
24	Musiri	7.46	7.44	2.73	295.31
		(8.35)	(8.97)	(2.89)	(271.13)
		[8.61]	[9.38]	[2.93]	[272.23]
		{7.86}	{8.07}	{2.80}	{290.38}

[a] Estimate corresponding to original SRTM DEM.
[b] Value in () corresponds to burnt SRTM DEM.
[c] Value in [ ] corresponds to burnt ASTER DEM.
[d] Value in {} corresponds to original ASTER DEM.

Table 6
Equivalent H–S ratios and length for catchments in Mahanadi basin derived based on 90 m resolution original and burnt SRTM DEMs, and 30 m resolution original and burnt ASTER DEMs. R_{ae}, R_{be} and R_{le} are dimensionless.

S. No.	Catchment	R_{ae}	R_{be}	R_{le}	L_e (km)
1	Manendragarh	8.10[a]	8.27	2.85	33.10
		(6.73)[b]	(6.40)	(2.60)	(31.87)
		[9.10][c]	[9.94]	[3.02]	[32.50]
		{8.53}[d]	{8.79}	{2.92}	{33.94}
2	Andhiarkhore	14.97	27.80	3.87	54.24
		(10.80)	(14.41)	(3.29)	(55.47)
		[3.21]	[2.58]	[1.79]	[56.87]
		{6.72}	{6.13}	{2.59}	{66.14}
3	Pathardih	7.45	7.39	2.73	49.20
		(6.52)	(6.11)	(2.55)	(51.57)
		[6.82]	[6.57]	[2.61]	[54.19]
		{7.80}	{8.05}	{2.79}	{53.33}
4	Ghatora	6.01	5.68	2.45	50.88
		(6.56)	(6.35)	(2.56)	(51.85)
		[7.23]	[7.11]	[2.69]	[57.36]
		{6.91}	{6.73}	{2.63}	{55.54}
5	Baronda	7.63	7.65	2.76	54.28
		(6.64)	(6.39)	(2.58)	(53.61)
		[6.55]	[6.20]	[2.56]	[55.85]
		{6.71}	{6.46}	{2.59}	{55.43}

(*continued on next page*)

Table 6 (*continued*)

S. No.	Catchment	R_{ae}	R_{be}	R_{le}	L_e (km)
6	Rampur	6.45 (5.84) [6.55] {6.81}	6.11 (5.43) [6.29] {6.66}	2.54 (2.42) [2.56] {2.61}	52.54 (52.37) [55.19] {53.69}
7	Salebhata	6.75 (6.12) [6.94] {7.79}	6.50 (5.81) [6.77] {7.92}	2.60 (2.47) [2.64] {2.79}	65.02 (65.13) [67.78] {67.21}
8	Kurubhata	7.17 (5.71) [6.60] {6.92}	7.07 (5.36) [6.40] {6.82}	2.68 (2.39) [2.57] {2.63}	61.93 (61.56) [64.87] {64.26}
9	Sundergarh	7.49 (5.92) [6.66] {7.39}	7.49 (5.52) [6.43] {7.37}	2.74 (2.43) [2.58] {2.72}	76.44 (76.29) [78.37] {77.86}
10	Kotni	8.53 (7.55) [8.29] {8.83}	8.82 (7.54) [8.54] {9.37}	2.92 (2.75) [2.88] {2.97}	86.23 (85.41) [87.51] {88.66}
11	Rajim	7.51 (5.95) [6.49] {7.16}	7.43 (5.55) [6.16] {7.20}	2.74 (2.44) [2.55] {2.68}	93.27 (91.96) [96.02] {92.62}
12	Bamnidhi	6.47 (5.12) [6.16] {6.97}	6.13 (4.68) [5.82] {6.80}	2.54 (2.26) [2.48] {2.64}	96.15 (92.56) [99.26] {97.99}
13	Kesinga	6.63 (5.51) [6.44] {7.40}	6.38 (5.09) [6.15] {7.34}	2.57 (2.35) [2.54] {2.72}	114.88 (115.85) [123.00] {121.85}
14	Kantamal	8.61 (5.89) [7.10] {8.86}	8.97 (5.53) [6.94] {9.32}	2.93 (2.43) [2.66] {2.98}	157.87 (155.97) [170.85] {162.68}
15	Jondhra	6.69 (5.82) [6.83] {7.17}	6.43 (5.46) [6.64] {7.06}	2.59 (2.41) [2.61] {2.68}	191.58 (191.17) [199.35] {206.49}
16	Seorinarayan	7.35 (6.39) [7.25] {7.63}	7.25 (6.19) [7.20] {7.68}	2.71 (2.53) [2.69] {2.76}	247.36 (238.99) [251.38] {253.57}
17	Basantpur	6.35 (5.65) [6.30] {6.81}	6.07 (5.32) [6.01] {6.61}	2.52 (2.38) [2.51] {2.61}	267.20 (262.40) [277.45] {279.31}
18	Tikarapara	4.47 (5.10) [4.69] {5.17}	3.89 (4.75) [4.18] {4.64}	2.11 (2.26) [2.17] {2.27}	378.80 (357.53) [366.89] {381.93}

[a] Estimate corresponding to original SRTM DEM.
[b] Value in () corresponds to burnt SRTM DEM.
[c] Value in [ ] corresponds to burnt ASTER DEM.
[d] Value in {} corresponds to original ASTER DEM.

location where the first bifurcation node just begins (OI) was also recorded. The derived information (given in Tables 3 and 4) was utilized to estimate channel network shape index β [by Eq. (15)] corresponding to various values specified for threshold area S (and its corresponding T).

Log–log plots of 'n versus S/S_0' and 'T versus S/S_0', and plot of 'β versus S/S_0' were prepared for each catchment and self-similarity properties were considered to be applicable to stream networks of the catchment if the log–log relationships are linear and if the channel network shape index β estimated using Eq. (15) remains constant across various scales ($0 \leqslant S \leqslant S_A$). The measures considered for verification of self-similarity properties included: (1) coefficient of determination R_n^2 for 'n versus S/S_0' relationship, and R_T^2 for 'T versus S/S_0' relationship, and (2) Mean of β (represented as $\bar{\beta}$) and standard deviation of β (represented as σ_β). The R_n^2 and R_T^2 values corresponding to 42 catchments were sufficiently close to 1.0, and σ_β values were fairly small (see Tables 3 and 4). Based on the results it was inferred that self-similarity properties are valid for stream networks in all the 42 considered catchments, irrespective of whether DEM source considered for the analysis is SRTM or ASTER. For brevity, log–log plots of 'n versus S/S_0' and 'T versus S/S_0', prepared for four typical catchments delineated based on SRTM and ASTER DEMs are shown in Fig. 5, and the corresponding plots of 'β versus S/S_0' are shown in Fig. 6. It can be noted from Fig. 5 that relationships are log-linear, while from Fig. 6 it can be noted that β is approximately constant across various scales. Similar observations were made based on plots corresponding to remaining 38 catchments delineated in this study using both SRTM and ASTER DEMs. These observations are consistent with those noted in previous studies (Moussa, 2008a, 2009) on catchments located in France based on IGN (Institut Geographique National) DEM.

Estimates of parameters α and λ, which were required for computation of equivalent H–S ratios, were considered to be slope and intercept of n versus S/S_0 plot respectively, based on Eq. (13). Subsequently, the estimates (presented in Tables 3 and 4) were utilized in Eqs. (16)–(18) to compute equivalent H–S ratios R_{ae}, R_{be}, and R_{le} for each of the 42 catchments delineated based on ASTER and SRTM DEMs. In addition, equivalent length L_e of highest order stream (in km) was estimated based on the following equation derived by Moussa (2009),

$$L_e = \left(OE + \beta S_0^{0.5}\right)\left(\frac{S_A}{2S_0}\right)^{\alpha-0.5}\left(\frac{R_{be}-R_{le}}{R_{le}}\right) \tag{20}$$

Values of estimated equivalent H–S ratios and L_e are presented in Tables 5 and 6 for catchments in Cauvery and Mahanadi river basins respectively. It can be noted from the values that Equivalent H–S ratios and L_e are sensitive to DEM source.

