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Impact of iron ore mining on suspended sediment response in a tropical catchment in Kudremukh, Western Ghats, India

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Abstract

Available secondary suspended sediment data from the 1980s was analyzed together with new data collected during 2001–2003 at instrumented sites upstream and downstream of open-cast mining activities ($\sim$4.2 km^2) in an enclosure within the Kudremukh National Park in south India. More than 50% of the suspended sediment load in both the Bhadra River and Bhadra Reservoir comes from mining-affected lands that occupy <1% of the total catchment area (1968 km^2). For baseflow conditions during the post-monsoon period of 2001, 0.02 Mg km^{-2} day^{-1} of suspended sediment was discharged at the upstream site compared with 0.74 Mg km^{-2} day^{-1} downstream of the mine. During the 2002 and 2003 monsoons, these rates increased to about 1.99 and 7.89 Mg km^{-2} day^{-1} for upstream and downstream sites, respectively. The specific sediment yield above the mine is 239 Mg km^{-2} year^{-1} versus 947 Mg km^{-2} year^{-1} downstream. Sediment concentration downstream was significantly higher than upstream for all conditions. The current annual suspended sediment load below the mine ranges from 100,000 to over 150,000 Mg, depending on the size and frequency of large rain events. During the 2002 and 2003 monsoon seasons, 20–30% of the total suspended sediment load during the sampling period of 67 and 123 days, respectively, was transported in one single day and over one-third of the total recorded suspended load is discharged in less than 4 days in each monsoon. Daily rainfall and maximum hourly rainfall intensity were reasonable predictors of daily sediment loads downstream of the mine ($R^2 = 0.71$ and 0.575, respectively; $p < 0.001$). However, the upstream response was not predicted well by these variables, suggesting an absence of rapid overland pathways and/or reduced availability of easily transportable sediment on the less-disturbed lands above the mining area. Large episodic sediment events downstream of the mine were associated with daily rainfall >150 mm and hourly intensities exceeding 20 mm. One hundred and nine such episodic events occurred between 1990 and 2001 alone. A conservative estimate of the total suspended sediment load in the Bhadra River after mining commenced in the 1980s is 1.37×10^6 Mg, although the actual value could be considerably higher, up to 10^7 Mg. Comparison of historic data and another study in 1994, with recent measurements confirm that mining and associated activities in Kudremukh National Park are the greatest sources of sediment entering the Bhadra River; and the Bhadra river carries considerably more sediment now than before mining started damaging riverine ecosystems and disrupting downstream water resources.

Keywords: Open-cast mining; Suspended sediment yields; Extreme monsoon rainfall events; Reservoir sedimentation; Tropical montane forest; Grasslands

1. Introduction

Impacts of open-cast mining can be environmentally detrimental. For example, mining-related stream sediment levels have been found to be orders of magnitude higher than those associated with other land-use changes, such as deforestation, agricultural intensification, road-building, and urbanization (Brown, 1974; Jackson, 1982; Bruijnzeel, 1990, 1993). While open-cast mining operations all over the world are known to have devastating effects on downstream ecosystems, the impacts in humid tropical areas are particularly severe (Pickup et al., 1981; Bird et al., 1984).

The Kudremukh iron ore mine is situated in an area of the Western Ghats Mountains, a region that is typically dominated by montane grasslands and evergreen forests. As the mine is located in a region that receives more than 6000 mm of rainfall annually, the potential for contributing to sediment loading in downstream water bodies and damaging endangered ecosystems is high.

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Government reports indicate that enhanced sediment loading in the Bhadra River following the initiation of mining was a source of concern (KERS, 1987; KSPB, 1987). One study concluded that an average of 47% of the stream-bed sediment in the Bhadra downstream of the mine originated from the mining areas alone (Shankar et al., 1994).

One study commissioned by Ministry of Environment and Forest indicated that the fish communities downstream of the mine were severely disrupted (CES, 2001). The absence of torrential fish species, for example, was attributed to mine-derived sediment disrupting habitat by suppressing filamentous algal growth on boulders, pebbles and cobbles. The fish community downstream of the mine was dominated by species tolerant of high turbidity levels. Another study showed that the rich amphibian community in Kudremukh is also disrupted by mining (Krishnamurthy, 2003).

Two recently commissioned studies (NIRCON, 1997; NEERI, 2000) reported contradictory findings regarding increased sediment loading in the river as a result of mining activity. These studies however did not collect sediment data during monsoon seasons when most of the rainfall and surface runoff occurs. Rivers in India, including the Bhadra, are known to carry more than 85% of their sediment loads during the monsoon months (Vaithiyanathan et al., 1992; Kale, 2002, 2003; Fig. 1). The recent studies also ignored available secondary data and the findings of the stream-bed sediment study (Shankar et al., 1994).

In this study we assess the influence of the mining activities in Kudremukh on the suspended sediment load in the Bhadra River. We examine historical records and collect new suspended sediment data upstream and downstream of the mine during one brief post-monsoon period in 2001 and two successive monsoon seasons in 2002 and 2003. Using these data we estimate the change in stream sediment load since the initiation of mining. The objectives of this research are two-fold: (1) document one environmental consequence of forest and grassland conversion to mining in this area; (2) gain a better understanding of the potential offsite impact of mining on downstream ecosystems.

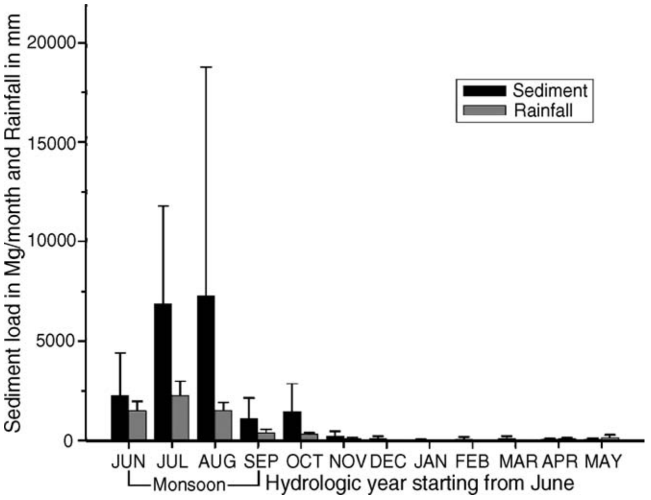

Fig. 1. Average suspended sediment load in Bhadra River based on historic Water Resources Development Organization data for Malleshwara, Kudremukh (KERS, 1987; KSPB, 1987). Note the overwhelming contribution of the monsoonal months (June–September).

2. Study site

2.1. Background

The Western Ghats Mountains are one of 25 global biodiversity hotspots (Myers et al., 2000). Ecosystem ‘‘services’’ provided by the Western Ghats ecosystems include reducing sediment inflow into irrigation and hydro-electric reservoirs, providing unpolluted water for drinking and other domestic uses, and sustaining fisheries in rivers and reservoirs. Sedimentation of reservoirs resulting from forest degradation in this area is of great concern (Babu et al., 2000). The Bhadra Reservoir, which has a catchment area of 1968 km^2, was commissioned in 1964 (Fig. 2). It now serves North Karnataka area by irrigating more than 1000 km^2 of agricultural lands and generating 33 MW of power.

