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Discharge and Sediment Transport in the Tropical Rivers of Kerala, India and their Controlling Factors

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Abstract: Kerala, the southern-most State of India, is characterized by its unique physiographic setup and 44 small rivers flowing across its narrow width. Based on 15 years (1986-87 to 2000-01) of daily sediment concentration and discharge data of 16 rivers, annual, seasonal, monthly, and daily variation in the suspended sediment yield of the State was analyzed and its controlling factors are discussed herein.

There is a marked variability in sediment yield characteristics from north to south and from year to year. Sediment concentration in the rivers varies between 167 mg/l and 2944 mg/l. Chaliyar River transported the highest annual average sediment load of about 0.40×10^6 t, whereas Meenachil River supplied the lowest of 0.04×10^6 t. Sediment yield varied between 40 and 250 t/km^2/year, with northern rivers showing larger yields. The central Kerala region, which is drained by major rivers and geologically stable, yielded lower values. Narrow land strips of northern and southern regions, characterized by steep slopes, were highly prone to erosion. Due to the variability in distribution of rainfall, the northern rivers transported major share of sediment during Southwest (SW) monsoon (75 to 95 %), whereas there was a substantial amount of sediment transport (20-55 %) during Northeast (NE) monsoon through the rivers from the southern region.

Key words: Sediment load, SW monsoon, NE monsoon, Kerala.

Introduction

The growing awareness on wide ranging environmental significance of suspended sediment transport by rivers has generated a considerable body of information concerning the sediment yields and their control by climate, man's activities, and other catchment characteristics (UNESCO, 1982; Peart and Walling, 1986; Vaithiyanathan et al., 1992; Chakrapani and Subramanian, 1993; Yang et al., 2002; Chakrapani, 2005).

The existing global estimates on sediment transport are based on a few large rivers, which include some low yielding rivers. Therefore, studies on medium and small rivers improve the database of the global estimates (Biksham and Subramanian, 1988). Walling and Fang (2003) stated that a larger database is required to provide a more definitive assessment of current trends in land–ocean sediment transfer by the world's rivers.

Quantitative assessments of river sediment loads were made for the major and medium rivers of the world (Holeman, 1968; Wilson, 1972; Dunne, 1979; Griffiths, 1982; Milliman and Meade, 1983; Keown et al., 1986; Lajczak and Jansson, 1993; Yang et al., 2002) and for Indian rivers (Abbas and Subramanian, 1984; Goswami, 1985; Biksham and Subramanian, 1988; Jha et al., 1988; Ramesh and Subramanian, 1988; Vaithyanathan et al., 1992; Chakrapani and Subramanian, 1993; Rao et al., 1997). These studies have contributed much to the

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understanding of the erosional and sediment yield processes and the regional factors influencing these processes.

Kerala, the southern-most State of India, is drained by 41 west flowing rivers, which discharge large amounts of sediment to the coastal region. The long coastal region consists of complex interlinking of backwaters, estuaries, and the Arabian Sea. Hence, for an integrated study of the coastal eco-system, it is required to analyze the spatial and temporal distribution of water and sediment load transported by these rivers to the coastal environment.

In the present study, an attempt was made to analyze the daily sediment and water yield data of 16 west flowing rivers of Kerala State. The sediment load varies monthly, seasonally, and annually in most of the rivers and hence short-term studies can result in under or over estimation of load. Therefore, a comprehensive picture of temporal and spatial variation of the sediment-carrying capacity of rivers of Kerala is presented here with its controlling factors, using discharge-sediment concentration data for 15 years.

Materials and Methods

Kerala State is situated in the humid tropics and lies between 8° 18' and 12° 48'N and 74° 52' and 77° 22'E. Based on physiography, the State can be divided from west to east as: the Lowlands with altitude less than 7.5 m, Midlands with altitude between 7.5 and 75 m, and the Highlands with altitudes greater than 75 m. The Western Ghat forms a continuous mountain wall on the eastern border of the State and a narrow coastal zone forms the western lowlands.