6.5. Comparison of morphometric descriptors of extracted and real channel networks

Maps of real river networks in Mahanadi and Cauvery river basins (containing the 42 catchments) were available from AISLUS (1998) at 1:1 million scale. The real river networks were digitized to facilitate (i) their comparison with networks extracted from ASTER and SRTM DEMs, and (ii) their use in ArcGIS framework for extraction of morphometric descriptors of the real networks. Visual comparison of the digitized real networks with networks extracted from ASTER and SRTM DEMs indicated that they are fairly close. Subsequently, to determine morphometric descriptors (S_0, S_A, OE, OI, α, λ and β) for each of the 42 catchments corresponding to the real network, the digitized network was burnt (or fenced) into each of the DEMs and the resulting burnt DEMs are referred to as burnt SRTM and burnt ASTER DEMs. Following this, the burnt DEMs were subjected to the procedure described in the Section 6.4 to determine the morphometric descriptors by specifying values for threshold area S that were considered for processing DEMs in Section 6.2. The descriptors were subsequently used in Eqs. (16)–(18) and (20) to estimate equivalent H–S ratios and L_e for each of the catchments. It is to be noted that burning/fencing of real network into a DEM involves modifying the elevation information of the DEM to be consistent with the real network. Consequently, the degree of agreement between stream network that results from processing of the DEM

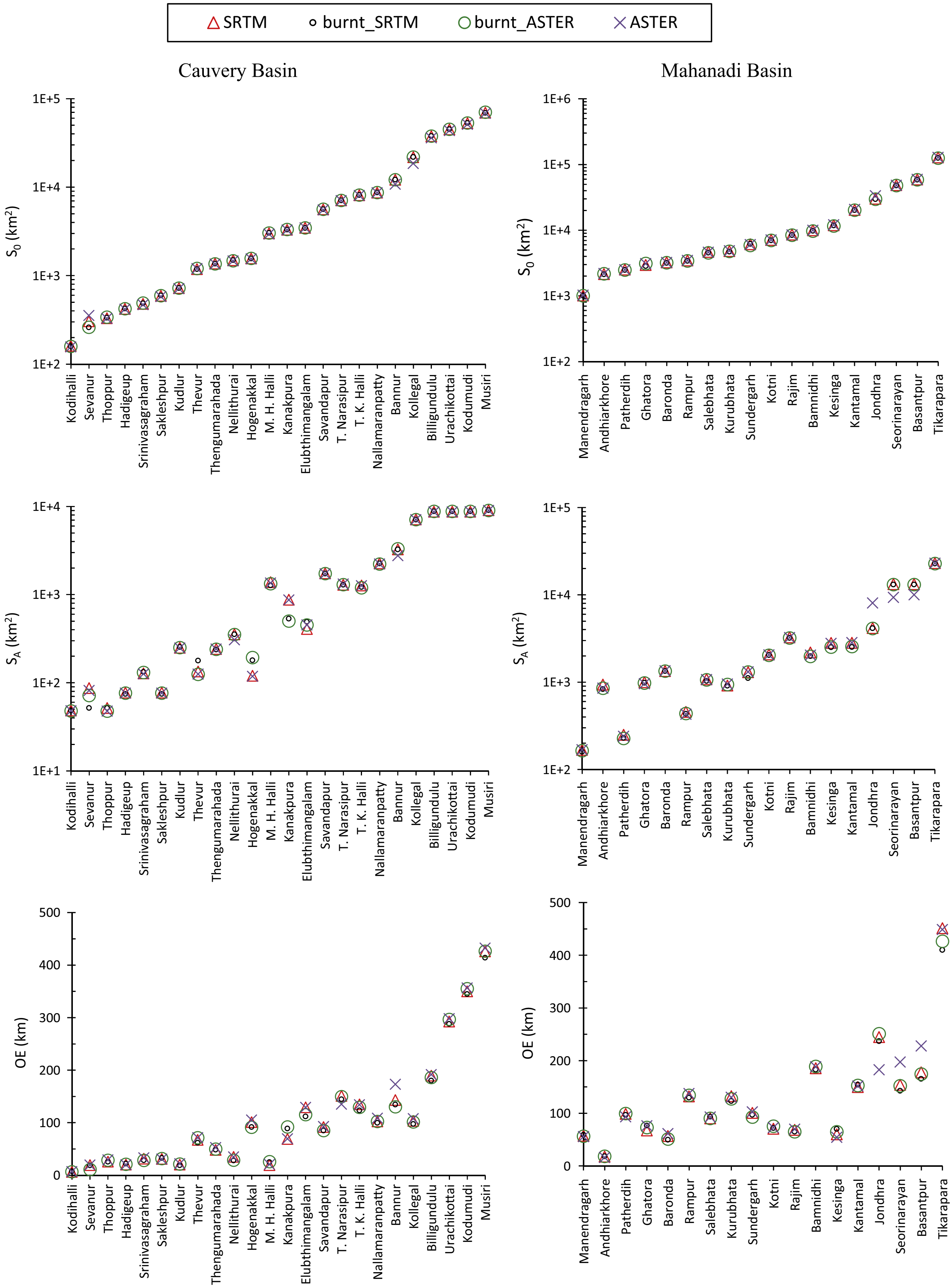

Fig. 7. Comparison of morphometric properties of channel networks extracted based on original and burnt SRTM and ASTER DEMs.

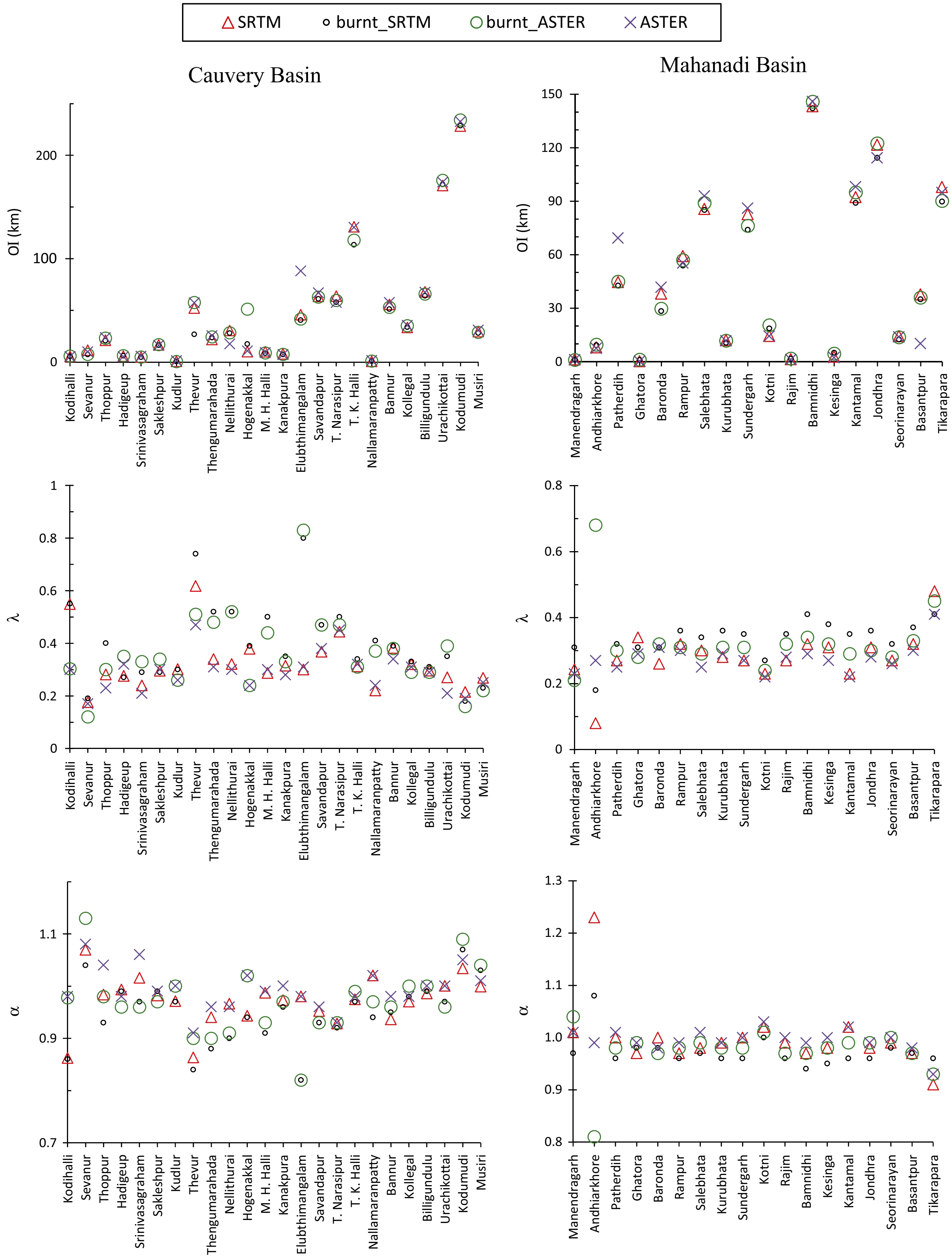

Fig. 7 (*continued*)

