IMPACT OF IRON ORE MINING IN KUDREMUKH ON BHADRA RIVER ECOSYSTEM

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1. EXECUTIVE SUMMARY

The Bhadra River, the Bhadra reservoir further downstream and the catchment provides critically important resources for wildlife in Kudremukh National Park and Bhadra Tiger reserve (Karanth, 1985; Karanth, 1992; Karanth et al, 2001). In addition it supports the livelihoods of a large human population of the region. Therefore the issue of sediment load and sedimentation caused by the mining operations of the KIOCL is a critical aspect of the impact of mining operations on the protected area.

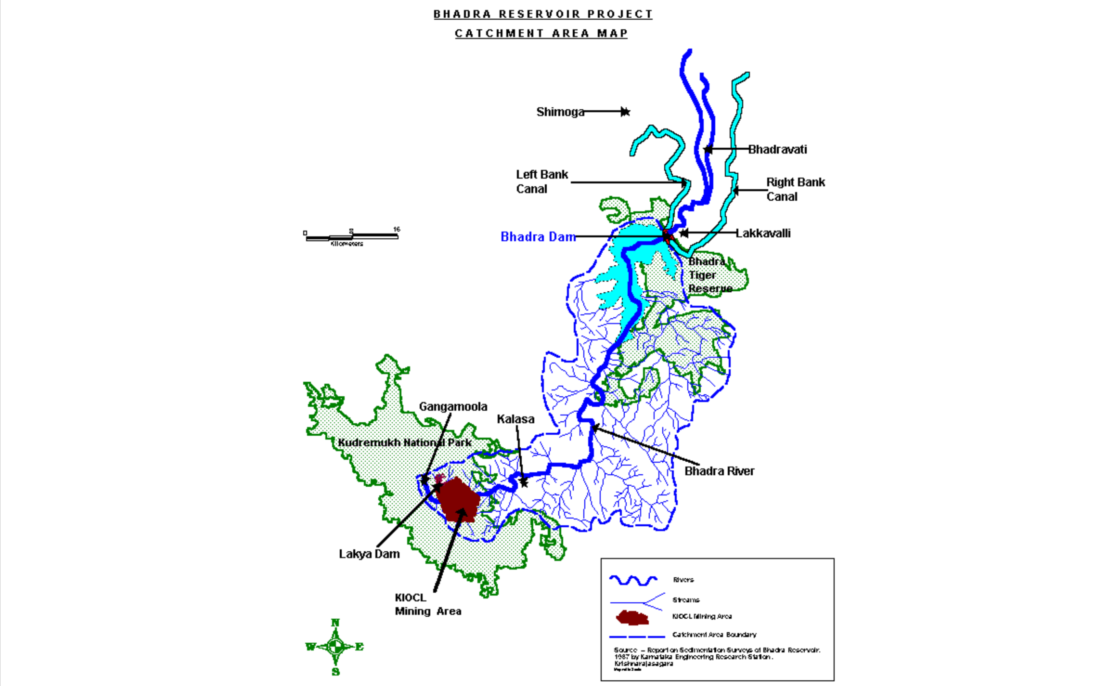
Centre for Wildlife Studies (CWS) and the Ashoka Trust for Research in Ecology and the Environment (ATREE) jointly studied the impact of Iron-ore mining in Kudremukh National Park on water quality of the Bhadra River. This study was funded by the Wildlife Conservation Society, New York as part of the efforts to understand human impacts on critical tiger habitats. The permission to carry out the study was given by the Government of Karnataka (vide GOK, NO WRD 63 MMB 2002).

This study was carried out during the monsoon of 2002 which is the first rigorous study done in the wet-season to assess the impacts of mining and associated activities in Kudremukh on the sediment load in the Bhadra river. The estimated contribution of this small sub-catchment (< 6 % of total Bhadra catchment) to the total load entering the reservoir in 1985 and 1986 was estimated to be *53 and 67 %* respectively. The sediment models indicate that the upstream site is mostly energy and supply limited whereas the downstream site is transport and energy limited implying a more readily accessible supply of sediment for the downstream site.

Sediment loading since the beginning of mining in the early 80's increased successively from 1,197 tons in 1984 to 49,429 tons in 1986 measured at Malleswara. From this study in the 2002 monsoon alone, more than 68,000 tons of sediment load was estimated at Nellibeedu, downstream of the KIOCL mining area at Malleswara, including one event in which over 19,900 tons was discharged in a single day. A minimum of 53 such similar rainfall events occurred in the time-period 1990 to 2002. These results prove that mining in Kudremukh National Park is the primary cause of very high sediment loads, and that a major proportion of the total load can occur from just a few very high rainfall events each monsoon. This study clearly demonstrates the adverse impact of mining in Kudremukh on sediment discharge in the Bhadra River and the Bhadra basin far beyond the devastation within the Kudremukh National Park.

We recommend the immediate stoppage of mining, continuous monitoring of the Bhadra River and the setting up of a restoration effort that will attempt to stabilize the slopes, reduce sedimentation and establish suitable vegetative cover on the abandoned mining areas.