Rich iron ore deposits in the upper catchment led to the establishment of the Kudremukh Iron Ore Company Limited (KIOCL) in 1976. A lease area of about 46 km^2 was granted to the company in the upper catchment of the Bhadra River (Fig. 2). The mine and plant facilities, including a tailings dam, were commissioned in 1980 after a road was cut through the forested mountains. This iron ore mine, the largest in India, was designed to produce 22.6 million Mg of crude ore annually. Prospecting of additional deposits led to additional road construction and mining activity downstream of the original site.

In 1987, the 600 km^2 Kudremukh National Park (KNP) was established to preserve the rich biodiversity in the area (Fig. 2). The park features a large stretch of rainforest and montane grassland that is the primary habitat for species including the lion tailed macaque and tiger (Karanth, 1985, 1992; Karanth et al., 2001). This area is part of the high priority (level-one) global-level tiger conservation unit (TCU-55) that is recognized by the Wildlife Conservation Society and the World Wildlife Fund (Wikramanayake et al., 1998, 1999). KNP has the largest expanse of Shola–grassland ecosystem (Jose et al., 1994) in the Western Ghats (Fig. 3a). The total amphibian species richness of KNP represents 20% of the whole Indian amphibian fauna (Krishnamurthy, 2003).

Sediment gauging at Malleshwara in the upper reaches of the Bhadra River catchment was initiated by the Water Resources Development Organization (WRDO) in late 1983. Subsequently, government reports noted a surge in sediment load that was related to mining. The following excerpts are indicative of the impacts resulting from KIOCL mining operations in the area (KERS, 1987; KSPB, 1987):

> ‘‘By visual observations during site inspection on 24 February 1987 it was observed that the main river passing through the mining area is red and muddy as against the clear water flowing in some of the tributaries the sub-catchment of which are not lying in the zone of mining ore.’’

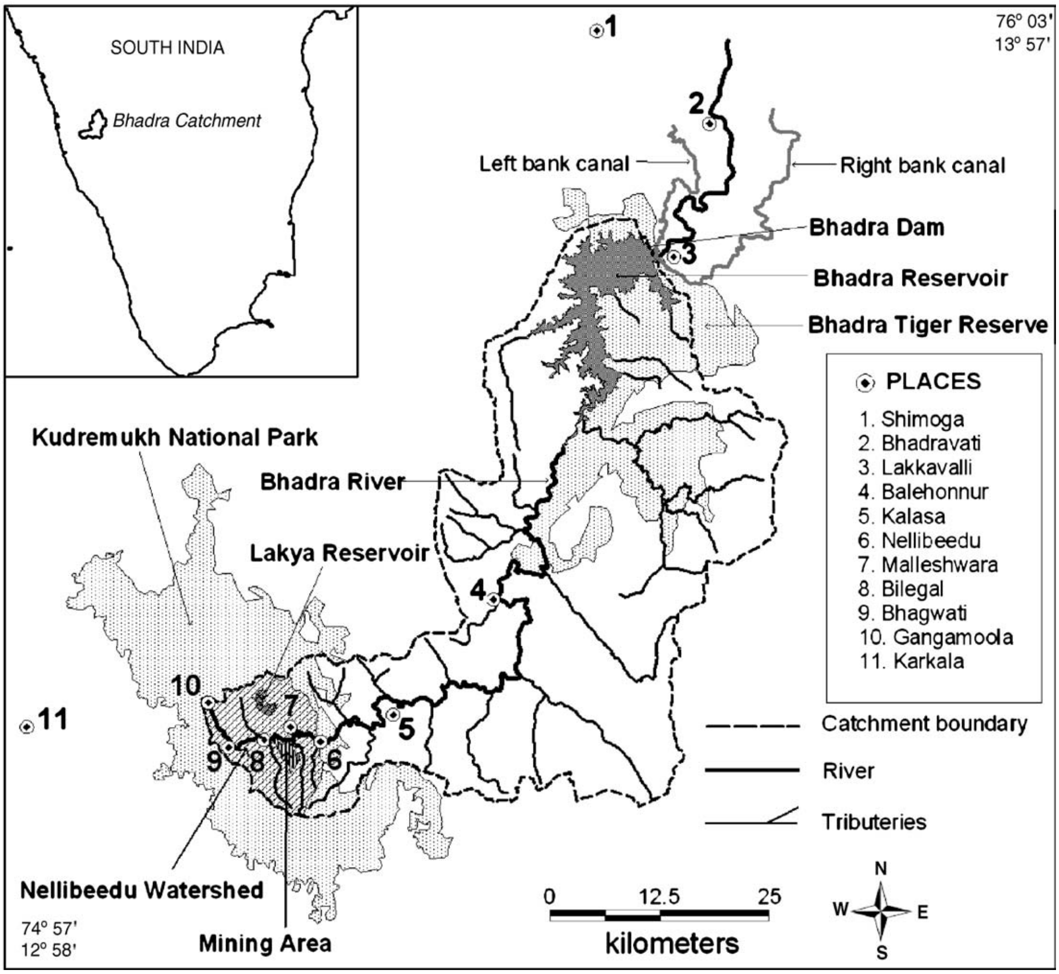

Fig. 2. Location of study area and measurement sites. The gauging sites for which secondary data is available are Malleshwara and Balehonnur on the Bhadra River. The Bhadra Reservoir is located just downstream of Balehonnur. The primary data were collected at Bilegal, upstream of the mine, and Nellibeedu, located downstream of the mine.

> "The river Bhadra passing through the catchment of KIOCL now carries heavy silt. This conclusion is supported by the silt gauging being conducted by the gauging sub-division under the control of WRDO since August 1983".

Eventually, scientists, conservationists, farmers, and concerned citizens who were either affected by sedimentation (Fig. 3b) or concerned about damage to wildlife habitat (Fig. 3c and d) campaigned to raise public awareness. Recently, the Supreme Court of India ordered the closure of KIOCL operations in Kudremukh by the end of 2005.

2.2. Physical setting

The study area is within an enclosure (46 km^2) that is legally excluded from the Kudremukh National Park (600 km^2), in Chikmagalur district of Karnataka, India. The elevation ranges from 100 to 1890 m a.s.l. and the slope gradients (estimated from 30 m DEM) are as high as 0.88 m m^{-1}; mean gradient is $0.18 \pm 0.11_{\mathrm{sd}}$ m m^{-1}. The geology is predominantly metamorphic gneiss with granite and quartz. Deposits of hematite and magnetite occur in a few sites. The 1:500,000 soil map (NBSSLUP, 1996) indicates the occurrence of deep, well-drained, gravelly clay and clayey soils in the upper catchment. The soils are partly sandy loam with local occurrences of laterite in the mining area. Annual average rainfall is 6200 mm $\pm$ 1370_{sd} (1966–2003); local annual totals approach 10,000 mm (Fig. 4a). Daily rainfall totals can exceed 400 mm (Fig. 4b), and there is significant orographic variability within the catchment (Krishnaswamy and Mehta, 2003). The entire Bhadra catchment receives 82% of its precipitation from the Southwest Indian Monsoon, which occurs between June and September (Irrigation department, 1998).