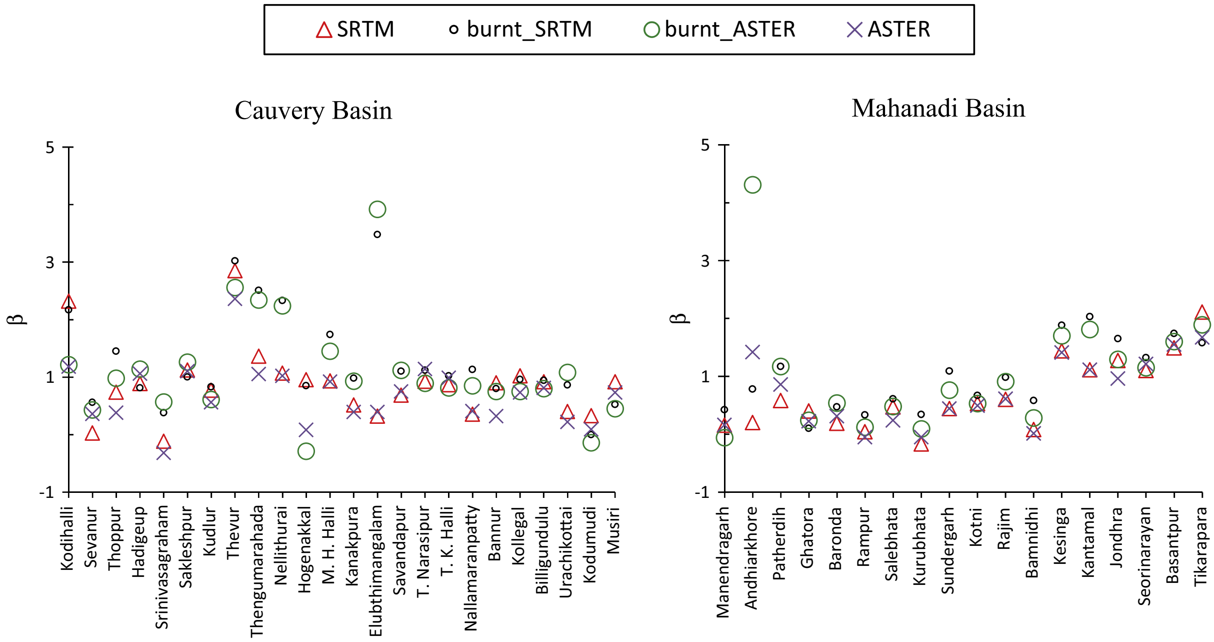

Fig. 7 (*continued*)

(corresponding to any value specified for threshold area) and the real network gets enhanced. In other words, burning of real network into a DEM ensures that the real(burnt) network would remain intact (fixed) in the network which results from processing of the DEM, irrespective of (i) the source and spatial resolution of the DEM, and (ii) threshold area specified for processing the DEM.

Values of morphometric properties determined for real networks (burnt ASTER and burnt SRTM DEMs) are presented in Tables 3 and 4 alongside the corresponding values derived from original (raw) ASTER and SRTM DEMs to facilitate comparison. Scrutiny of the morphometric descriptors, equivalent H–S ratios and L_e (Figs. 7–9) indicates the following:

(1) Areas (S_0 values) for catchments delineated based on burnt DEMs are fairly close to catchment areas determined by CWC based on topographical surveys, as expected. Values of S_0 based on original DEMs are closer to those based on burnt DEMs for majority of the 42 catchments, exceptions being catchments of Sevanur, Bannur and Kollegal gauges. Catchment areas delineated based on ASTER and SRTM DEMs are larger for Sevanur gauge due to additional delineated area in North-western part of the catchment (Fig. 9(i)), while catchment areas delineated based on ASTER DEM are marginally lower in the case of Kollegal and Bannur gauges due to reduction in delineated area in south-western part of the catchments (Fig. 9(ii) and (iii)).

(2) Values of S_A (threshold area for which the first bifurcation node just begins) determined for burnt SRTM and ASTER DEMs (which account for real channel networks) are fairly close to those determined for original SRTM and ASTER DEMs for majority of the 42 catchments (Fig. 7, Tables 3 and 4). Value of S_A for burnt DEMs differ considerably in the case of Sevanur and Thevur catchments, whereas values of the descriptor for ASTER DEM are significantly different from those for SRTM DEM and burnt DEMs in the case of Bannur, Jondhra, Seorinarayan, and Basantpur catchments. Further, values of the descriptor for burnt DEMs differ from those for original DEMs in the case of Hogenakkal and Kanakpura catchments. These observations can be attributed to (i) difference in location of the first bifurcation node in stream network with change in DEM source (e.g., see Thevur, Hogenakkal, Kanakpura, Bannur, Basantpur in Fig. 9), or difference in DEM characteristics even if location of the first bifurcation node in stream network is the same (e.g., see Sevanur, Jondhra, Seorinarayan in Fig. 9).

(3) Values of *OE* (total length of the channel network corresponding to the case where threshold area S is equal to S_A) determined for burnt SRTM and ASTER DEMs (which account for real channel networks) are fairly close to those determined for original SRTM and ASTER DEMs for majority of the 42 catchments. It can be noted from Fig. 7 that difference in *OE* for burnt DEMs is considerable in the case of Tikarapara catchment. Further, it can be seen that values of the descriptor for ASTER DEM are significantly different from those for SRTM DEM and burnt DEMs in the case of Bannur, Jondhra, Seorinarayan and Basantpur catchments, whereas the same corresponding to burnt DEMs differ considerably from those for original DEMs in the case of Kanakpura and Tikarapara catchments. The differences is OE could be attributed to differences in S_A values corresponding to different DEM sources (e.g., Kanakpura, Bannur, Jondhra, Seorinarayan and Basantpur catchments), and to uncertainty associated with DEM source (even if difference in S_A is insignificant), as can be noted for catchment corresponding to Tikarapara gauge (Fig. 7).

(4) Difference in OI (distance from catchment outlet to point I on stream network at which the first bifurcation node just begins) is considerable for several catchments (see Figs. 7 and 9). Values of OI for burnt DEMs differ considerably in the case of Thevur, Hogenakkal and Jondhra catchments. Further, OI for ASTER DEM is significantly different from that for SRTM DEM and burnt DEMs in the case of Nellithurai, Elubthimangalam, Patherdih and Basantpur catchments, while OI for burnt DEMs differ from those for original DEMs in the case of TK Halli, Baronda, Sundergarh and Tikarapara catchments. These differences are attributed to uncertainty associated with DEM source.

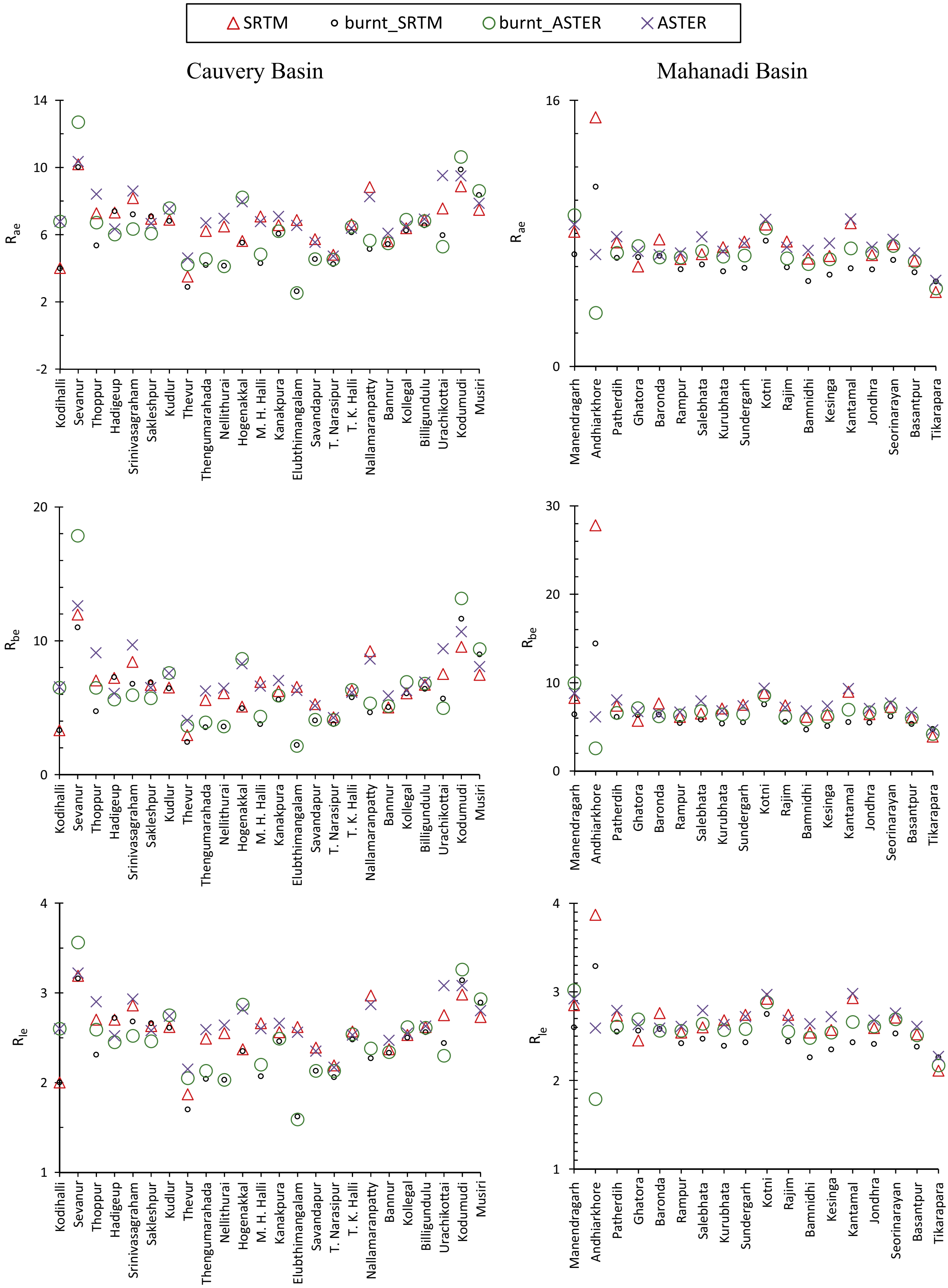

Fig. 8. Comparison of equivalent H–S ratios and equivalent length of highest order stream for channel networks extracted based on original and burnt SRTM and ASTER DEMs.