2. INTRODUCTION AND BACKGROUND



Source: Centre for Wildlife Studies

Figure 1: The Bhadra reservoir catchment area

The Kudremukh NP and surrounding catchment area of Bhadra River are critical habitats for the highly endangered tiger (Karanth et al, 2001). They form a part of the high priority (level-1) global level tiger conservation unit (TCU-55) identified by WCS-WWF U.S.A (Dinerstein et al, 1997, Wikramanayake et al. 1999).

Kudremukh has the largest extent of bio-diversity rich shola-grassland ecosystems located in a hilly, high rainfall region (6000-7000 mm yr^{-1}) in the Western Ghats, a global biodiversity hotspot. The Kudremukh National Park is a rich repository of biodiversity and has significant populations of many endangered and globally significant flora and fauna including the Lion Tailed Macaque, Great Hornbill and the tiger. In addition the Bhadra River and its tributaries are the habitat of several fish and mollusc species besides the endangered otter. Downstream of Kudremukh, the Bhadra river flows past the recently established Bhadra Tiger Reserve, an area rich in moist deciduous forests and habitat for several large mammals and is particularly rich in avifauna and drains into the Bhadra reservoir which is one of the important irrigation storage projects in Karnataka (Figure 1).

Kudremukh Iron Ore Company Limited (KIOCL) has been conducting its mining operations on an area of 4,604.55 ha in the Western Ghats for over 20 years. Opposition to its activities has built up over the years - from environmentalists and wildlife conservationists who are concerned about the threat to the region's flora and fauna, to farmers who are affected by the pollution of the streams that originate in the mining area.

The Kudremukh area is subject to rainstorms of high erosivity or long duration in the monsoonal months, especially July and August. The rainfall in Kudremukh is perhaps one of the highest for any open-cast mining operation in the world. Over 400 mm has been recorded in a single day. A few spells of extremely high erosivity that account for much of the rainfall is characteristic of these hills. The topographic and rainfall characteristics in combination with the open-cast mining activities, road-building and other land-surface disturbances caused by the KIOCL operations has been resulting in high sediment discharges in the Bhadra river system in the short and long-term.

Consequently it was considered to be of priority by CWS and ATREE to study the impact of the open-cast iron ore mining in the region.

3. MINING AND SEDIMENTATION

The sediment response of catchments is controlled by a complex function of ecological, climatic and geomorphic responses. Land-use and land-surface changes in the upper catchments can enhance sediment yields high above levels under undisturbed conditions. Impacts of open-cast mining are very severe; the magnitudes of post-disturbance sediment levels maybe orders of magnitude higher compared to other land-use changes such as deforestation, agricultural intensification, road-building and urbanisation (Brown, 1974; Jackson, 1982; Bruijnzeel, 1990; Bruijnzeel, 1993). Open-cast mining all over the world is known to have devastating effects on downstream ecosystems, but the impacts in humid tropical areas is particularly severe (Bird et al, 1984).

4. PREVIOUS ASSESSMENTS OF MINING IMPACT

Concern over the impacts of mining in Kudremukh on water quality in the Bhadra River and sediment loading of the Bhadra reservoir was expressed by officials of the Karnataka State Government as early as 1985 (Rao, 1987). Government departments concerned with irrigation have repeatedly expressed concern about the impacts of mining and noted the increased sedimentation of the Bhadra River and reservoir (Irrigation Department, 1987).

NIRCON Engineering Consultants conducted a rapid Environmental Impact Assessment (EIA) and Environmental Management Plan (EMP) in 1997. NEERI (National Environmental Engineering and Research Institute) conducted an EIA for KIOCL (NEERI, 2000). Subsequently the Centre for Ecological Sciences of the Indian Institute of Science (IISC) did a rapid assessment of the impacts of mining on flora and fauna including water quality (CES, 2001). One of the glaring drawbacks in these reports is the extremely limited and inadequacy of the water-quality component and the omission of wet-season sampling of streams. In the wet-season rivers in India carry enormous amounts of sediment loads. Many rivers carry between 85 % to nearly 100 % of the entire annual load in the monsoon months (Vaithiyanathan et al, 1992). In a situation where opencast mining is being conducted the sediment discharges could be order of magnitude higher in the wet-season compared to the dry season. It is thus extremely surprising that the earlier studies did not sample for sediment discharge or other water quality parameters during the crucial monsoon months when the area is subject to severe rainstorms of high erosivity.

5. SEDIMENT CONTRIBUTION OF KIOCL MINING AREA

5.1 Secondary Data (Comparing Malleswara and Ballehonnur):

There is data on sediment generated by the Water Resources Development Organization (WRDO) both before and after mining started in 1981. There is some daily and monthly data from the Malleswara gauging site immediately downstream of the KIOCL area, as well as the annual inflow of sediment into the Bhadra reservoir estimated by WRDO by summing up the sediment discharge measured at Balehonnur on the main Bhadra and Muthodi on Somavahini (Rao, 1987). The estimated inflows of sediment into the Bhadra reservoir for two years, 1985 and 1986 (for which data from the gauging station immediately downstream of the mining area is also available), are 35,047.252 and 73,764.479 metric tons respectively. The sediment discharge from the gauging station at Malleswara immediately downstream of the mining area in these two years was estimated to be 18,625.21 and 49,429.1 tons respectively. The estimated contribution of this small sub-catchment (< 6 % of total Bhadra catchment) to the total load entering the reservoir in 1985 and 1986 is thus a staggering *53 and 67 %* respectively (Figure 2). These figures assume greater significance in the light of the fact that out of the 108 km^2 catchment only about 4.2 km^2 had been broken up and mined until 2000, about 14 km^2 is occupied by the mining township, roads and small areas of agriculture. The rest of the catchment barring has primarily Shola forest and grassland vegetation, which are known to have very low sediment contributions. Thus a very small part of the catchment affected by mining directly and indirectly has apparently increased the sedimentation of the Bhadra reservoir in the 1980s.