2.3. Measurement locations

The secondary suspended sediment data used in this study was collected in the 1980s by WRDO at Malleshwara (upstream catchment area = 108 km^2, Fig. 2). In 2001, we established two new suspended sediment collection sites on the Bhadra River. While the Malleshwara location was appropriate for assessing mining impacts in the 1980s, by the time of our 2001–2003 study, mining impacts had spread farther

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Fig. 3. (a) Undisturbed Shola–grassland ecosystems in the Kudremukh National Park upstream of the mining area. (b) Bhadra River with heavy sediment load at Balehonnur, which is downstream of mining area. Note the iron-rich sediment deposit on the river bank (August 1996). (c) One of the mining-affected areas in Kudremukh National Park. (d) Landslide and debris falling from the mining area into Bhadra River. (e) Clear water from a stream emerging from a Shola grassland sub-catchment that is undisturbed by mining activity flowing into the sediment-rich Bhadra River downstream of mining area (August 1996). (f) Bhadra River flowing from undisturbed catchment into mining affected catchment.

downstream. Thus, a new downstream collection site at Nellibeedu was established (Fig. 2). Lands in the 140.7 km^2 catchment above Nellibeedu are affected by roads, ‘‘mined-out’’ areas (Fig. 3c), minor landslides that extend down to the river (Fig. 3d), and outflows from a tailings dam, a sewage treatment plant, and two check dams. The contrast in sediment load from Shola-grassland-dominated catchments and that of mining- and road-affected catchments is obvious (Fig. 3e). The total area either directly or indirectly affected by mining operations is at least 8 km^2. However, the actual ‘‘broken-up’’ area was only about 4.2 km^2 in 2000, just prior to our study.

The second new measurement site was established at Bilegal, which is located upstream of the mine—and therefore not influenced by mining activities. Land cover in the 40.7 km^2 catchment above Bilegal is about 90% Shola grassland–evergreen forest, but also includes small patches of agricultural lands, grazing areas, and some roads and trails (Figs. 2, 3a, and f; Table 1).

3. Methods

3.1. Rainfall

Daily rainfall was measured at Bilegal in 2002 and 2003 using standard non-recording gauges. Hourly rainfall depths were recorded manually when feasible in 2002. In 2003, a second non-recording rain gauge was used to record hourly rainfall depths at Bilegal. In a few cases of low values of daily rainfall that lasted less than an hour, the hourly rain gauge recorded higher values than the daily gauge. These spurious data were omitted from our statistical analyses. The daily rainfall and hourly intensities are expected to vary spatially

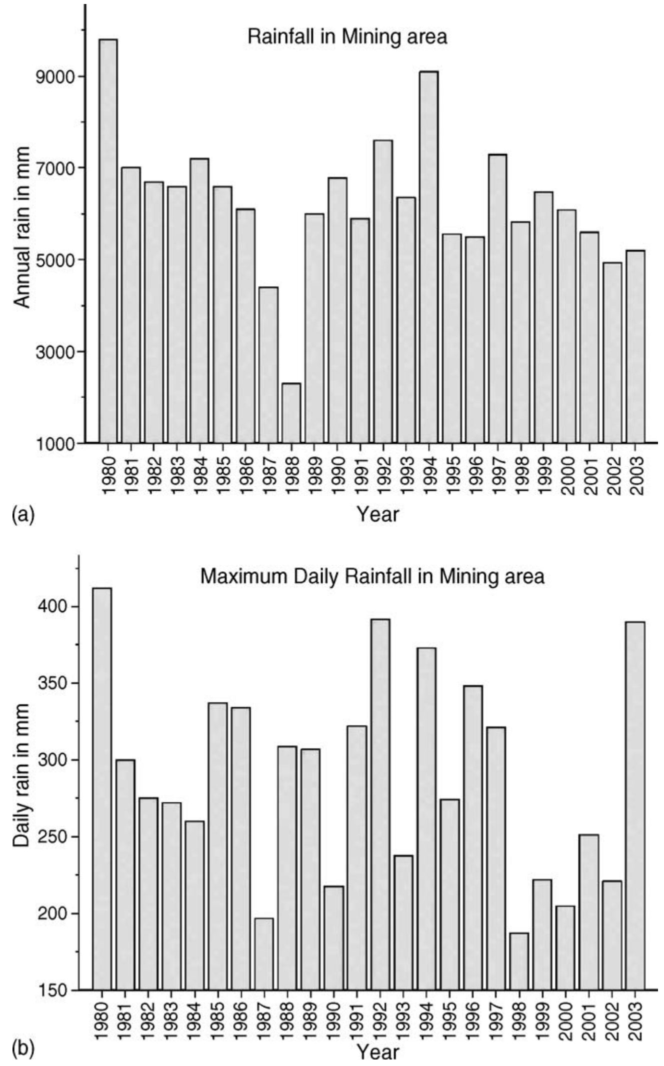

Fig. 4. (a) Annual rainfall for Malleshwara, Kudremukh (CES, 2001). (b) Maximum daily rainfall by year for Malleshwara, Kudremukh.

Table 1
Land cover characteristics of watersheds upstream and downstream

Land cover	Bilegal		Nellibeedu	
	Percentage of area	Area (km^2)	Percentage of area	Area (km^2)
Shola/evergreen forest	57.47	23.39	38.80	54.59
Grassland	39.09	15.91	51.86	72.96
Agriculture/grassland[a]	3.19	1.30	1.80	2.53
Water	0.25	0.10	1.90	2.67
Mining	0.00	0.00	3.46	4.87
Iron ore tailings	0.00	0.00	2.19	3.08
Total area		40.70		140.70

[a] *Note*: The ''agricultural/grassland'' class indicated in the table is a mixed class and it is not possible to reliably distinguish between the two in this mixed class. It is likely to be dominated by cultivated fields, grazing pastures and fallow fields.

within the catchment (Krishnaswamy and Mehta, 2003); thus, we recognize that rainfall data collected at Bilegal may not be totally representative of the rainfall distribution in the entire catchment for all storms.

3.2. Stream discharge

For the 2001 post-monsoon sampling, only temporary staff gauges were established at both the Bilegal and Nellibeedu sites, thus no discharge values were available for analysis. However, for the monsoon seasons of 2002 and 2003, discharge was estimated at locations with newly installed permanent staff gauges. Rating curves were established to convert stage to discharge using stream velocities taken with a current meter at three points on a cross-section and at two depths (about 0.20 and 0.80 times the depth from water-surface to stream bed). At high discharges, the current meter could not be safely employed. Velocity was therefore estimated by timing the travel time of floating objects. Discharge was calculated by the velocity-area method. Stage readings were made at both sites at least twice a day, with more frequent readings taken during the rising and falling limbs of selected storms. The rating curve data are presented elsewhere (Krishnaswamy and Mehta, 2003).