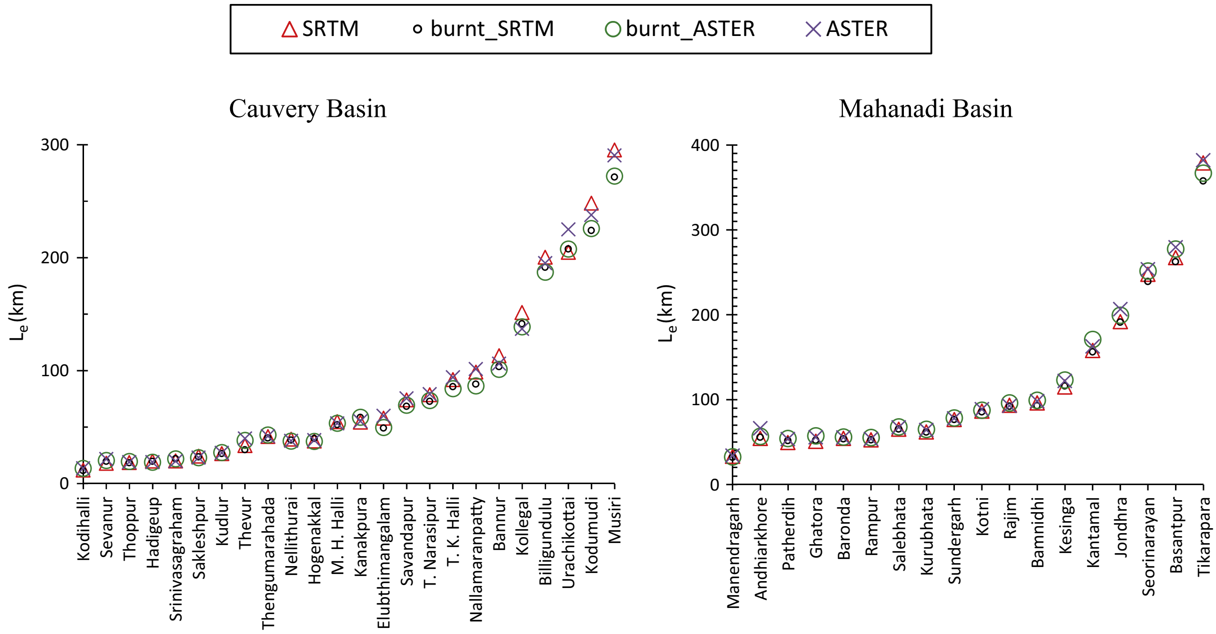

Fig. 8 (*continued*)

(5) Differences in values of α, λ [slope and intercept of number of sources (n) versus S/S_0 plot], β (channel network shape index) and equivalent H–S ratios that are determined by processing burnt as well as original SRTM and ASTER DEMs are considerable for several catchments (Figs. 7 and 8). The differences are significant for catchments corresponding to Elubthimangalam and Andhiarkore gauges. For any chosen catchment, the differences in α and λ are attributed to variability in n versus S/S_0 relationships for channel networks corresponding to different DEMs (e.g., see Fig. 5), while differences in β (channel network shape index) are attributed to uncertainty in values of various morphometric descriptors (α, OE, S_A and S_0 determined based on different DEM sources) that influence value of β (see Tables 3 and 4, Eq. (15)). On the other hand, differences in equivalent H–S ratios are attributed to DEM based uncertainty in values of parameters λ and α that are used for computing them (Fig. 8, Eqs. (16)–(18)).

(6) Difference in values of L_e (equivalent length of highest order stream) that are determined by processing burnt as well as original SRTM and ASTER DEMs are marginal for most catchments (Fig. 8). This behavior is attributable to combined effect of differences in morphometric descriptors β, OE, S_A (or OI) and S_0 in addition to equivalent H–S ratios, all of which have uncertainty associated with DEM source.

From the foregoing analysis based on burnt SRTM and ASTER DEMs (which account for real channel networks) it was inferred that difference in S_0, S_A, OE, and OI tend to be marginal for most of the catchments, while differences in α, λ and β could be considerable as they are relatively more sensitive to DEM source. Differences in values of the descriptors determined from original SRTM and ASTER DEMs are large for several catchments. Further, values of morphometric descriptors determined by processing burnt SRTM and ASTER DEMs (which account for real channel networks) are closer to those determined from original SRTM DEM (than to those from original ASTER DEM) for majority of the 42 catchments. The DEM based uncertainty in values of morphometric descriptors α and λ results in uncertainty in equivalent H–S ratios.

6.6. Effect of DEM source based uncertainty on equivalent GIUH

In order to investigate implications of DEM source based uncertainty on hydrological response of catchments, equivalent GIUH (E-GIUH) was constructed for each of the 42 catchments utilizing equivalent H–S ratios estimated corresponding to each of the original and burnt DEMs. The E-GIUH for a catchment was constructed by substituting R_{be}, R_{ae}, R_{le} and L_e of the catchment for R_b, R_a, R_l and L_Ω respectively, in Eq. (19).

Results presented in previous section indicated that values of morphometric descriptors determined by processing burnt SRTM and burnt ASTER DEMs (which account for real channel networks) are closer to those determined from original SRTM DEM (than to those from original ASTER DEM) for majority of the 42 catchments. As SRTM DEM gave the best network for the study area, E-GIUH determined based on burnt SRTM DEM was considered as the basis to compare E-GIUHs determined based on original SRTM and ASTER DEMs, as well as burnt ASTER DEM.

Time to peak flow $t_p^{burnt\_SRTM}$ (in hours) and peak flow $q_p^{burnt\_SRTM}$ values of E-GIUH derived based on burnt SRTM DEM were compared with the corresponding values t_p^{DEM} and q_p^{DEM} for E-GIUH derived based on each of the other DEMs (i.e., original SRTM DEM, original ASTER DEM, and burnt ASTER DEM) in terms of Relative-bias (R-bias) as,

$$\left.\begin{aligned} \text{R- }\textit{bias in } t_p \textit{ for a } \text{DEM} &= \left(\frac{t_p^{burnt\_SRTM} - t_p^{\mathrm{DEM}}}{t_p^{burnt\_SRTM}}\right) \times 100 \\ \text{R-}\textit{bias in } q_p \textit{ for a } \text{DEM} &= \left(\frac{q_p^{burnt\_SRTM} - q_p^{\mathrm{DEM}}}{q_p^{burnt\_SRTM}}\right) \times 100 \end{aligned}\right\} \tag{21}$$

Comparison of time to peak flow t_p (in hours) of E-GIUH derived based on burnt SRTM and burnt ASTER DEMs indicates that t_p is fairly close for most of the catchments in Cauvery basin (Fig. 10), exceptions being Kodihalli (R-bias = 25%), Srinivasagraham (R-bias = 14%), Thevur (R-bias = 20%), M. H. Halli and T. K. Halli (R-bias = 5–10%). On the other hand, in the case of Mahanadi basin, t_p values for E-GIUHs corresponding to burnt SRTM and ASTER DEMs differ by about 0–10% in the case of 13 of the 18 catchments. The difference is significant (>10%) in the case of Manendragarh,