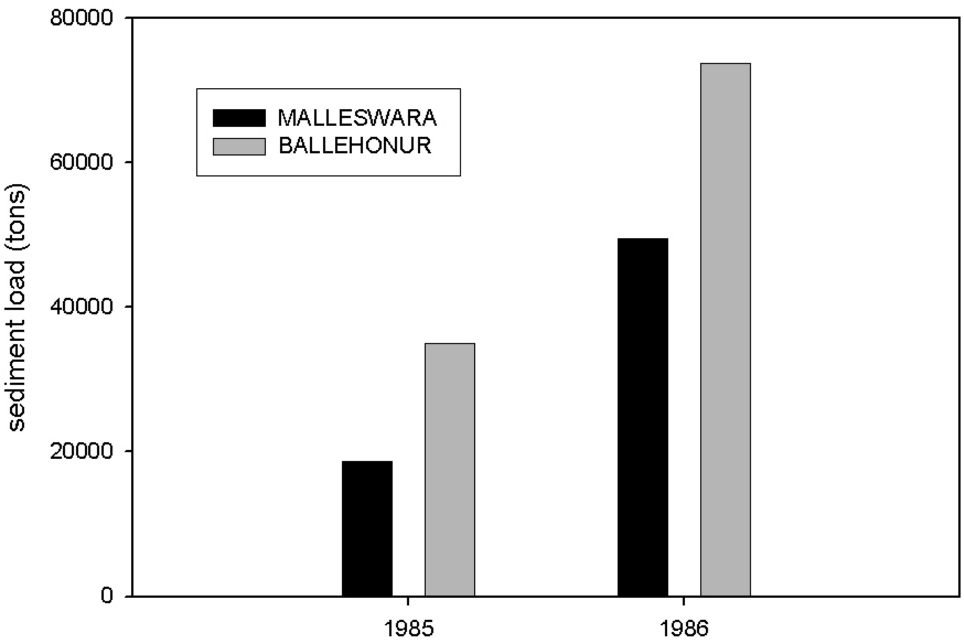


Figure 2: Historical loading at Malleswara and Balehonnur

5.2 Secondary Data (Wet season: Comparing monsoon loading to annual loading at Malleswara)

Monthly sediment load data from Malleswara was analysed for the years 1984-1986 (WRDO). Average monthly data from these three years confirms the fact that most of the sediment loading occurs (Historical loading at Malleswara and Balehonnur) during the wet monsoon months in the study area. The entire Bhadra catchment receives 82% of its basin inflow from the Southwest monsoon between June and September (Irrigation department, 1998). For the three years 1984-1986, these months accounted for 88% of the total annual sediment load (Figure 3). Figure 3: Average monthly sediment load at Malleswara (1984-1986)

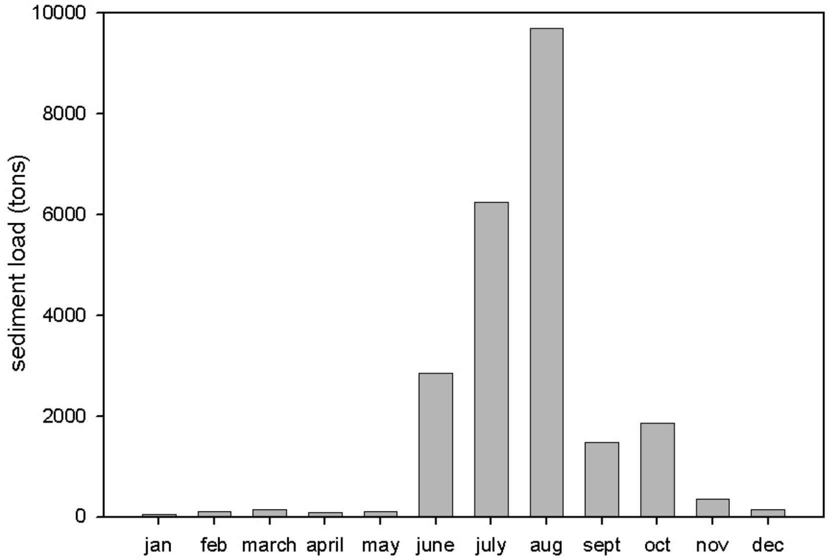


Figure 3: Average monthly sediment load at Malleswara (1984-1986)

5.3 Secondary Data (Dry season)

A site inspection by the STAC sub-committee on soil conservation on 24/2/87 ***during the dry season*** revealed that the river Bhadra passing through the KIOCL area carried heavy sediment load (Irrigation Department, 1987). This indicates severe and sustained impact of mining on sediment transport even during the dry season. This assessment was supported independently by the data collected by WRDO during this period (see above).