3.3. Sediment

In the post-monsoon period of 2001, a total of 28 and 34 grab samples were collected at the upstream and downstream sites within a 22-day period. During the 2002 and 2003 monsoon sampling periods, 670 upstream and 836 downstream suspended sediment samples were collected over a total of 190 days. All samples collected with a US DH-59 depth-integrated sampler at least twice a day, with more intensive sampling during monitored rain events. During dangerous high-discharge situations, grab samples were taken from safe streamside locations in lieu of depth-integrated sampling in the stream. The sediment–water samples ranging between 100 and 300 ml were analyzed by filtering through 0.45-μm, 47 mm diameter Cellulose nitrate membrane filters (Sartorius) using a water-operated glass filter pump and the dry weight was assessed by oven-drying the filters at 105 °C for 24 h.

Daily suspended sediment load estimates for the monsoon periods in 2002 and 2003 were calculated as the product of mean daily flow and mean sediment concentration for each day using the appropriate conversion constant:

$$\text{Load}\,(\text{Mg day}^{-1}) = \frac{Q \times \text{SEDCONC} \times 86{,}400}{1{,}000{,}000} \qquad (1)$$

where SEDCONC is daily mean sediment concentration (mg l^{-1}); Q is daily mean flow ($\text{m}^3\,\text{s}^{-1}$).

Mean daily flows were estimated as the average of all estimated instantaneous flow values recorded in a single day. Since gauging was more frequent during storm events, these could be biased towards higher values. Total sediment load over the sampling period was the sum of the individually estimated daily loads. Specific sediment yield was calculated

Table 2
Summary of sediment and streamflow data collected at the upstream Bilegal and downstream Nellibeedu locations during the 2001 post-monsoon and the 2002 and 2003 monsoons periods

	2001		2002		2003	
	Bilegal	Nellibeedu	Bilegal	Nellibeedu	Bilegal	Nellibeedu
No. of sampling days	22	22	67	67	123	123
Total rain received (mm)	100	100	3400	3400	5200	5200
Median daily discharge ($m^3 s^{-1}$)	NA	NA	30	69	23	118
Mean sediment con. ($mg\,l^{-1}$)	2.61	12.47	22.4	164.6	47.3	108.6
Median sediment con. ($mg\,l^{-1}$)	1.5	8.0	10.6	75.8	6.92	36.3
Maximum sediment con. ($mg\,l^{-1}$)	21	61	181	3308	1779	1854
Sediment yield[a] ($Mg\,km^{-2}\,day^{-1}$)	NA	NA	1.34	7.93	2.82	8.81
Sediment yield[b] ($Mg\,km^{-2}\,day^{-1}$)	0.02	0.74	1.44	7.0	2.36	7.84
Mean daily sediment yield ($Mg\,km^{-2}\,day^{-1}$)			1.39	7.47	2.59	8.33
Monsoon sediment yield[a] ($Mg\,km^{-2}\,year^{-1}$)	NA	NA	161	952	338	1057
Monsoon sediment yield[b] ($Mg\,km^{-2}\,year^{-1}$)	NA	NA	173	840	283	941
Mean monsoon sediment yield ($Mg\,km^{-2}\,year^{-1}$)			167	896	310.5	999
Grand average of daily sediment yield[c] ($Mg\,km^{-2}\,day^{-1}$)	Bilegal		1.99			
	Nellibeedu		7.89			
Grand average of monsoon sediment yield[c] ($Mg\,km^{-2}\,year^{-1}$)	Bilegal		239			
	Nellibeedu		947			

[a] Sediment yield estimated using Eq. (1) with daily mean flow and mean sediment concentration. Total load is the sum over the total number of sampling days. Daily mean Sediment yield is calculated by dividing total load by number of sampling days and catchment area (40.7 km^2 for Bilegal, 140.7 km^2 for Nellibeedu). Estimated monsoon yield is obtained by multiplying total number of monsoon days (120) with mean sediment yield per day. This can be considered almost as an annual sediment yield because the monsoon accounts for the bulk of the annual load.

[b] Total load is estimated using median daily flow and mean sediment concentration in Eq. (1) both calculated over the entire sampling period. Sediment yield is calculated as in a. Estimated monsoon yield is obtained by multiplying total number of monsoon days (120) with mean sediment yield per day. This can be considered almost as an annual sediment yield because the monsoon accounts for the bulk of the annual load.

[c] Grand averages are based on mean taken across 2 years and two methods: a and b above.

by dividing the total sediment load by catchment area. Since, no daily flow estimates are available for the 2001 post-monsoon period, we assumed that baseflow conditions were similar to those in 2002 and 2003 for the limited period of record. We applied Eq. (1) to the overall mean daily sediment concentration and the overall median flow over the entire sampling period to generate estimates of total sediment load and yield for 2001. These alternative sediment load and yield estimates were also calculated for the monsoons of 2002 and 2003 (Table 2) for comparison with the post-monsoon 2001 results. These median-based alternate estimates are less sensitive to effects of over-estimation of flows at higher stage and the bias of individual mean daily flows during periods with higher flows. This second estimate thus provides a lower bound for our estimates, especially for the downstream site affected by mining. Further details of the sediment sampling, rainfall measurement and stream gauging are available elsewhere (Krishnaswamy and Mehta, 2003).

To establish a relationship between both daily rainfall and maximum recorded hourly rainfall (as independent variables) and daily sediment loads, the following non-linear regression model was used:

$$\text{Load}\,(\text{Mg}\,\text{day}^{-1}) = 10^{\left(\frac{a(\text{DR or MHR})}{b(\text{DR or MHR})}\right)} + \varepsilon \qquad (2)$$

Load is daily sediment load (Mg); DR is daily rainfall (mm); MHR is maximum recorded hourly rainfall depth in a day (mm), and ε is the error $\sim N(0, \sigma^2)$. Parameter 'a' represents the asymptotic sediment load achieved as the independent variable increases indefinitely. Parameter 'b' can be interpreted as the value of the independent variable corresponding to generating half the asymptotic sediment load; it also determines the shape of the curve.

3.4. Watershed characterization

The topography and land cover of the Bilegal and Nellibeedu watersheds were characterized using available topographic maps and satellite images. Contours (20 m interval) and drainage features were digitized from 1:50,000 Survey of India topographic sheets. IDRISI Geographical Information System (GIS) software was used to derive a digital elevation model (DEM) (Fig. 5a) and topographic variables, including slope and aspect. A 29th March 2002 Landsat ETM+ image with 30 m spatial resolution was used to derive a land-cover and land-use map using IDRISIs unsupervised classification module (Fig. 5b). Table 1 lists the land-cover percentages determined from both satellite-derived land-use maps and other available maps (e.g. CES, 2001). For area estimations, we did not account for unimproved roadways and trails—these features are arguably important contributors to sediment loads, as have been shown elsewhere on disturbed landscapes (Reid and Dunne, 1984; Ziegler and Giambelluca, 1997; Ziegler et al., 2004; Sidle et al., 2004).