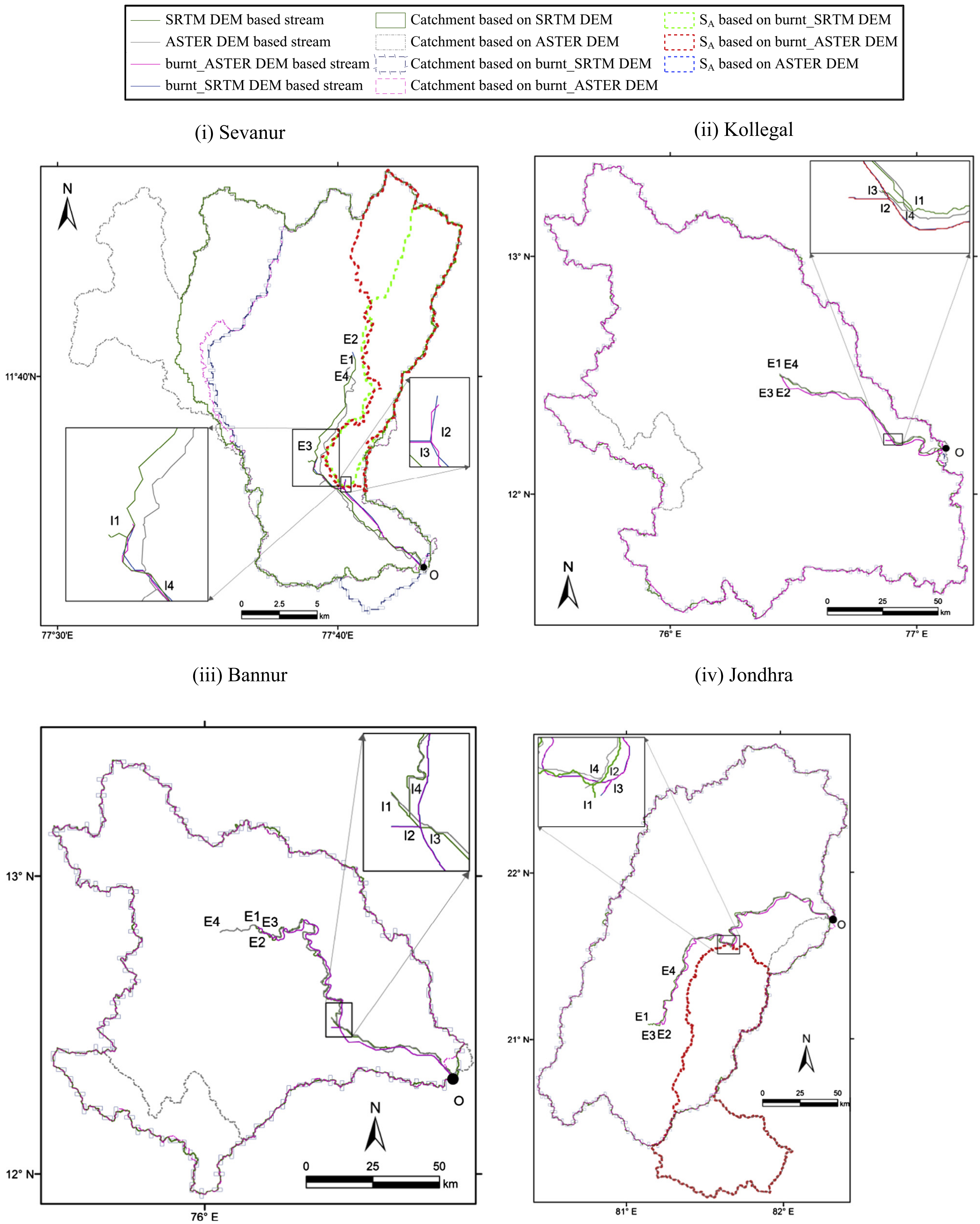

Fig. 9. Catchment boundary and morphometric descriptors corresponding to original and burnt SRTM and ASTER DEMs. O is catchment outlet; (OE1, I1), (OE2, I2), (OE3, I3) and (OE4, I4) denote total stream length (in km) and first bifurcation node corresponding to SRTM, burnt SRTM, burnt ASTER and ASTER DEMs respectively when $S = S_A$. The inset figure shows magnified view of first bifurcation nodes corresponding to various DEMs.

Baronda and Bamnidhi catchments (Fig. 10). Similarly comparison of R-bias in t_p values for E-GIUHs derived based on original SRTM and ASTER DEMs indicate that their t_p values differ considerably in the case of 10 out of 24 catchments in Cauvery basin (Fig. 10). The difference is significant in the case of Sevanur (30%), Hogenakkal (10%), Nallamaranpatty (10%) and Kollegal (12%). On

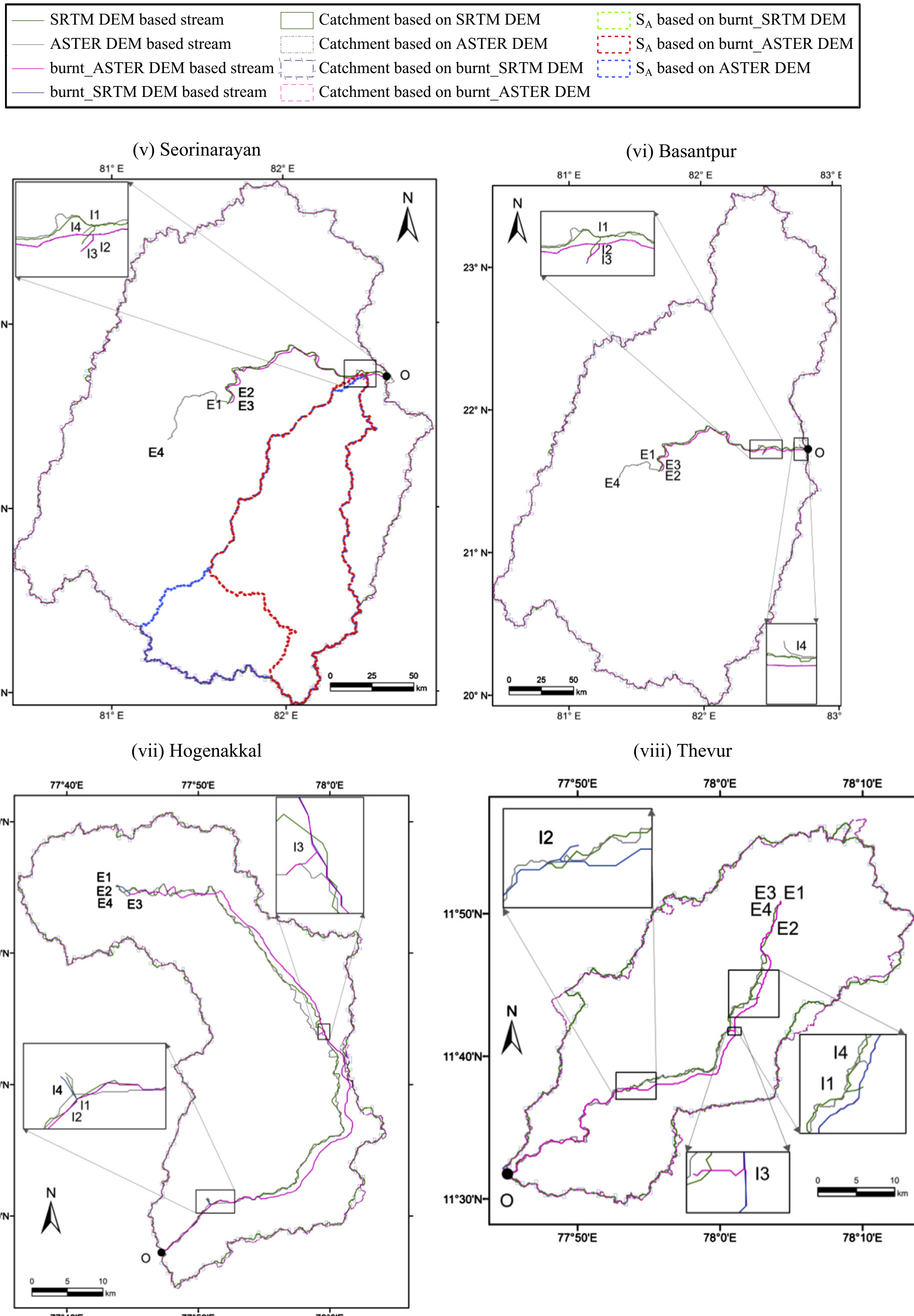

Fig. 9 (*continued*)