5.4 Secondary Data (Monsoon 2001)

The data from the end of August and early September 2001 collected downstream of Malleswara corroborates this. The absence of a relationship between sediment concentration and flow suggests that the sediment source is located very close to the river and is a point source rather than emerging from non-point erosion of hill slopes and stream banks in a major part of the catchment.

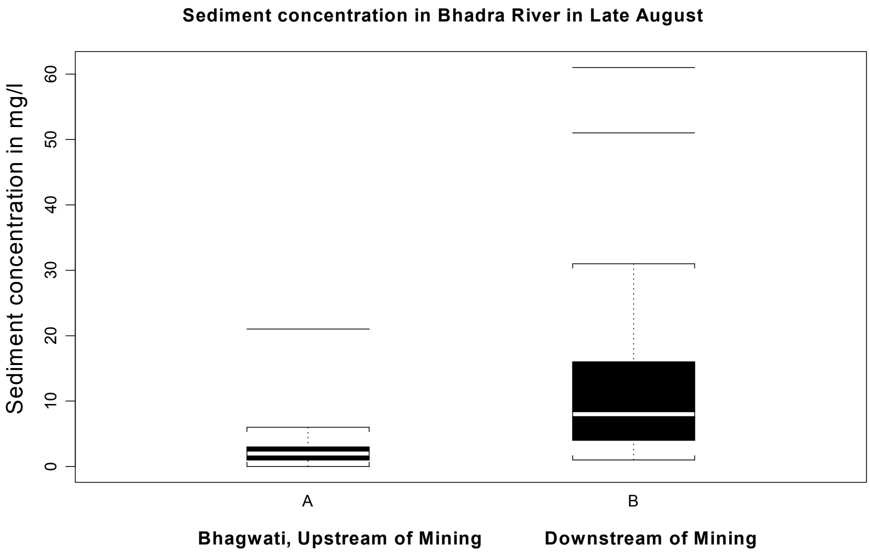


Figure 4: Box and Whiskers data on sediment concentration: End August 2001

The comparison of sediment concentrations measured using surface grab samples and filtered through 0.45 micron membrane filters in late August 2001 upstream and downstream of the mine even at the end of the monsoonal period indicates that the mining area contributes a significantly higher sediment load compared to the mining (Figure 4). Depth integrated samples are likely to give even higher sediment concentrations since the coarser particle sizes are probably underestimated using surface grab samples.

The available data on sediment loading from the 1980s, supplemented observations by governmental agencies and the more recently initiated sediment sampling in August 2001 suggests very strongly that:

1. The mining operations have already led to very high sediment discharges in the Bhadra River and led to enhanced siltation of the Bhadra reservoir and

2. The mining operations continue to impact the water quality of the Bhadra River. The impacts of KIOCL mining operations are event throughout the Bhadra basin and extend far beyond the devastation within the Kudremukh National Park. The claim that the mining operations at Kudremukh are not degrading the Bhadra River system cannot be accepted based on the poorly designed and inadequately sampled EIA studies done so far

5.5 2002 Monsoon study of impact of mining

A fully instrumented study was undertaken in the monsoon of 2002 to assess the sediment discharge in the Bhadra River upstream and downstream of the mining area in Kudremukh as a follow up to the initial study undertaken in August and September 2001 which had limited sediment sampling combined with analyses of available secondary data from the 1980s. This is the first study that envisages sediment sample collection in the wet-season since neither the NEERI nor IISc studies addressed this issue.

5.5.1 Methodology: Between January and April 2002, field teams established two gauging sites, one at the Bilegal bridge upstream of the mining area and the second at Nellibeedu bridge downstream of the mining area. The catchment area upstream of Nellibeedu is 140.7 km^2, and wholly encompasses the mining area. The catchment feeding the Bilegal gauging site (40.7 km^2) has no mining influences and is mostly Shola grassland-evergreen forest. Stream profiles at the two sites were established by April 2002. Intensive sampling of rainfall, stream stage and velocity, and water samples at both sites, was conducted from July 3rd to September 7^{th}, 2002.

Although analysis presented in this report was based on data collected in the monsoon of 2002, sediment and stream gauging is being continued in the monsoon of 2003 also.

5.5.2 Field methods

Rainfall: A Non-recording type rain gauge was maintained at Bilegal for the entire sampling period The rain gauge at Bilegal was used for rainfall intensity measurements, with rain totals measured as frequently as possible within a day. Daily rainfall totals were also collected at Bhagawati, 5km upstream of Bilegal for 27 days. Rainfall from Malleswara (KIOCL township) downstream allowed a comparison of rainfall at three stations along the river Bhadra. Rainfall at Bilegal was used for all analysis.

***Stream stage**:* Stage measurements were taken at both sites using the established staff gauges. These were taken at least twice a day, with more intensive measurements during rain events.

Streamflow: Streamflow was calculated using the velocity-area method. Stream velocity was measured at three points along each cross-section at 2 depths, for varying stages, using a current meter. Stream velocity at higher stages was measured using the float method.

Sediment concentration: Depth integrated suspended sediment samples were taken using a hand-held USDH-59 sampler. Water samples were collected at least twice a day at each site, with more intensive sampling during rain events. During intensive sampling, grab samples were sometimes taken in lieu of depth-integrated samples. The sediment samples were analyzed at the laboratory set-up at the ATREE office in Bangalore. Sediment samples were filtered through 0.45 micron membrane filters and dry weight was assessed using aluminium boats and a drying oven.