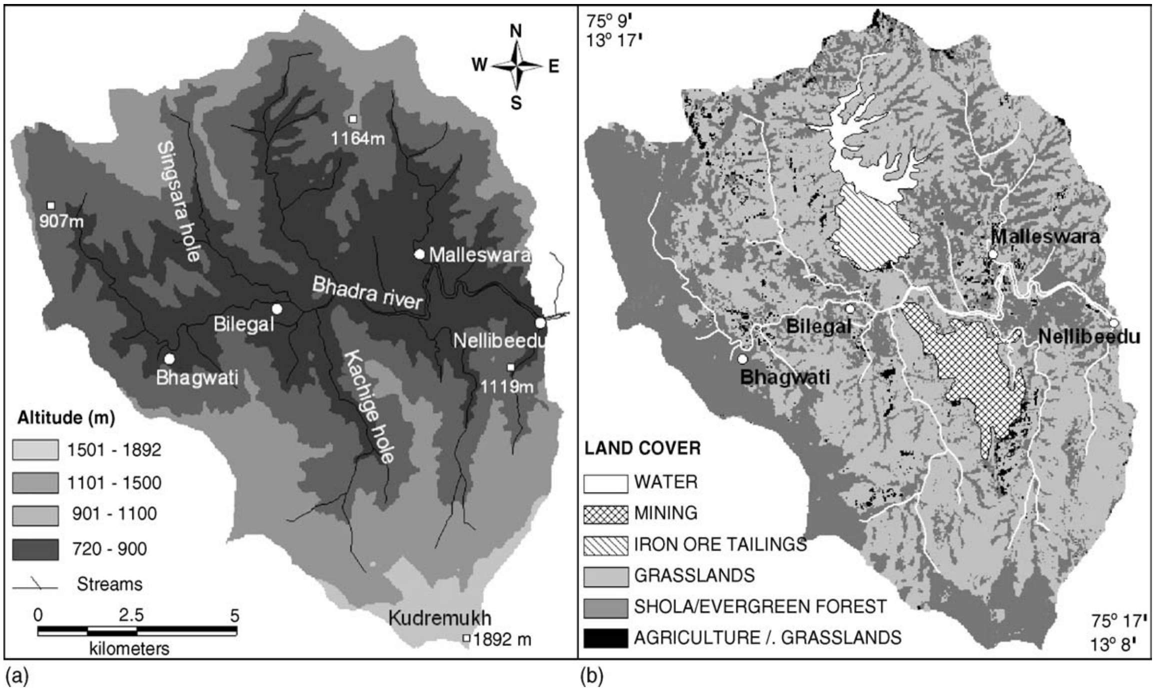

Fig. 5. (a) Elevation map of upper Bhadra Catchment defined at Nellibeedu with study sites indicated. (b) Land-cover and land-use map of upper Bhadra Catchment defined at Nellibeedu with study sites indicated.

4. Results

4.1. Secondary data

Monthly suspended sediment loads determined by WRDO at the Malleshwara site for the period from August 1983 to 1989 (Fig. 6) were based on a daily sampling regime. The annual load for the 1983–1984 hydrologic year (June 1983 to May 1984) was reconstructed by adding estimated sediment loads for June and July, assuming an average proportional contribution of these months relative to the total annual load for the year. Sediment data were not available for the 1987–1988 hydrologic year.

The WRDO (KERS, 1987; KSPB, 1987) suspended sediment data for the Bhadra River gauged at Malleshwara and sediment inflow into Bhadra Reservoir for the years 1983–1989 are shown in Fig. 7. The major sediment contributor to the reservoir was the main channel of the Bhadra River, which was gauged at Balehonnur (Fig. 2); only minor contributions came from another stream draining into the reservoir further downstream (data not shown). The maximum daily sediment load in the Bhadra River was recorded during 1987–1988 hydrologic year (4884 Mg). The only sediment concentration data from prior to mining activities was collected during the 1978–1979 hydrologic year at Balehonnur (CES, 2001).

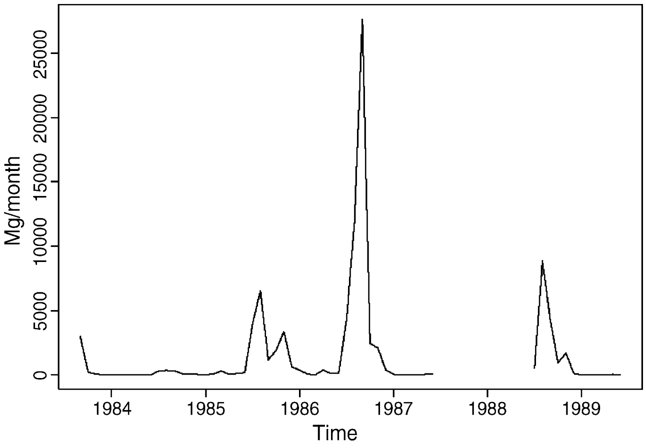

Fig. 6. Time-series of monthly suspended sediment load in Bhadra Fiver gauged at Malleshwara by Water Resources Development Organization (KERS, 1987; KSPB, 1987).

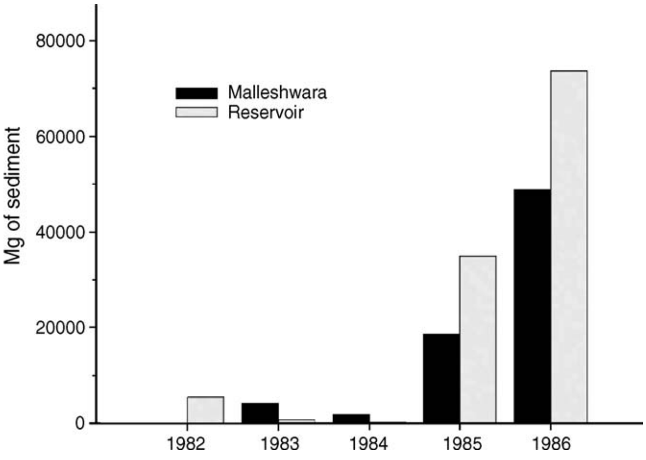

Fig. 7. Comparison of suspended sediment load inflow to the Bhadra Reservoir with the corresponding sediment load in the upper Bhadra River at Malleshwara, downstream of the mining area (KERS, 1987; KSPB, 1987).