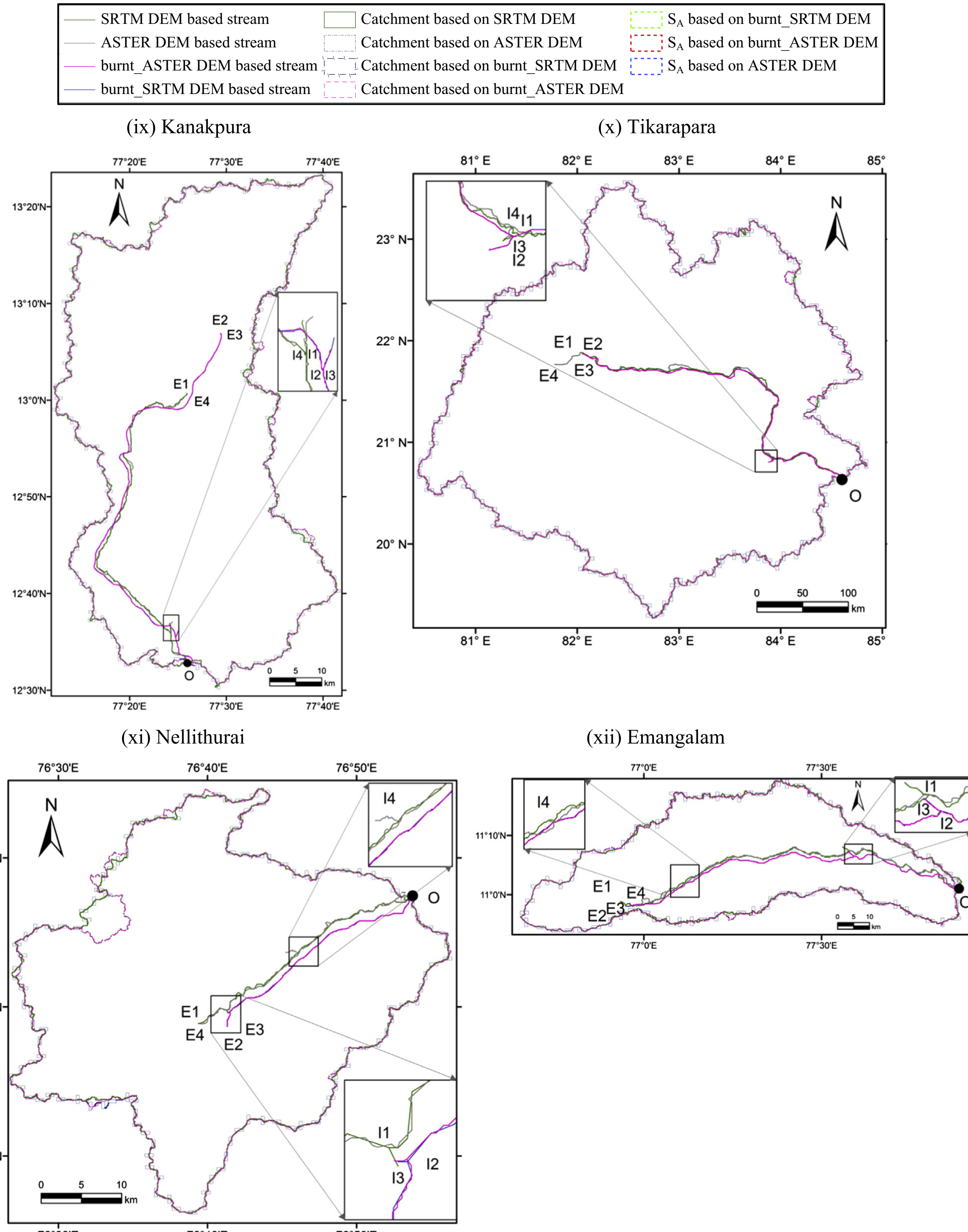

Fig. 9 (*continued*)

the other hand, in the case of Mahanadi basin, considerable differences in t_p are found in case of 8 out of 18 catchments. The differences are significant for Andhiarkhore (17%) and Sundergarh (12%) catchments (Fig. 10). The t_p estimates for E-GIUHs based on original DEMs and burnt ASTER DEM differ significantly with respect to t_p estimate for E-GIUH based on burnt SRTM DEM in the case of Kodihalli (25%), Thevur (20%), M. H. Halli (10%), Manendragarh (20%), Baronda (10%), Kotni (9%) and Bamnidhi (13%).

Comparison of q_p values of E-GIUH derived based on burnt SRTM and burnt ASTER DEMs indicated that the values differ

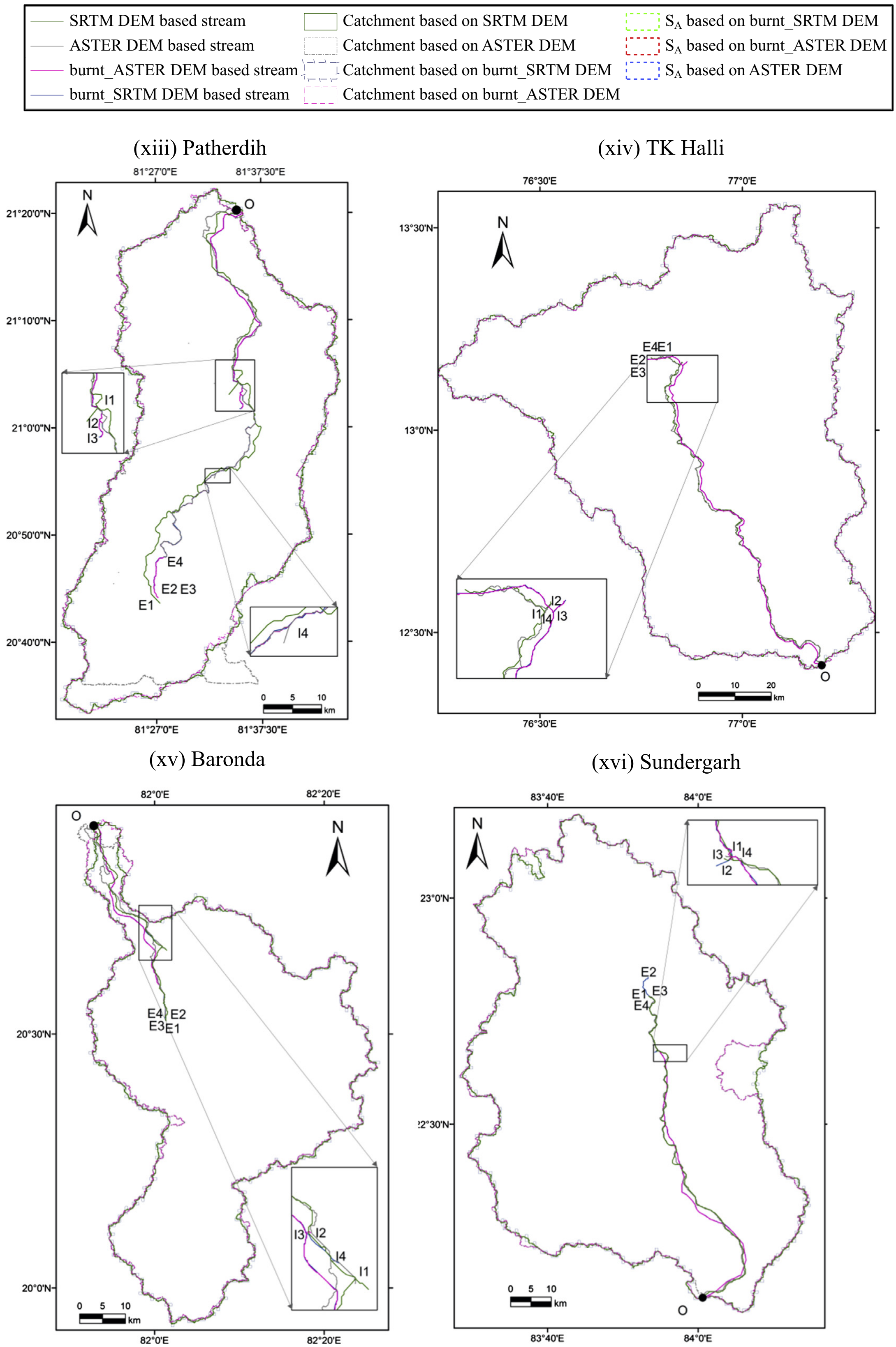

Fig. 9 (*continued*)

marginally (0–6%) in the case of most of the catchments in Cauvery and Mahanadi river basins (Fig. 10). Significant difference is found for Thevur (17%) and Hogenakkal (16%) catchments in Cauvery basin. Comparison of R-bias in q_p values derived based on the original SRTM and ASTER DEMs indicates that they differ marginally (0–5%) for most of the catchments (Fig. 10). Significant difference can be noted for Sevanur (18%), Thevur (10%), Bannur (10%), Kollegal (10%) and Andhiarkhore (26%) catchments.