6. WATERSHED CHARACTERIZATION

Topography, landcover/landuse, pedology and rainfall characteristics are the important factors driving sediment transport. A combination of GIS/RS techniques was used to characterize the watershed in order to assist in analyzing the results.

Digital Elevation Model (DEM): Contours and drainage features were digitized from 1:50000 Survey of India topographic sheets (numbers 48 O3, O4, O7, O8). IDRISI GIS were then used to derive a DEM (Figure 5) and secondary maps such as slope and aspect.

Land-cover map: A 30m LANDSAT TM image (Visible and Near-Infra Red bands) were used to derive a landcover map using IDRISI's unsupervised classification module (Figure 6). Table 1 lists the landcover areas in proportion to total watershed area.

Table 1: Landuse proportions

Area (km^2) (% of watershed)	Total	Shola forest	Grassland	Mining affected	Urban built up	Water	Bare soil	Agri-culture
Bilegal	40.4	23.2 (57.4 %)	15.8 (39.1%)	0.0 (0%)	0.5 (1.2%)	0.1 (0.25%)	0.4 (1%)	0.4 (1%)
Nellibeedu	140.7	50.3 (35.7 %)	73.4 (52.2%)	4.88 (3.5%)	2.0 (1.4%)	2.6 (1.8%)	6.42 (4.6%)	0.9 (0.6%)