The State receives an average annual rainfall of about 3000 mm. It ranges in the lowlands from 900 mm in the south to 3500 mm in the north; in the midlands, from 1400 mm to 4000 mm; and in the highlands, from 2500 mm to 6000 mm (CWRDM, 1995). About 60% of the annual rainfall is received during the Southwest (SW) monsoon and 25% during Northeast (NE) monsoon.

Forty four (44) small to medium rivers originate from the Western Ghats, out of which 41 flow towards west and the other three rivers towards east. Periyar, Bharathapuzha, Pamba, and Chaliyar are the major rivers of the State. The net annual discharge from all these rivers is estimated to be 77,900 MCM. The catchment area and the discharge carried by these rivers are small compared to other major rivers in India.

The Central Water Commission (CWC), Govt. of India, is maintaining 16 sediment gauge sites in the State for suspended sediment sampling. Location of these rivers and the gauge sites is shown in Figure 1. The daily suspended sediment concentration (mg/l) and corresponding discharge (cumec) data were collected for 15 years (1986-87 to 2000-01) from the CWC (CWC, 2001).

Table 1 gives the characteristic of the river basins studied. The daily data on suspended sediment concentration (mg/l) were converted into sediment load (ton). Total discharge (Q) and sediment load (S) for each month were estimated from the data. The percentage discharge and sediment load during different seasons were estimated. The annual average sediment load, sediment yield, and maximum sediment concentration values for each of the river basins are given in Table 1.

Results and Discussion

Sediment Yield

Average sediment yield values (t/km^2) are given in Table 1. Northern rivers are having comparatively large values (210-250), followed by southern rivers (90-130). Central Kerala rivers yielded unstable rates (40 to 130). Many of the major rivers of the State drain this region and the

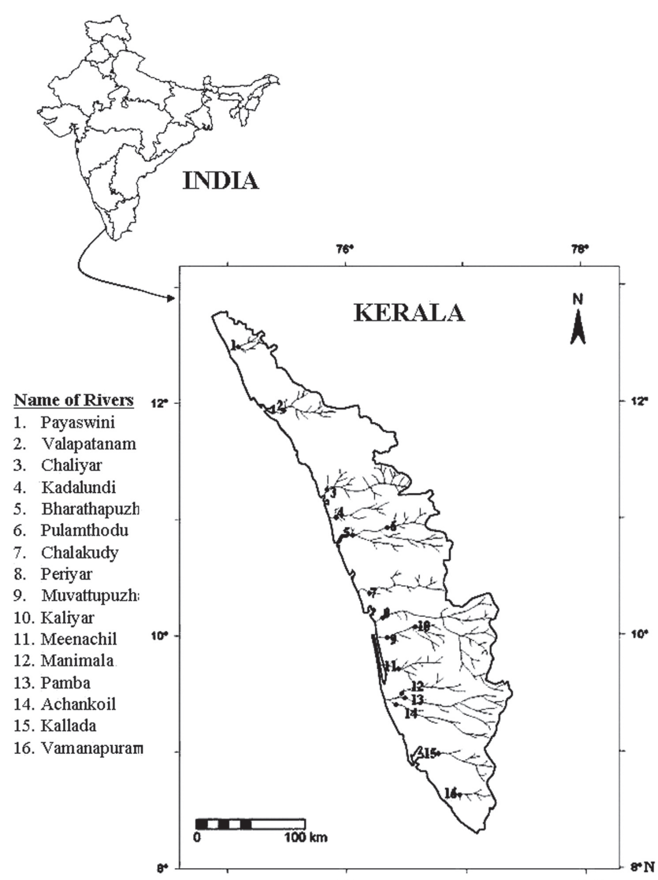

Figure 1: Location of the rivers with the gauge sites.