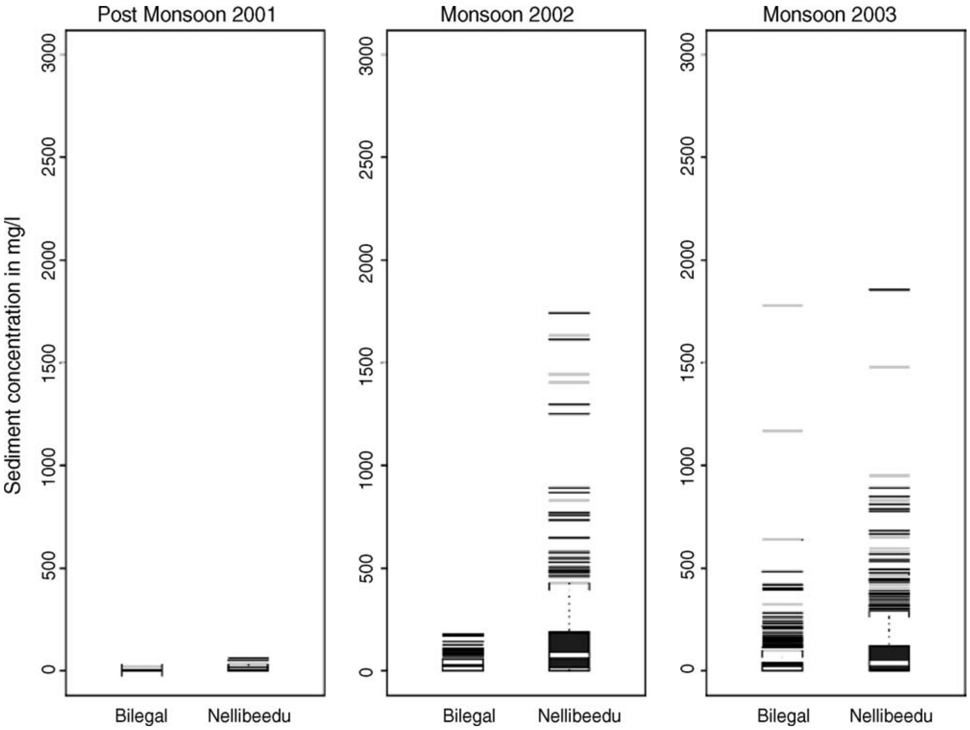

Fig. 8. Box and Whiskers plots of suspended sediment concentration recorded upstream (Bilegal) and downstream (Nellibeedu) of the mining-affected area during post-2001 monsoon period and the 2002 and 2003 monsoon periods. In the box plots, the median is in white inside the box; the 25th and 75th percentiles define the ends of the box; the length of the box is the inter-quartile range; whiskers indicate the largest and smallest values above and below the box that are less ≤1.5 times the inter-quartile range from either end; and outliers exceeding these, if any, are indicated by lines outside the upper and lower whiskers.

Those data indicate only that sediment concentration ranged from 41 to 171 mg l^{-1}.

4.2. Primary data

Stream width and corresponding estimated bankfull discharge at Bilegal were about 19 m and 90 $m^3 s^{-1}$, respectively; at Nellibeedu these values increased to 58 m and 1889 $m^3 s^{-1}$, respectively. Mean baseflow, which was estimated based on minimum stage during the 2002 and 2003 gauging periods, was about 0.35 $m^3 s^{-1}$ at Bilegal; 11 $m^3 s^{-1}$ at Nellibeedu. Median daily flows for Bilegal were 30 and 23 $m^3 s^{-1}$ for the observation periods of 2002 and 2003, respectively; downstream at Nellibeedu the median daily flows in 2002 and 2003 were 69 and 118 $m^3 s^{-1}$.

Sediment concentrations determined during the three study periods are shown in Fig. 8. Estimated sediment load and measured rainfall depths for the monsoons of 2002 and 2003 are shown in Fig. 9. In general, sediment concentration downstream of the mine was higher than that upstream during the 2001 post-monsoon and the 2002 and 2003 monsoon sampling periods (Fig. 9, Table 2). The median sediment concentration downstream of the mine was five to seven times greater than that at the upstream site during all three periods. Furthermore, all maximum downstream sediment concentrations exceeded the corresponding maximum upstream concentrations (Fig. 8, Table 2) and is considerably higher than the maximum reported value of 171 mg l^{-1} for 1978–1979 (before mining started) for Balehonnur, downstream of the mining site. In 2001, sediment concentration in the downstream site was significantly higher (mean 12.47 mg l^{-1}) than the upstream site (mean 2.61 mg l^{-1}) based on paired t-test and Wilcoxon rank sum tests, $p < 0.0001$). The 95% confidence intervals for the paired difference in daily averaged sediment concentrations (mg l^{-1}) between downstream and upstream site were (47.93, 117.53) and (12.35, 53.78) in 2002 and 2003, respectively. The paired t-test and Wilcoxon rank sum tests were both significant ($p < 0.003$).

During the 2001 post-monsoon period, mean sediment yield at the upstream site was 0.02 Mg km^{-2} day^{-1}, compared with 0.74 Mg km^{-2} day^{-1} downstream (Table 2). During the two monsoon periods in 2002–2003, sediment yields (averaged across years and methods, Table 2) increased to more than 1.99 and 7.89 Mg km^{-2} day^{-1} at the upstream and downstream locations, respectively. This amounts to over 130,000 Mg $year^{-1}$ of suspended sediment discharge downstream of the mine each monsoon. The difference in monsoon sediment yields between the 2 years (Table 2) was related, in part, to the differing magnitude and frequency of large rainfall events and possibly the incomplete sampling coverage of the monsoon in 2002.

5. Discussion

5.1. Sediment dynamics

At the time of completion of the Bhadra Dam Project in 1964, and up until the 1980s, sedimentation of the reservoir was not considered to be a major environmental problem, probably

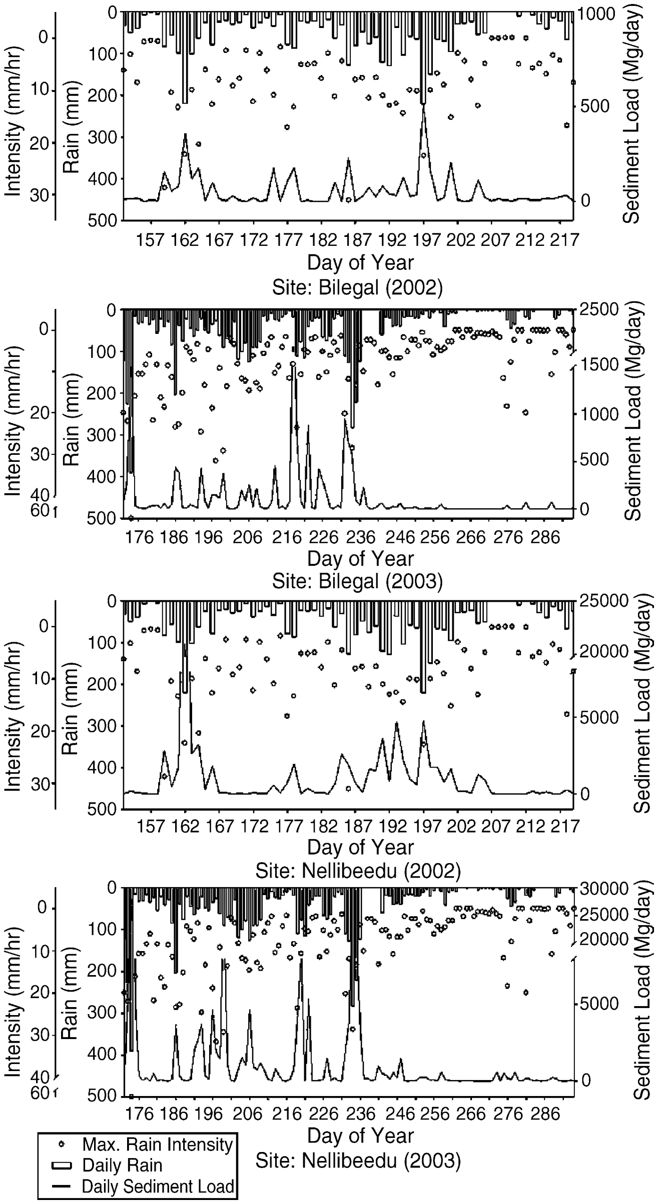

Fig. 9. Time-series of daily suspended sediment loads at Bilegal (upstream) and Nellibeedu (downstream), maximum hourly rainfall depth, and daily rainfall. The data collection periods include the 2002 and 2003 monsoon seasons.

because most of the catchment was vegetated by forest, grassland, and relatively low-impact coffee plantations (KERS, 1987; KSPB, 1987). Additionally, it may have taken some years for the bed-load sediment component to migrate down-river to the reservoir. The WRDO sediment measurements taken downstream of the mine at Malleshwara from 1983 to 1989 indicated large increases in suspended sediment loads during the monsoon months of some years (Figs. 1 and 6; CES, 2001). Comparison of the suspended sediment load at Malleshwara and total suspended sediment inflow into the Bhadra Reservoir indicated that although the area affected by mining was less than 1% of the total catchment area draining into the reservoir, it was the major contributor to reservoir sedimentation, comprising more than 50% of the total suspended sediment load inflow in 1985 and 1986 (Fig. 7).