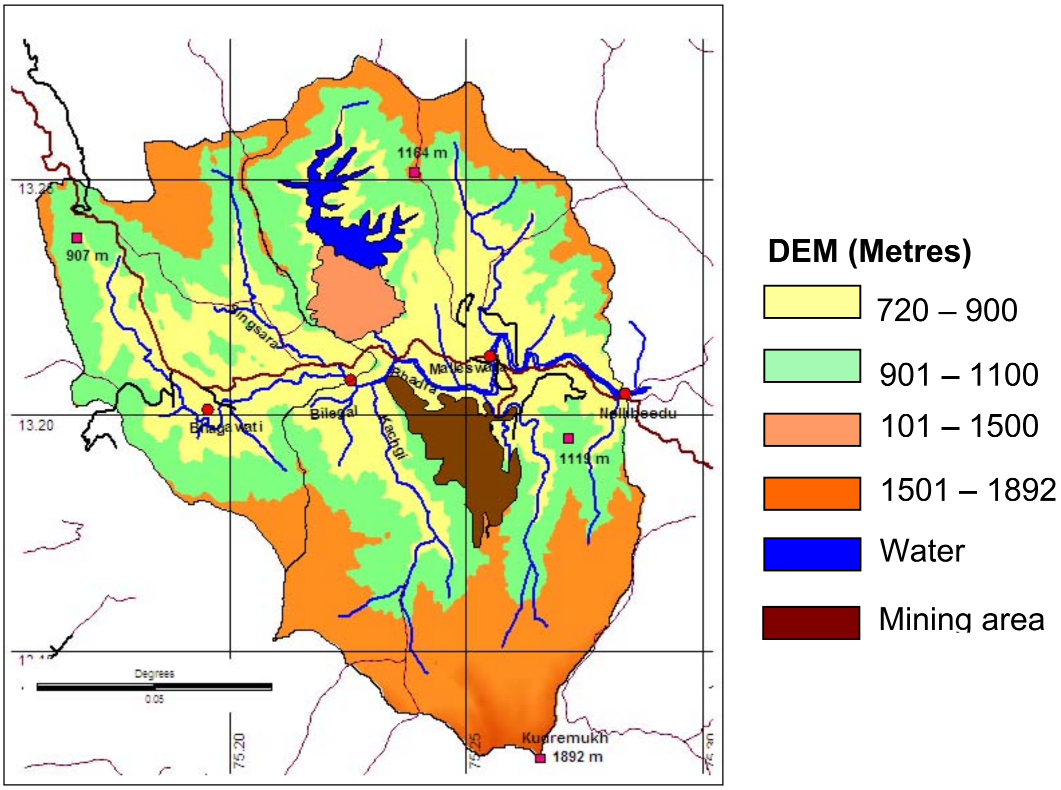


Figure 5: Digital Elevation Model (DEM) of the study area

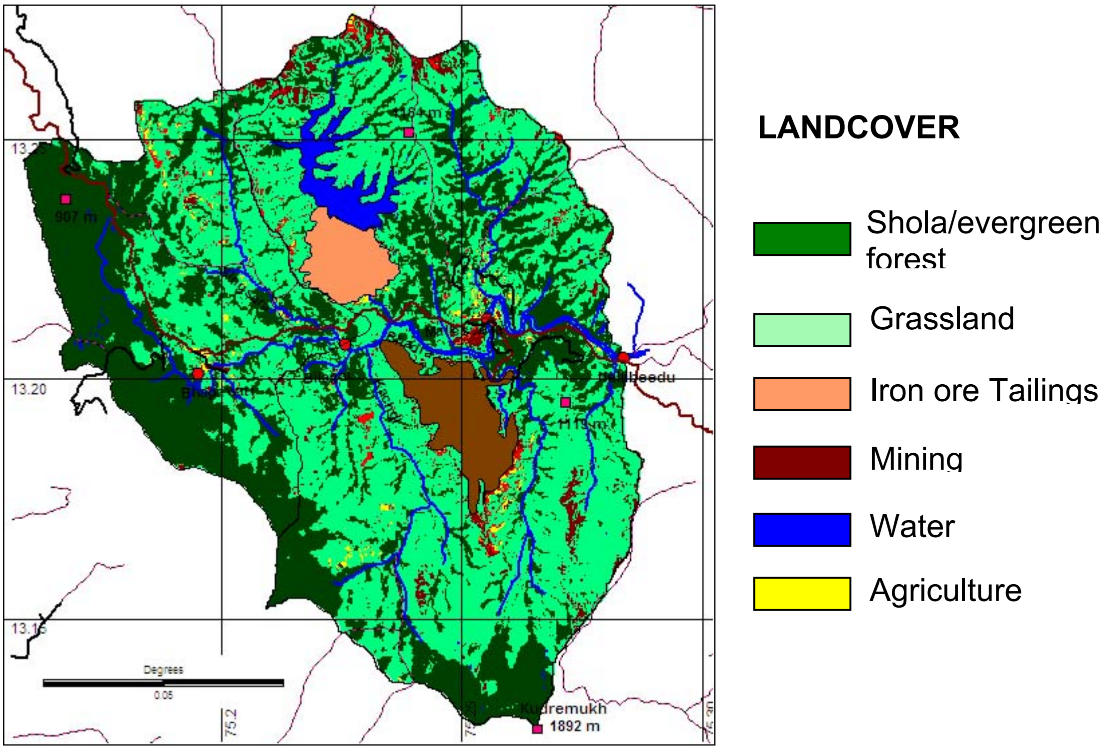


Figure 6: Land-cover map of the study area

7. DATASETS AND DERIVATION OF DAILY SEDIMENT LOAD ESTIMATES

The original dataset consists of instantaneous stage measurements corresponding to the sediment sampling, with a total of 276 samples upstream and 339 samples downstream for the 67 day sampling period. This instantaneous data set was compiled into a daily data set of daily rainfall, maximum hourly rainfall intensity within a day, daily mean flow and daily mean sediment concentrations. A second data set for a subset of the sampling period consisted of intensive stream stage measurements- 583 readings from August 6th to September 2nd at the upstream site; and 993 readings from July 14th to September 1st at the downstream site. These two data sets were used to derive a mean daily flow record for the sampling period, and two estimates of mean daily sediment concentration, to arrive at 2 estimates of daily sediment loads at each site.

7.1 Daily rainfall

Daily rainfall records from the station at Malleswara from 1990 to 2002 (KIOCL 2002) were also analyzed in relation to the occurrence of major rainfall events and the potential for episodic export of large sediment loads. The relationship between daily rainfall totals and hourly rainfall intensity derived from the monsoon of 2002 (Figure A1.2b, Appendix 1) was used to analyze this record. The maximum daily rainfall for each month was used to generate a time-series to give a minimum bound on the occurrence of extreme events capable of generating excessive sediment movement.

7.2 Daily mean flow

Polynomial Stage-flow rating curves established at each site were used to calculate instantaneous flow on the original instantaneous data set, and a daily average calculated thereof. Similarly, a daily average flow was also calculated on the intensively sampled data set. The first estimate could be biased to higher flow estimates, since sampling was more frequent during storm events. Therefore a regression was run on the two estimates, and the daily average flow from the intensively sampled dataset extended for the entire 67 days. This derived mean daily flow was used for all subsequent analysis (see Appendix 2 for model details).

7.3 Daily mean sediment loads

Two methods were adopted to estimate daily mean sediment concentrations. In the first case, a daily average was calculated on the instantaneous sediment concentration record. The derived daily mean sedimentation concentration was used with the daily mean flows to estimate daily sediment loads.

In the second case, once again an attempt was made to utilize the intensively sampled dataset. First, a predictive generalized additive model was generated between instantaneous sediment and flow readings. This was run on the intensively sampled dataset to arrive at corresponding sediment concentrations, from which a mean daily sediment concentration was estimated for the subset of the sampling period.

To complete the data record for the remaining time period, another predictive generalized additive model was constructed on the mean daily sediment concentration and mean daily flow derived from the instantaneous dataset. This model was run on the mean daily flow for the time period missing in the intensive record, to estimate the daily mean sediment concentration for that period. This second estimate of sediment concentration was used with the mean daily flow for an alternate estimate of sediment load (See Appendix 3 for sediment model details).