Table 1: Characteristics of the river basins studied

Name of the river basin (from north to south)	*Average annual rainfall (mm)*	*Length of river (km)*	*Catch. area (km^2)*	*Ave. slope (m/m)*	*Average yearly discharge (MCM)*	*Average yearly sediment load (Ton)*	*Sediment yield (t/km^2)*	*Max sediment conc. (mg/l)*
Payaswini	4000	105	957	0.012	2384	239934	251	1090
Valapatanam	3600	101	1070	0.013	3543	252144	236	613
Chaliyar	3800	169	1876	0.012	4175	401614	214	1024
Kadalundi	3400	86	750	0.013	1303	85171	113	345
Bharathapuzha	2300	209	5755	0.009	4326	369186	64	1163
Pulanthode	2600	78	940	0.013	1756	101771	108	791
Chalakudy	3600	120	1342	0.010	1798	50234	38	167
Periyar	3200	244	4234	0.007	6895	320029	76	739
Muvattupuzha	3100	92	1208	0.011	5068	157001	130	595
Kaliyar	3000	71	405	0.014	1194	44667	110	557
Meenachil	3000	61	615	0.017	1756	36566	60	1091
Manimala	3300	90	731	0.012	1795	70486	96	559
Pamba	3600	176	1713	0.009	4016	156851	92	896
Achankovil	2600	138	810	0.005	1247	77130	95	904
Kallada	2800	92	1210	0.016	1636	104447	86	802
Vamanapuram	2200	88	540	0.020	701	68619	127	2944

region may be tectonically stable as inferred by Anderson et al. (2005) from their analyses of central Kerala rivers. The seasonal variation of sediment yield for different regions of the State is shown in Figure 2.

Annual Sediment Load Variation

Chaliyar River transported the highest average sediment load of 0.40×10^6 t, whereas Meenachil River yielded the lowest sediment load of 0.04×10^6 t. Most of the rivers showed a decreasing trend in sediment load transported during this period. Figure 3 shows the trends in average annual discharge and sediment load for the rivers of Kerala over the study period. The figure shows that corresponding to a slight increase in the average discharge, there is a drop in the sediment transported over the 15 years of study period. When individual rivers are considered, almost all the rivers from the central and southern region showed a marked decrease in sediment load corresponding to increase in discharge. This is due to the many storage/diversion structures coming up within these river systems during the last decade.

Annual variation of sediment load depends on the rainfall and discharge in the rivers. During the period of analyses, the Chaliyar supplied the maximum sediment load (0.82×10^6 t) and Meenachil supplied minimum sediment load (0.015×10^6 t). The minimum and maximum values of discharge and sediment load and its ratio is given in Table 2.

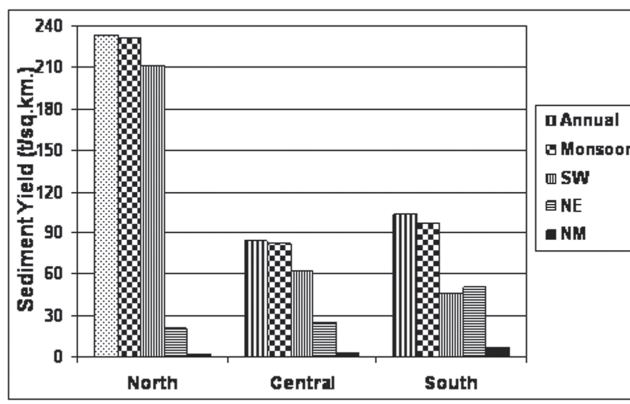

Figure 2: Seasonal variation of sediment yield for different regions of Kerala.

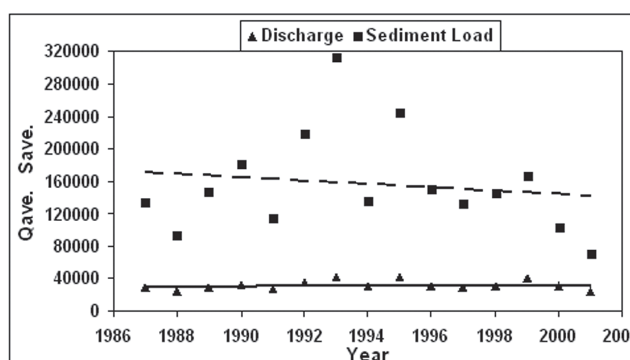

Figure 3: Trend in discharge and sediment load for 15-year study period.