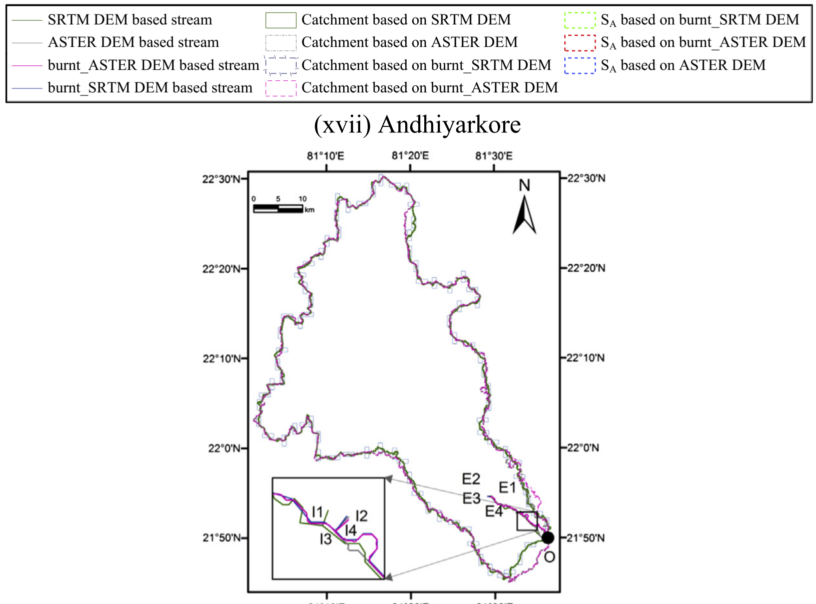

Fig. 9 (*continued*)

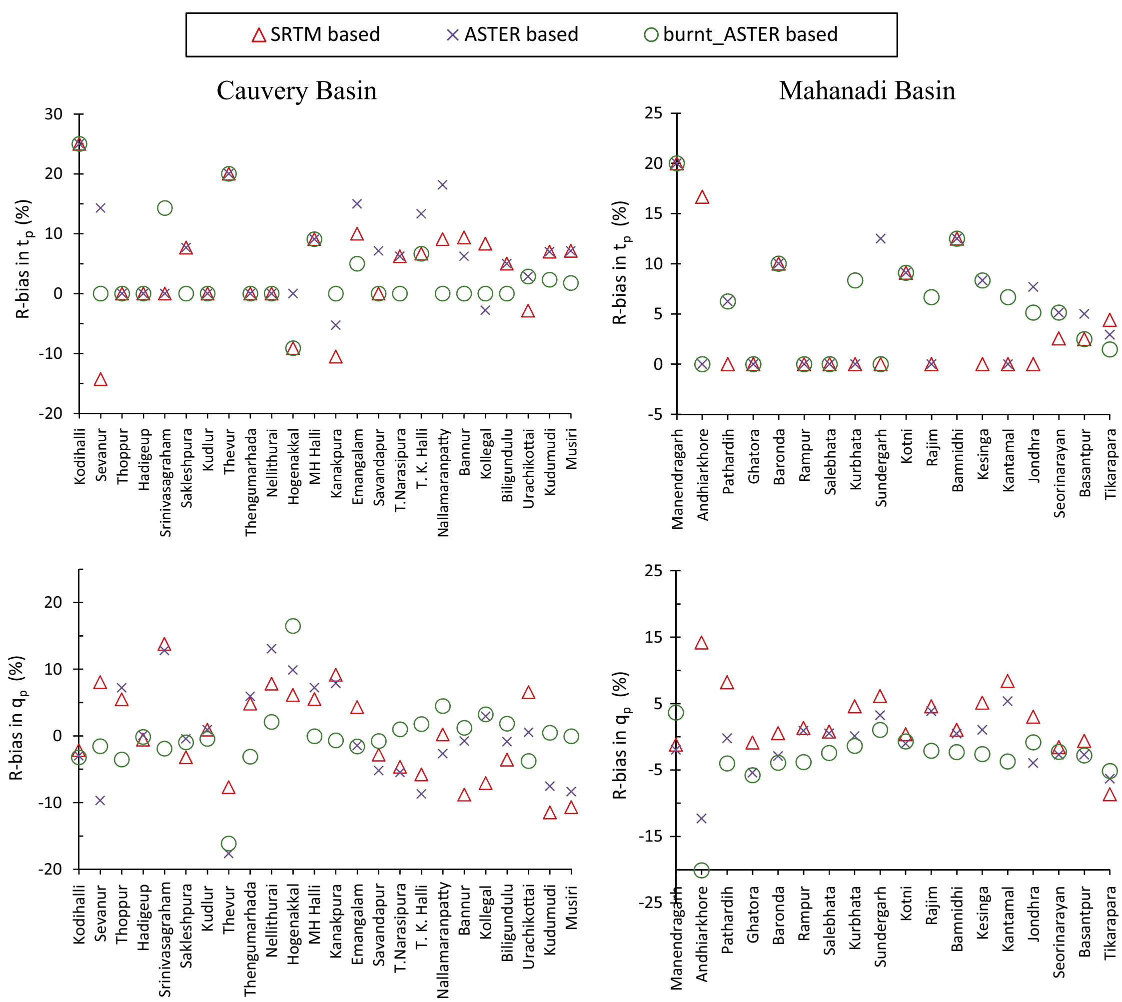

Fig. 10. Comparison of t_p (in hours) and q_p (in h^{-1}) of E-GIUHs derived based on original SRTM and ASTER DEMs, and burnt ASTER DEM with respect to t_p and q_p of burnt SRTM DEM.

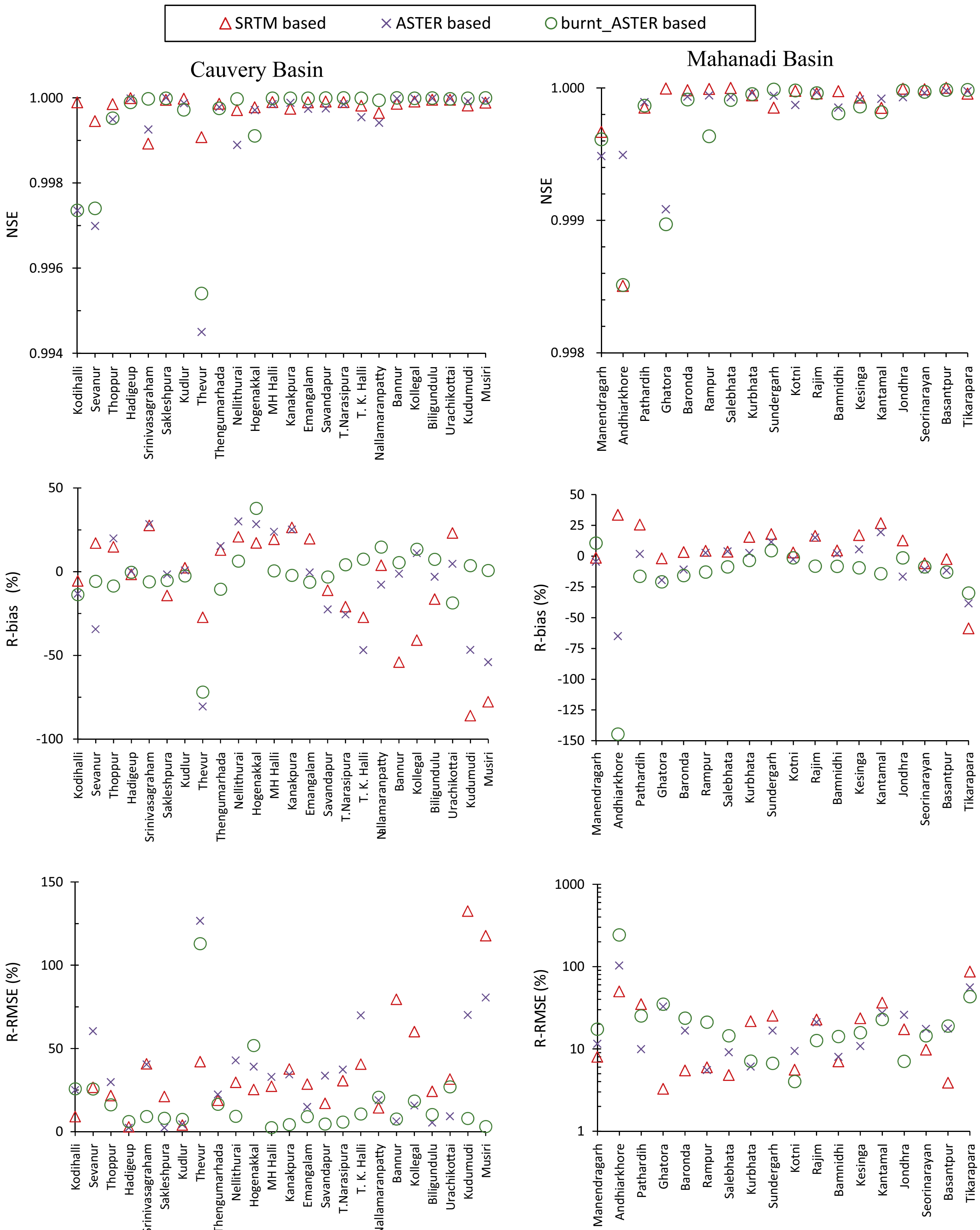

Fig. 11. Comparison of E-GIUHs derived based on original SRTM and ASTER DEMs, and burnt ASTER DEM with respect to burnt SRTM DEM.