8. RESULTS

8.1 Sediment concentration

A total of 276 samples upstream, and 339 samples downstream were analysed for suspended sediment concentration. The comparisons of the results from upstream and downstream sites clearly indicate the substantial impacts of mining on the water quality of the Bhadra River. Note the number of sediment samples exceeding 500 mg/l and reaching over 3000 mg/l at the downstream site. **The mean and maximum sediment concentrations at the downstream site after the mining area are 161 and 3308 mg/l, approximately an order of magnitude or more higher than the corresponding figures for the upstream site which are 22 and 181mg/l respectively. The box and whiskers plot (Figure 7) indicates many samples exceeding 500 mg/l. These are very high sediment concentrations indicative of the impact of mining.**

Table 2 Summary statistics on sediment concentrations (also see Figure 7)

Sediment (mg/l)	Mean	Min	Max	Std Dev	Median
Bilegal (upstream)	22.34	0.0	181.2	32.1	10.55
Nellibeedu (downstream)	161.12	0.0	3308.1	302.6	74.28

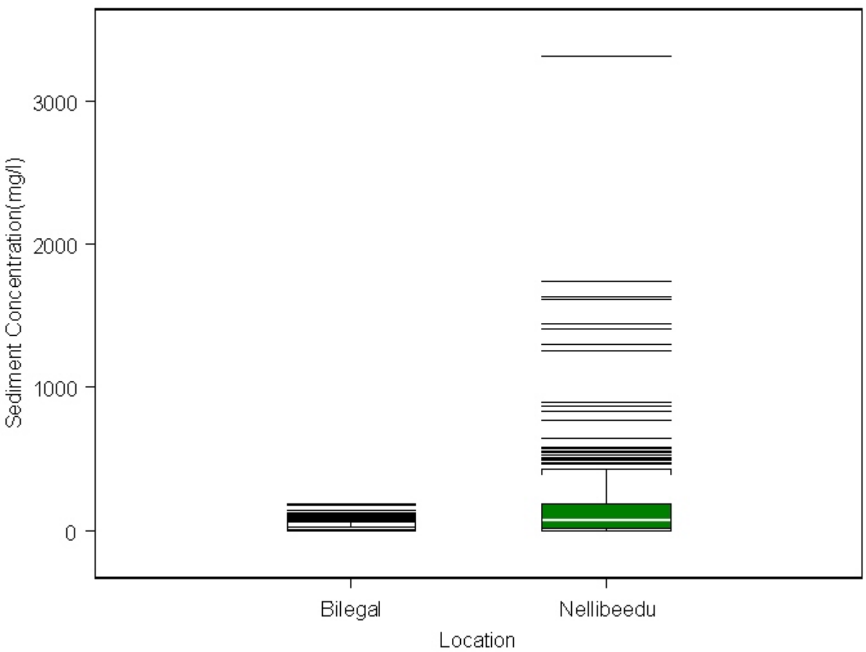


Figure 7: Sediment concentrations- July-August 2002

8.2 Relationships of Flow and Sediment concentration with rainfall amount and intensity

The instantaneous data set was compiled into a daily data set of daily rainfall, maximum hourly rainfall intensity, daily mean flow and daily mean sediment concentrations. This daily data captures the within-day variability of both flow and sediment concentrations because of the sampling protocol which covered both the wet and dry periods within each day. As expected, relationships between the logs of daily mean flow and logs of daily mean concentrations at both sites showed a significant correlation, while the same using the instantaneous data set did not show significant correlations. This can be explained by the fact that the flow response to rainfall and the sediment response to flow also depend on antecedent rainfall/catchment wetness considerations. Given that the distance between the two sampling sites is less than 10km, it follows that the derived daily data sets would capture the peaking pulses of both flow and sediment for the day.

Figures 9 and 10 (see below) are time series plots of rainfall, stage and sediment concentrations constructed to visualize the interactions of these variables at the upstream and downstream sites.

***Observations*:**

1. Streamflow and sediment concentrations show correlated trends. Rising streamflows correspondingly carry higher sediment loads compared to the falling stages of streamflow, indicating that sediment flushed during rainstorms is quickly mobilized and transported. The box plot figure (Figure 7) also shows that the sediment concentrations downstream of mining are much higher.

2. The flow response of the stream as well as its sediment concentration is related not just to the amount of rainfall, but also the intensity. In the relatively dry period from day 4 to day 6 (6th July to 8th July), both streamflow as well as sediment concentration were lower at both sites, compared to the high streamflows and concentrations during the very wet period between day 10 to 12 (12th July and 14th July). Consider also the effect of a high rainfall intensity storm on 9th July after the dry period. The daily rainfall was 82mm with a maximum recorded hourly intensity of 28.6mm hr^{-1}. The almost immediate peak in stream flow both upstream and downstream shows the quick response to intense rainstorms indicative of a substantial component of surface run-off and preferential sub-surface flow in this mountainous sub-catchment. However what is distinct about the downstream site affected by the run-off from the mining area and township is that the sediment response to rainfall intensity of comparable magnitude is at much higher levels even though the two sampling sites are less than 10 km apart.

3. The daily mean sediment concentration models (page and Figure A3.4) indicate that the upstream site is mostly energy and supply limited whereas the downstream site is transport and energy limited implying a more readily accessible supply of sediment for the downstream site.

8.3 Sediment load estimates

Estimates of daily sediment load at both sites were derived from the daily average sediment concentration and daily average flow. Table 3 summarises the statistics for the same. It is clear from the skewed nature of the data (evident from the enormous difference in the mean and median of the load estimates), and from the figures 9 and 10, that relatively few storm events have contributed to very high sediment loads. For the downstream site, the load estimate on July 12^{th} (figure 10) was the maximum, accounting for as much as 29% of the total load estimated over the sampling period of 67 days. Similarly, at the upstream site the load estimated on Aug 16^{th} was 11% of the total. Sediment load estimates were refined with the help of intensive hourly measurements of flow, from which an improved estimate of daily average flow was computed.