Table 2: Variation of discharge, *Q* (MCM) and sediment load, *S* (ton)

Name of the river	*Max Q*	*Min Q*	*Max/Min*	*Max S*	*Min S*	*Max/Min*
Payaswini	3301	1543	2.2	404286	119574	3.4
Valapatanam	4742	1904	2.5	470511	67935	6.9
Chaliyar	6060	2158	2.8	814941	156087	5.2
Kadalundi	1950	806	2.4	152549	44032	3.5
Bharathapuzha	6785	2645	2.6	769037	154816	5.0
Pulanthode	2470	1046	2.4	194727	42833	4.6
Chalakudy	2765	1115	2.5	130120	15408	8.5
Periyar	9968	4867	2.1	646802	87188	7.4
Muvattupuzha	6703	3894	1.7	230057	88270	2.6
Kaliyar	1578	945	1.7	72632	29260	2.5
Meenachil	2311	1334	1.7	61756	14041	4.4
Manimala	2398	1282	1.9	108041	34442	3.2
Pamba	5397	3117	1.7	501562	65770	7.6
Achankovil	1912	747	2.6	182022	17724	10.3
Kallada	2839	902	3.2	564145	39037	14.5
Vamanapuram	1134	288	3.9	278977	21606	12.9

Minimum and maximum *Q* and *S* values coincided in the same years for most of the rivers. Maximum variation in the load was observed for Kallada river basin, where the ratio was about 14.5. Generally, it was seen that the southernmost rivers showed high ratio. These rivers were characterized by heavy transport of sediment load during NE monsoon season. The variation of the ratio, for discharge was almost constant (around 2) except for the southern-most rivers Kallada (3.2) and Vamanapuram (3.9). This implies an extreme inter-annular variability in sediment transport corresponding to a small change in discharge, which was more predominant in the river basins of southern Kerala.

Seasonal Variation

The seasonal variation of discharge and sediment load is shown in Table 3. Except for Muvattupuzha, the discharge during monsoon season was in the range of 87-98% of the annual discharge. SW monsoon was the major source of monsoon discharge for northern rivers. However, the percentage discharge during SW monsoon decreased steadily from north to south, about 84% in the north to 50% in the south. On the other hand, the NE monsoon yielded about 13% discharge for the northern rivers, whereas the percentage was about 30% for the southern rivers.

In the case of sediment load, all the northern rivers yielded about 98-100% of the sediment load during monsoon season whereas for the southern rivers this percentage was about 92-95%. Similar observations were also made for other major rivers in India (Goswami, 1985; Biksham and Subramanian, 1988; Ramesh and Subramanian, 1988; Vaithiyanathan et al., 1992). SW monsoon sediment load ranged from 90-95% for northern rivers whereas this was about 40-55% for southern rivers. During NE monsoon season, northern rivers yielded 5-20% of the total sediment load whereas for the southern rivers, this was about 40-54%. The seasonal contribution of discharge and sediment load for different regions of the State is shown in Figure 4.

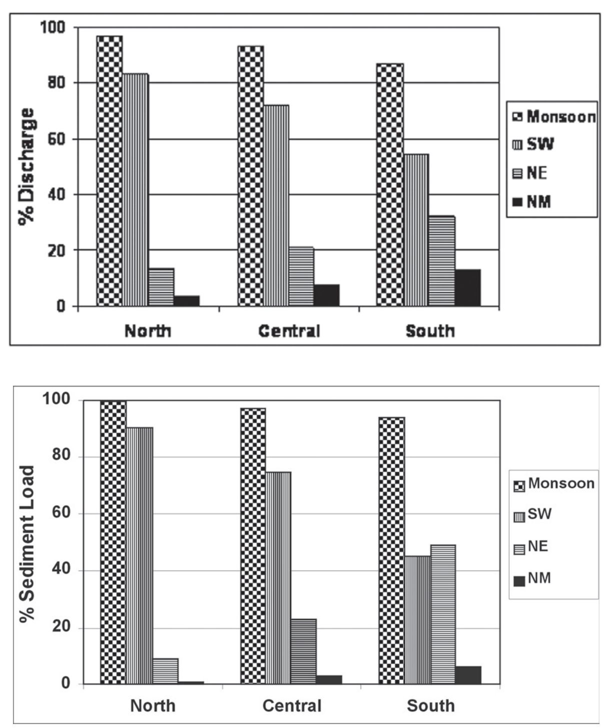

Figure 4: Seasonal variation of discharge and sediment load contributions for different regions of Kerala.