In addition, E-GIUH derived for each of the 42 catchments based on the original SRTM and ASTER DEMs and burnt ASTER DEM were compared with E-GIUH derived based on burnt SRTM DEM to quantify difference in terms of R-bias, Relative Root Mean Square Error (R-RMSE) and Nash–Sutcliffe Efficiency (NSE).

$$\text{R-}bias(\text{DEM}) = \left(\frac{1}{N}\sum_{t=1}^{N}\frac{q_t^{burnt\_SRTM} - q_t^{\text{DEM}}}{q_t^{burnt\_SRTM}}\right) \times 100 \qquad (22)$$

$$\text{R-}RMSE(\text{DEM}) = \left[\sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(\frac{q_t^{burnt\_SRTM} - q_t^{\text{DEM}}}{q_t^{burnt\_SRTM}}\right)^2}\right] \times 100 \qquad (23)$$

$$\text{NSE}(\text{DEM}) = 1 - \frac{\frac{1}{N}\sum_{t=1}^{N}\left(q_t^{burnt\_SRTM} - q_t^{\text{DEM}}\right)^2}{\frac{1}{N}\sum_{t=1}^{N}\left(q_t^{burnt\_SRTM} - \bar{q}_t^{burnt\_SRTM}\right)^2} \qquad (24)$$

where $q_t^{burnt\_SRTM}$ and q_t^{DEM} denote respectively ordinate of E-GIUH derived based on burnt SRTM DEM and other DEM (i.e., original SRTM, or original ASTER DEM, or burnt ASTER DEM) corresponding to time $t(t = 1, \ldots, N)$; and $\bar{q}_t^{burnt\_SRTM}$ denotes mean of N ordinates of E-GIUH derived based on burnt SRTM DEM.

In the case of Cauvery basin, R-bias and R-RMSE values were generally least in the case of E-GIUHs derived based on burnt ASTER DEM (Fig. 11). Further, among E-GIUHs corresponding to original DEMs, those based on original SRTM DEM have low R-bias and R-RMSE for majority of catchments having area less than or equal to 9080 km^2. In the case of Mahanadi basin, R-bias values noted in the case of E-GIUHs derived based on original DEMs and burnt ASTER DEM are comparable and none of those DEMs is consistent in yielding the least values. R-RMSE values noted for E-GIUHs derived based on original SRTM DEM are generally least for majority of the catchments. Interestingly, NSE values are fairly close to 1.0 in the case of all the 42 catchments, implying that the statistic is ineffective in quantifying difference in E-GIUHs.

Differences between E-GIUH determined for each of the catchments based on real channel network (derived from burnt SRTM DEM) and E-GIUHs derived using different DEM sources could be attributed to DEM-based uncertainty associated with estimates of (i) equivalent H–S ratios, which in turn depend on self-similarity properties (λ, α) of channel network, and (ii) equivalent length of highest order stream (Eq. (20)) that depends on self-similarity properties (λ, α) and other morphometric descriptors (β, OE, OI, S_A and S_0) of stream network. Thus it can be concluded that uncertainty associated with DEM source cannot be ignored in hydrological studies involving E-GIUHs.

7. Summary and conclusion

There is dearth of attempts to test a methodology which was recently proposed by Moussa (2009) for computing equivalent H–S ratios (based on self-similarity properties of channel networks) and the corresponding E-GIUH. In this perspective, hypothesis of self-similarity" was tested on 42 catchments in two Indian river basins (Cauvery and Mahanadi) having wide range in their areas (156 km^2 to 1,24,450 km^2) by considering two different DEMs (30 m resolution ASTER and 90 m resolution SRTM). The hypothesis was found to be valid for all the 42 catchments. Following this, morphometric descriptors (S_0, S_A, OE, OI, α, λ and β), equivalent H–S ratios and E-GIUHs for the catchments obtained corresponding to the two DEMs were compared.

Comparison of morphometric descriptors of stream network in the catchments obtained by processing the original ASTER and SRTM DEMs indicated considerable differences. Comparison of the descriptors with those of the real network (obtained by processing burnt DEMs resulting from burning/fencing digitized real network into original DEMs) indicated that descriptors determined by processing burnt SRTM and burnt ASTER DEMs (which account for real channel networks) are closer to those determined from the original SRTM DEM (than to those from the original ASTER DEM) for majority of the 42 catchments. Thus, it can be concluded that SRTM DEM provides the best network for the study area, and burnt SRTM that results from inserting (burning/fencing) real network into SRTM DEM can be considered reliable for extracting morphometric descriptors for catchments in Mahanadi and Cauvery river basins.

In the case of burnt SRTM and ASTER DEMs, differences in S_0, S_A, OE, and OI were marginal, while differences in α, λ and β were considerable. Differences found in equivalent H–S ratios were consistent with those found in self-similarity properties α and λ. On the other hand, differences in L_e were marginal for most catchments, as the parameter is a function of several morphometric descriptors and equivalent H–S ratios. Differences in E-GIUH were evident owing to DEM based uncertainty in values of equivalent H–S ratios and L_e.

Equivalent H–S ratios and length of highest order stream determined for catchments in Cauvery and Mahanadi river basins find use in modeling hydrological response of the catchments. Extended research is underway to examine self-similarity properties and determine equivalent H–S ratios and E-GIUH for catchments in other river basins of India. It is also of interest to explore sensitivity of the estimates to additional DEM sources (e.g., Cartosat), and to base E-GIUH construction on conceptual models other than Nash model.

Acknowledgements

Authors express their gratitude to reviewers and the Editors for their constructive reviews that resulted in improving quality of the work. The second author acknowledges Ministry of Earth Sciences, Govt. of India, for grants provided through Project No. MOES/CTCZ/16/28/10 and Central Water Commission, India, for the data provided towards the research work.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2015.06.049.

References

AISLUS, 1988. Watershed Atlas of India, All India Soil and Land Use Survey, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India, New Delhi.

Beer, T., Borgas, M., 1993. Horton's laws and the fractal nature of streams. Water Resour. Res. 29 (5), 1475–1487.

Central Water Commission (CWC), 2012. Integrated hydrological data book. Hydrological data directorate, information systems organization, Water planning and projects wing, New Delhi, India.

Gupta, V.K., Waymire, E., Wang, C.T., 1980. A representation of an instantaneous unit hydrograph from geomorphology. Water Resour. Res. 16 (5), 855–862.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geo. Soc. Am. Bull. 56, 275–370.

Howard, A.D., 1967. Drainage analysis in geologic interpretation: a summation. AAPG Bull. 51, 2246–2259.

Jain, S.K., Singh, R.D., Seth, S.M., 2000. Design flood estimation using GIS supported GIUH approach. Water Resour. Manage. 14 (5), 369–376.

La Barbera, P., Rosso, R., 1989. On the fractal dimension of stream networks. Water Resour. Res. 25 (4), 735–741.

Moussa, R., 2008a. Effect of channel network topology, basin segmentation and rainfall spatial distribution on the geomorphologic instantaneous unit hydrograph transfer function. Hydrol Process. 22, 395–419.

Moussa, R., 2008b. What controls the width function shape, and can it be used for channel network comparison and regionalization? Water Resour. Res. 44, W08456. http://dx.doi.org/10.1029/2007WR006118.

Moussa, R., 2009. Definition of new equivalent indices of Horton-Strahler ratios for the derivation of the Geomorphological Instantaneous Unit Hydrograph. Water Resour. Res. 45, W09406. http://dx.doi.org/10.1029/2008WR007330.

Moussa, R., Bocquillon, C., 1996. Fractal analysis of tree-like channel networks from digital elevation model data. J. Hydrol. 187, 157–172.

Rodríguez-Iturbe, I., A. Rinaldo, 1997. Fractal River Basins, Chance and Self-Organization. Cambridge Univ. Press, New York, 547 pp.

Rodríguez-Iturbe, I., Valdés, J.B., 1979. The geomorphologic structure of hydrologic response. Water Resour. Res. 15 (6), 1409–1420.

Rosso, R., 1984. Nash model relation to Horton order ratios. Water Resour. Res. 20 (7), 914–921.

Scheidegger, A.E., 1965. The algebra of stream-order numbers. US Geol. Surv. Prof. Pap. N. 525 (B), 187–189.
Scheidegger, A.E., 1968a. Horton's law of stream numbers. Water Resour. Res. 4 (3), 655–658.
Scheidegger, A.E., 1968b. Horton's laws of stream lengths and drainage áreas. Water Resour. Res. 4 (5), 1015–1021.
Schumm, S.A., 1956. Evolution of drainage systems & slopes in badlands at Perth Anboy, New Jersey. Geo. Soc. Am Bull. 67, 597–646.
Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topology. Geo. Soc. Am Bull. 63, 1117–1142.
Strahler, A.N., 1957. Quantative analysis of watershed geomorphology. Trans. AGU 38 (6), 913–920.
Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In: te Chow, Ven (Ed.), Handbook of Applied Hydrology. McGraw-Hill, New York, pp. 4–39.
Tarboton, D.G., 1996. Fractal river networks, Horton's laws and Tokunaga cyclicity. J. Hydrol. 187, 105–117.
Zernitz, E.R., 1932. Drainage patterns and their significance. J. Geol. 40, 498–521.