The 120-day monsoon period accounts for the bulk of annual suspended sediment load in the Bhadra River, therefore, we can compare the estimated sediment yields with annual totals from other regions. For example, the average estimated monsoon sediment yields determined at the upstream Bilegal site ($239\ \mathrm{Mg\ km^{-2}\ year^{-1}}$, Table 2) are lower than the upper annual limit of $500\ \mathrm{Mg\ km^{-2}\ year^{-1}}$ for undisturbed forested catchments in humid tropical areas (summarized by Bruijnzeel (2004)). Downstream of the mine at Nellibeedu, however, estimated monsoon sediment yield increased four-fold compared to upstream (Bilegal) to $947\ \mathrm{Mg\ km^{-2}\ year^{-1}}$ (Table 2), even though the proportion of natural vegetative cover in the catchment for both sites is greater than 90% (Table 1) and the catchment area increases by $100\ \mathrm{km^2}$. Sediment yield per unit area generally decreases with increasing catchment area (Jansson, 1988), but this pattern may be reversed when secondary mobilization of stored sediment, drastic land disturbances or channel sediment sources are dominant (Dedkov and Moszherin, 1992; Schiefer et al., 2001; Krishnaswamy et al., 2001). The major difference between upstream and downstream sediment sources is the mining activity, which occupies a small area but is a major source of sediment. In agreement with these findings from mining-related lands are the results from a prior study which showed that while 97% of stream-bed sediments upstream of the mine were "natural catchment" materials, 47% of the sediments below were "mine-derived" (Shankar et al., 1994).

The analysis of the daily sediment load data downstream of the mine indicates the importance of a few events to the total suspended sediment load during the monsoon seasons (Fig. 9). In 2002 at Nellibeedu, for example, the largest estimated daily event (July 12, DOY = 193) contributed >28% of the total suspended sediment load during the 67-day sampling period. In comparison, the largest event in 2003 (DOY = 174) contributed >18% to the sediment load during that 123-day sampling period. Just two events in the 2002 sampling period were sufficient to produce one-third of the total suspended sediment load over the entire sampling period; and three events produced more than one-third of the load in the 2003 sampling period. The *minimum* hourly rainfall rate and total daily rainfall depth associated with the events that generated the large sediment loads during 2002 and 2003 were approximately $20\ \mathrm{mm\ h^{-1}}$ and $100\ \mathrm{mm\ day^{-1}}$, respectively. The upstream sediment dynamics were somewhat different. In 2002, for example, the largest daily rainfall depth recorded at Bilegal (DOY = 228) contributed only 11% of the suspended sediment load over the entire sampling period. The contribution of the largest daily event to the upstream load in 2003 was just over 16% (DOY = 218); similar in magnitude to the largest daily event downstream during that year (DOY = 174). During, the largest daily event at the downstream site in 2002 (July 12, DOY = 193), downstream sediment yield was more than 20-fold greater than upstream yield on the same day, even though rainfall in the upper catchment is expected to be higher (Krishnaswamy and Mehta, 2003). Thus daily sediment dynamics in the upstream site were not strongly coincident with the downstream site.

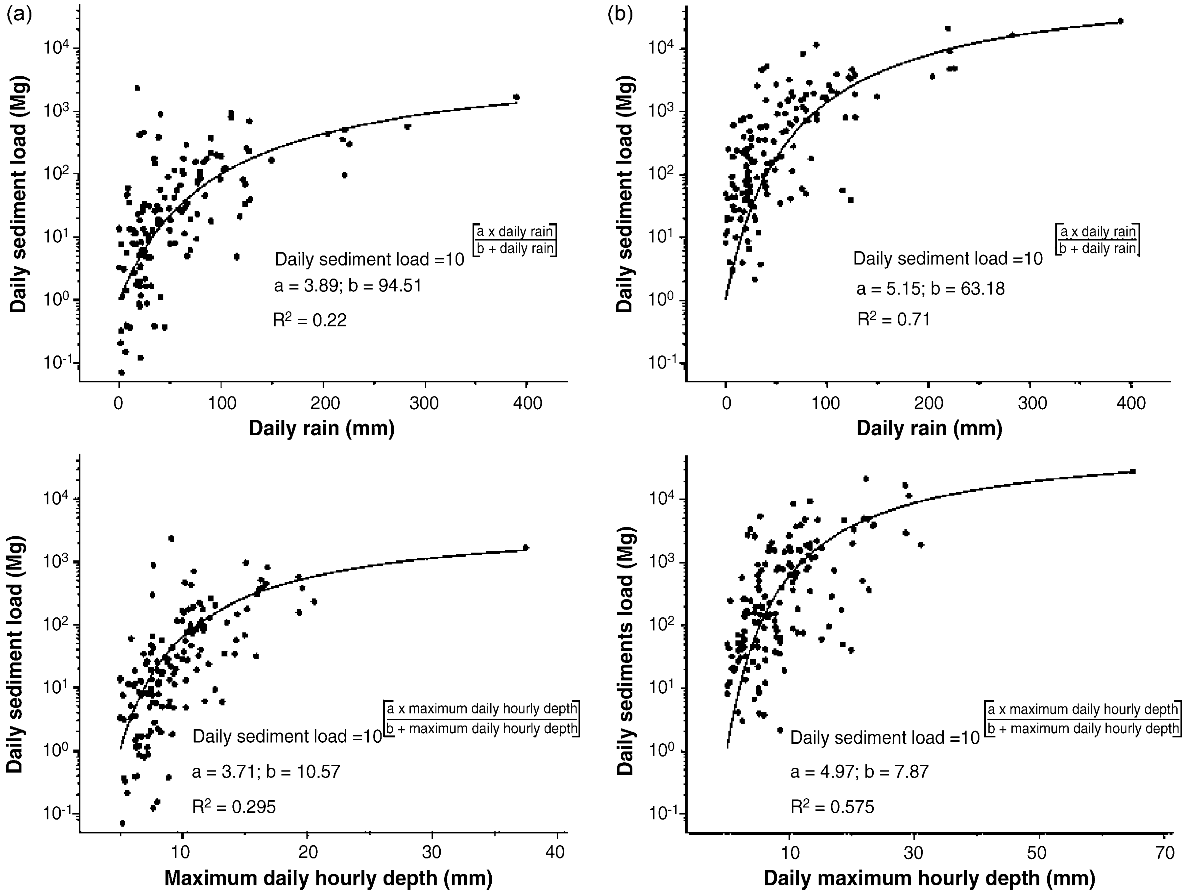

Fig. 10. (a) Scatter plots of daily suspended sediment load recorded at Bilegal (upstream of the mine) and corresponding recorded daily and hourly rainfall depths. (b) Scatter plots of daily suspended sediment load recorded at Nellibeedu (downstream site) and corresponding recorded daily and hourly rainfall depths.