Table 3: Seasonal variation of % *Q* and % *S* for the rivers

Name of the river	*% Discharge (Q)*				*% Sediment Load (S)*			
	Monsoon			*Non-monsoon*	*Monsoon*			*Non-monsoon*
	SW	*NE*	*Total*		*SW*	*NE*	*Total*	
Payaswini	83.5	13.5	97.0	3.0	90.0	9.5	99.5	0.5
Valapatanam	86.2	11.3	97.5	2.5	94.0	5.3	99.3	0.7
Chaliyar	79.6	15.8	95.4	4.6	87.0	11.9	98.9	1.1
Kadalundi	77.3	20.0	97.3	2.7	79.0	19.6	98.6	1.4
Bharthapuza	74.5	19.7	94.2	5.8	79.9	18.1	98.0	2.0
Pulamthode	72.6	21.8	94.4	5.6	73.8	24.3	98.1	1.9
Chalakudy	75.7	16.8	92.5	7.5	84.2	14.1	98.3	1.7
Periyar	67.9	18.2	86.1	13.9	89.8	8.3	98.1	1.9
Muvattupuzha	56.9	19.2	76.1	23.9	65.9	25.4	91.3	8.7
Kaliyar	77.1	18.9	96.0	4.0	75.7	22.6	98.3	1.7
Meenachil	69.7	22.8	92.5	7.5	71.8	23.7	95.5	4.5
Manimala	69.4	23.6	93.0	7.0	68.1	27.4	95.5	4.5
Pamba	65.5	23.3	88.8	11.2	54.9	40.3	95.2	4.8
Achankovil	62.3	29.7	92.0	8.0	53.9	41.7	95.6	4.4
Kallada	50.7	32.4	83.1	16.9	39.8	53.8	93.6	6.4
Vamnapuram	50.3	35.2	85.5	14.5	41.4	51.4	92.8	7.2

* Seasons as per the Indian Meteorological Department (IMD) norms
M - Monsoon (June to Nov.)
NM- Non-monsoon (Dec. to May)
SW - Southwest monsoon (June to Sept.)
NE - Northeast monsoon (Oct. and Nov.)
W - Winter (Dec. to Feb.)
S - Summer (March to May)

Monthly Variation

The monsoon months—July, August, October, and November—were primarily responsible for majority of the annual sediment transported in river basins. SW monsoon is predominant within the northern and central parts of the State, while NE monsoon is a major factor for the southern region. The monthly variation of rainfall, discharge, and sediment load for rivers from different regions of the State is shown in Figure 5. The sediment load peaked during SW monsoon for most of the northern rivers, while two peaks were noticed for the southern rivers. For northern rivers, July contributed about 45-50% of sediment load. Southern rivers showed two peaks with July accounting for 20-30% sediment load whereas October or November contributed 20-40% of annual load.

Daily Variation

Analysis of daily sediment data for the individual rivers indicated that very few days during the monsoon months accounted for the bulk of annual sediment load. The highest sediment concentration for a day was 2,944 mg/l, recorded on 14th November 1992 for the Vamanapuram, which accounted for 64% of the annual sediment load.

- Valapatanam River supplied 48% of annual sediment load on 23rd July 1989.
- Vamanapuram supplied 39% of its annual load on 8th August 1986.
- On November 15th, 1992, Kallada transported 30% of its annual load.
- For Pamba, two days in October 1992, accounted for 43% of its annual load.
- Four days in July 1989 accounted for 51% of annual load in Periyar.
- Meenachil River transported 49% of annual load in three days of July 1991.
- Four days in July 1989 accounted for 43% of annual load in Chaliyar.
- Achankoil supplied 43% of its annual load during four days in August 1986.

Particle Size

Suspended sediment particles are divided into three size groups by CWC, coarse (diameter > 0.2 mm), medium (0.2 mm > diameter > 0.075 mm) and fine (diameter < 0.075 mm). Due to the gentle slope and decreased flow velocity at the downstream reaches, there was total dominance of finer particles at the gauging stations. Fine particle fraction was of the range 65-79% for northern rivers, 78-93% for central rivers and about 86-90% for southern rivers. The northern rivers, Payaswini, Valapatanam, and Chaliyar, transported large fraction of coarse particles during SW monsoon season.

Factors Controlling the Sediment Yield Characteristics

Rainfall

It was noted that the seasonal and spatial distribution of rainfall is the major factor controlling the sediment load patterns of the rivers studied. As seen from Table 1, the average annual rainfall is the maximum for the northern regions, which resulted in heavy sediment yield from the northern rivers. About 75% of this rainfall occurred in the SW monsoon season for northern-most rivers. However, within the southern region, percentage of the SW monsoon rainfall was almost equal to that during NE monsoon season. Therefore, the discharge and sediment load peaked during July/August for northern rivers, while it indicated two peaks during July/August and October/November for central and southern rivers, as shown in Figure 5. The southern-most rivers were transporting larger amount of sediment load during NE monsoon season.

Discharge

It is reasonable to believe that a strong relation exists between sediment load and water discharge under natural conditions. Therefore, establishing a relationship between sediment load and water discharge (rating curve) in a river basin is desirable. It is observed that good correlation existed between water and sediment discharge for different rivers of the State. The rating curve drawn with the average annual discharge and sediment load for all the rivers is shown in Figure 6. It was found that the relation between discharge and sediment load improved by segregating the data into different seasons and regions. The NE monsoon season produced relations with poor goodness of fit as this season was characterized with heavy sediment yielding events.