The limited data on sediment concentration and approximate suspended sediment yields during 2001 indicates that even with reductions in flow, differences between upstream and downstream sites persists during low-flow conditions. These differences are attributed to nearby point like source sediment inputs related to the mining and associated activities.

5.2. Prediction of sediment loads

In general, daily sediment load downstream of the mine at Nellibeedu was positively related to daily total rainfall and maximum hourly intensity (Fig. 10a and b). Non-linear regression models with daily rainfall and maximum daily hourly rainfall intensity as independent variables were significant predictors of daily suspended sediment load ($R^2 = 0.71$ and 0.575, respectively, $p < 0.001$), although sediment loads at particular levels of these independent variables were quite variable. The 95% confidence interval for the predicted sediment load from the daily rainfall model applied to reliable daily rain data (156 days in 2002 and 2003) is (125,500 and 181,600 Mg). Comparison to that of the summed measured daily load (225,800 Mg, $n = 156$ days) for the same set of days reveals the uncertainty in the regression models. Using the average sediment yield (947 Mg km^2 year^{-1} from Table 2 multiplied by catchment area, 140.7 km^2) and the average of the 95% confidence values from above suggests that annual sediment load downstream of the mine is at least 130,000 Mg and could be over 150,000 Mg year^{-1} for rainfall conditions similar to 2002 and 2003.

In contrast to the downstream site (see above), the non-linear regression models for the upstream site, Bilegal, with daily rainfall and daily maximum hourly intensity as independent variables, explained only 22% and 29%, respectively, of the variability in daily sediment loads. Differences in estimated values of parameters '*a*' and '*b*' of the fitted non-linear regression Eq. (2) for upstream and downstream sites (Fig. 10) are also indicative of differences in the presence of sediment sources and sediment transport pathways. We attribute the difference in the rainfall–sediment relationships at the upstream versus the downstream sites to the comparative absence of surfaces generating rapid, infiltration-excess overland flow with large stores of easily-eroded sediment (e.g., mining surfaces, roads, mine tailings, overflow from check dams) upstream of the mine.

We developed a linear regression model to predict the maximum hourly intensity using daily rainfall totals recorded during the 2002 and 2003 collection periods ($R^2 = 0.57$, $p < 0.001$). Maximum hourly intensities *exceeding* 20 mm h^{-1}, which are associated with the largest sediment loads (>10,000 Mg day^{-1}) in 2002 and 2003, were typically generated when daily rainfall totals *exceeded* 150 mm. Between January 1990 and the end of October 2002 daily rainfall (Malleshwara, secondary data) exceeded this 150-mm threshold on 114 days, a frequency of 8.8 events year^{-1}. A total of 109 events were recorded between 1990 and end-2001. The frequency of large daily events (i.e., >150 mm) was greater in the years (1990–2001) prior to 2002 and 2003 (9.1 versus 5.0 events year^{-1}). Most of these events were covered in the gauging and sampling in 2002 and 2003.

If we assume the average daily sediment load for each large event is the minimum value (i.e., 10,000 Mg), the episodic export of suspended sediment by these events alone would be about 1.0×10^6 Mg during the 1990–2001 period. Thus, the minimum sediment released after mining can be approximated as follows: (a) the average annual values for the 1980s using the historical WRDO data totaling 126,150 Mg; (b) the 1.0×10^6 Mg value for episodic events during the period 1990–2001; (c) an approximate value of 150,000 Mg for 2002–2003 (using estimates described above and the average specific yield from Table 2 multiplied by catchment area). A conservative estimate of the total suspended sediment exported from the catchment between 1983 and 2003 is therefore 1.37×10^6 Mg, or 462 Mg km^2 year^{-1}. Since the area occupied by direct mining activities during this period was generally less than 4.2 km^2, the approximate minimum estimated suspended sediment yield from the mining area (after accounting for baseline contributions from the undisturbed part of the catchment based on assumed similarity to upstream catchment sediment yields) exceeds 7700 Mg km^2 year^{-1} over this entire period. A similar calculation for 2002–2003 based on average sediment yields from Table 2 suggests sediment yield from the mining area to be over 23,000 Mg km^{-2} year^{-1}.

The actual sediment yield could be even higher, than our conservative estimates, because in the 1980s sediment loads were constructed from daily rather than storm-based sampling data, and the total suspended load for that entire period (~9 years) used in our estimate is lower than the storm-based sampling estimates for 2002 and 2003 alone. The rainfall regime in the 1980s does not appear to be very different from the 1990 to 2003 period (Fig. 4) and the sediment loads in the late 1980s could be much higher. Also, our sediment estimates for 1990–2002 are entirely based on high events (>150 mm) and do not include any contribution from the rest of the storm events. Finally, we have not included the small contributions from the non-monsoon period for our estimated loads for 1990–2003. Thus the suspended sediment load could be considerably higher than our 1.37×10^6 Mg estimate. An approximate upper bound for the total suspended sediment load discharged in the Bhadra River following the initiation of mining could be assumed to be about 1×10^7 Mg of which over 80% can be attributed to the mining activity. Furthermore, inclusion of the bed-load component could increase the total sediment load estimate by at least another 10% (Milliman and Meade, 1983). We cannot directly infer from the available data that sediment load in the Bhadra river has increased over time since 1981 (after mining started) but the comparisons of upstream and downstream sediment loads suggest that the sediment load in the Bhadra river has been enhanced considerably and remained high ever since mining started.

6. Conclusions

Mining by the Kudremukh Iron Ore Company Limited (KIOCL) in an enclosure within Kudremukh National Park in southern India has affected the sediment dynamics of the Bhadra River in the last couple of decades. This is evident in the comparison of historical and contemporary sediment yield data collected upstream and downstream of the mine. The data suggest that the sediment load in the Bhadra River increased as mining operations progressed. The current estimated annual specific sediment yield above the mine is 239 versus 947 Mg km^{-2} year^{-1} downstream. Despite occupying less than 1% of the catchment area, mining is the single largest source of suspended sediment (>50%) in the Bhadra River, and hence the Bhadra Reservoir. Large quantities of sediment are released episodically from roads, tailings, check dams, mining slopes, tailings, and other mining debris source areas (Fig. 3c and d). Our preliminary data suggest that more than one-third of the total annual suspended sediment load may originate from as few as two or three large rainfall events during each monsoon season. Storm events producing these high loads typically have maximum hourly intensities of about 20 mm h^{-1} and total depths exceeding 150 mm. In general, rivers in peninsular India are considered somewhat stable and more-or-less unsusceptible to rapid changes in sediment load (Kale, 2002). The Bhadra River, however, appears to be an exception, probably because of the influence of open-cast mining operations in the upper basin. Mining and associated activities such as road construction in the high rainfall areas of the Western Ghats may disrupt hydrological and sediment linkages in these previously forested and grassland ecosystems.

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