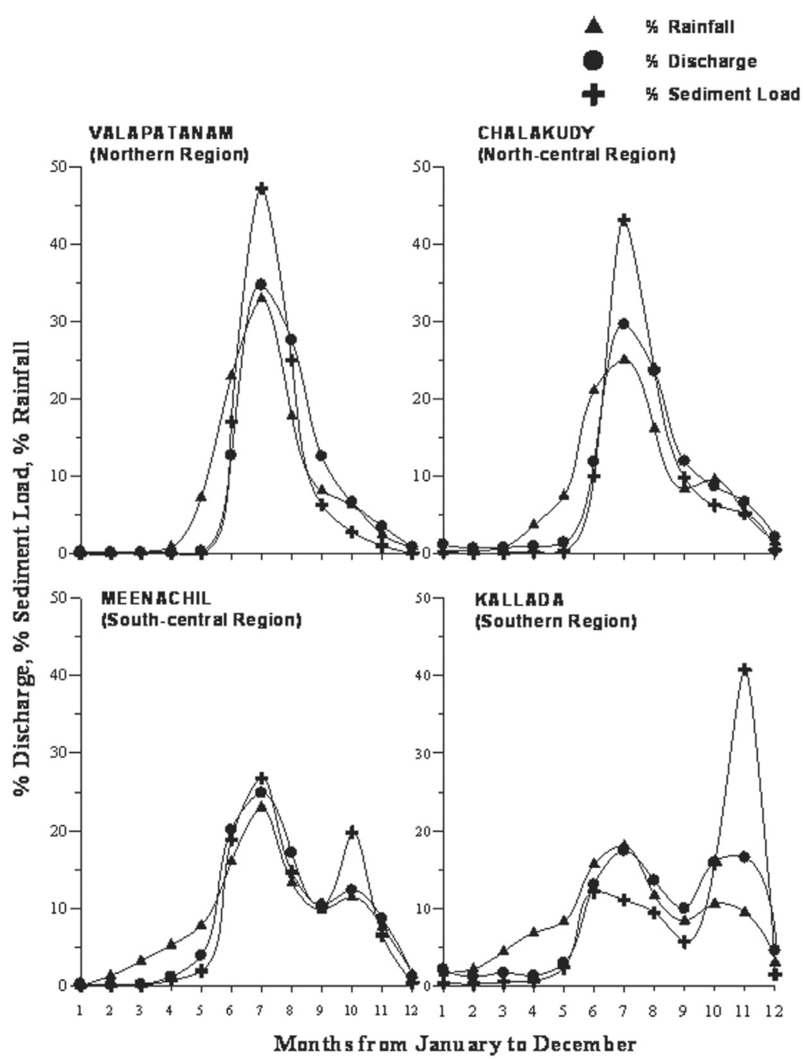

Figure 5: Monthly variation of rainfall, discharge and sediment load for the rivers from different regions of the state.

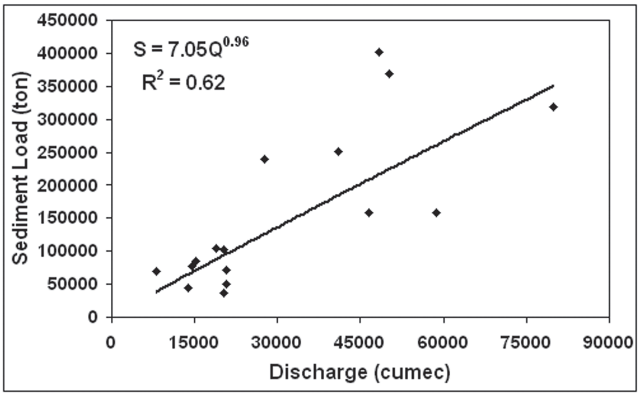

Figure 6: Rating curve for the rivers of the state.

The annual sediment load from each river varied with corresponding changes in discharge over the entire duration of the available data. However, it was found that the S/Q fraction was not a constant and generally maximum for the northern rivers (6 to 9), decreased towards the central rivers (2 to 7) and again increased for southern rivers (4 to 8.5). The increase in discharge from year to year was associated with a similar increase in sediment load. However, the larger ratio for northern and southern rivers indicated that the sediment load is not entirely dependent on the discharge but on the availability of material to transport also.

Geology

Geology is one of the important factors, which controls the amount and texture of sediment transported by a river. However, in the present case, geological distribution, from upstream to downstream for most of the river basins was similar. The upstream reaches are covered by crystalline rocks with low sediment yield and the midlands are by sedimentary rocks with high erodibility. Hence, geology may not be a major factor for the variability in sediment load from individual rivers of the State. However, the central Kerala region is considered to be tectonically stable (Anderson, 2005), and hence the sediment yields are low from this region. Detailed monitoring of smaller tributaries is required to estimate the contribution of each of these geological formations.

Soils and Land Use

Lateritic and coastal loams cover the major soil types of the State, with the upstream reaches consisting of forest loams. There are mainly five broad categories of land use distributed unevenly: arable land, forestland, plantation, grassland, and waste lands.

Slopes of the Western Ghats in the central Kerala are covered by dense forest (Periyar reserve forest). This region resists soil erosion and this can be the cause of low sediment yield rates for the rivers of this region. However, it was noticed that encroachment along the river banks and agricultural activities are encouraging accelerated erosion.

In the forested regions, landslide is rare in spite of heavy rainfall and the steepness of the hill slopes. Soil creep appears to be the only significant mechanism that contributed sediment to stream channels, especially during NE monsoon for the southern rivers. In cultivated areas, the sediment sources were more diverse and it is important to identify them separately to indicate their relative importance.

Slope

The State of Kerala is having maximum width at the centre (about 130 km) and narrows towards northern and southern regions (about 30 km). These extreme northern and southern regions are characterized by steep slopes, where northern slopes extends almost up to the coast. These features are attributed to the high sedimentation rate within these regions.

Catchment Size

Brune (1948) showed that sediment yield generally decreases with catchment size, in proportion to the –0.15 power of the catchment area. Similar result has been reported in many other studies (Figure 7). The rivers studied here also followed the same relationship:

$$\text{Sediment yield, } S_y = 304.3\,A^{-0.15}\ (R^2 = 0.044)$$

The average annual sediment load and discharge can be correlated to catchment area as:

$$\text{Sediment load, } S = 304.3\,A^{0.85}\ (R^2 = 0.59)$$

$$\text{Discharge, } Q = 167.1\,A^{0.72}\ (R^2 = 0.63)$$

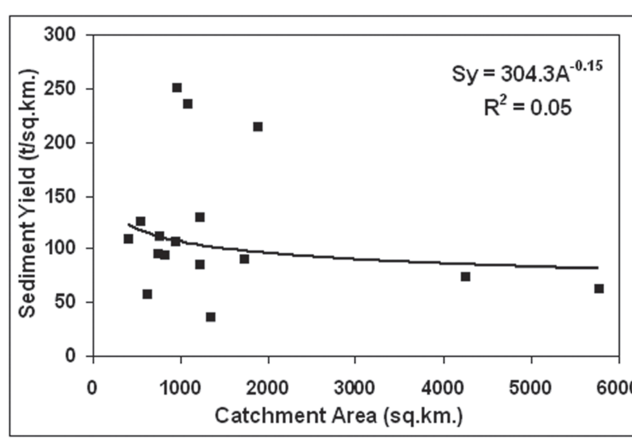

Figure 7: Relationship between sediment yield and catchment area.

This demonstrated that drainage area has an important control on discharge and sediment load. Several of the small river basins are being eroded more intensively than the bigger catchments. Both long-term averages and yearly amounts indicated that erosion rates are highest in small basins.

Conclusion

The present study was formulated to understand the temporal and spatial variation in suspended sediment input by the tropical rivers of Kerala State, India, to the coastal geo-environment of the state and to identify the factors influencing these variations.

The daily suspended sediment concentration data for the period from 1986-87 to 2000-01 were collected for 16 west flowing rivers of the State. This data was converted into monthly, seasonal and annual amounts to compare the sediment carrying characteristics of individual rivers and seasonal variations.

Large variations were noticed in the sediment load carried by individual rivers and between individual years for a river basin. In general, sediment yield pattern followed the seasonal distribution of rainfall, discharge and topography of the river basin. It is found that slight variations in any of these parameters resulted in drastic changes in the sediment transport through rivers. This signifies the importance of studies in sediment dynamics for the tropical rivers. The salient points from this study are listed below:

- Northern and southern Ghat regions are more prone to erosion than the central region.
- Distribution of rainfall and topographical features are the major factors influencing the sediment yield.
- Monsoon supplies major share of sediment load; SW monsoon is the driving factor for northern region, whereas both SW and NE monsoons control the sediment flow pattern for southern regions.
- Sediment yield during non-monsoon season is very low for northern rivers, whereas there is a sizeable contribution for southern rivers.
- Southern rivers show a sharp increase in sediment transport during NE monsoon corresponding to a moderate rise in discharge.
- Within central Kerala, erosion processes have become more stabilized than northern and southern regions, which results in lower sediment yields.
- Few days in monsoon accounts for bulk of the sediment load.
- Northern rivers exhibit a uni-mode distribution for the monthly sediment load, whereas the distribution is bi-modal for the southern rivers.

Sediment yield values suggest low transport of sediment load in spite of humid tropical climate, which is favourable for weathering and erosion. The reason may be due to the settling of sediment particles or over-abstraction of sand (sand mining) from midland regions. Often, the fluvial system may try to balance this condition by fulfilling its carrying capacity by bank or bed erosion, which could be again detrimental to the ongoing surface processes.

It was observed that the quantity of sediment transported downstream shows a decreasing trend over the years corresponding to increase in discharge, the reasons for which have to be investigated. For sound and sustainable management of coastal zones, it is important to understand the balance between erosion and retention and to quantify the exact amount of the sediments reaching this eco-system.

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