It is clear from figures 9 and 10 and preliminary statistics that rainfall intensity has a very big influence on sediment transport. The maximum loads occurred not just when high rainfalls occurred, but also when these high rainfalls occurred at very high rain intensities. On July 12^{th}, 219mm of rainfall was recorded with a maximum rainfall intensity of 22.3mm hr^{-1}. On that day, estimated sediment contribution for the entire watershed (area 140.7 km^2) upto Nellibeedu was 141 Tons/ km^2, whereas at Bilegal (watershed area 40.4 km^2) upstream of the mining area, the sediment contribution was 6.3 tons/ km^2, twenty three times less. It is clear that the intervening 100 km^2, which contains the entire mining lease area with the township and the actual mining-affected area of 4.88 km^2, is the major contributor to the sediment load in the Bhadra River.

Table 3a Summary statistics on daily mean sediment loads over 67 days of sampling

Mean Daily Sediment Loads (tons)	Mean	Min	Max	Median	Sum (67 days)
Bilegal (upstream)	40.15	0.0	306.2	10.1	2690.1
Nellibeedu (downstream)	1018.63	0.0	19911	159.19	68248.5

Table 3b Summary statistics on daily median sediment loads over 67 days of sampling

Median Daily Sediment Loads (tons)	Mean	Min	Max	Median	Sum (67 days)
Bilegal (upstream)	32.77	0.0	214.15	5.46	2195.5
Nellibeedu (downstream)	828.43	0.0	18906	142.82	55505.1

Table 3c Alternate estimate on daily mean sediment loads over 67 days of sampling

Median Daily Sediment Loads (tons)	Mean	Min	Max	Median	Sum (67 days)
Bilegal (upstream)	45.9	0.06	303.1	19.5	3079.2
Nellibeedu (downstream)	1148.5	0.0	11345.8	447.9	76952.2

The available data and analysis (Figure A2) suggest that it takes approximately at least 85 mm of rainfall a day to generate potential rainfall intensities of over 20 mm hr^{-1}. Assuming that rainfall intensities exceeding 20 mm hr^{-1} are likely to generate daily sediment loads in excess of 10,000 tons. A minimum of 53 such events occurred between 1990 and 2002 based on the maximum daily record for each month for this period.

9. CONCLUSIONS

Secondary data as well as the monsoon study presented in this report confirm that not only has the sediment load in the Bhadra River dramatically increased as a result of the mining (see Figure 8), but also that a very small fraction of the watershed area, comprising the KIOCL mining site, is by far the major contributor to sediment loads in the Bhadra River. Sediment loading since the beginning of mining in the early 80's increased successively from 1,197 tons in 1984 to 49,429 Tons in 1986 measured at Malleswara. From this study based on only 67 days of 2002 monsoon alone, more than 68,000 tons of sediment load were exported as estimated for Nellibeedu just downstream of KIOCL's mining area at Malleswara. This study clearly shows the severe impact of KIOCL's mining on the sediment load in the Bhadra River.

Although the Supreme Court has ordered the closure of KIOCL operations in Kudremukh by 2005, it is important that rigorous gauging of streamflow, sediment and rainfall needs to be continued, to monitor the water quality as well as levels of sediment inflow into the Bhadra reservoir. It can be expected that it will be a fairly long time before sediment levels decrease significantly downstream of the mined area because of the exposed mined area as well as steep terrain and rainfall characteristics. Therefore apart from stoppage of mining it is essential to undertake the restoration of the mined area on a priority basis as directed by the Supreme Court.

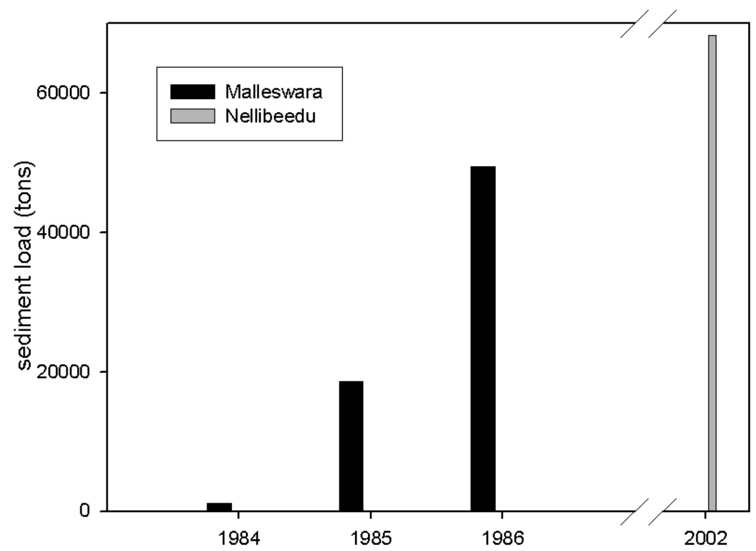


Figure 8: Historical loading at Malleswara compared to recent loading at Nellibeedu

10. Recommendations

This study recommends that:

1. An analysis of the particle size distribution and iron ore content of the sediments sampled along the bed and banks of the Bhadra River downstream of Malleswara and upto the reservoir should be done to assess the source of the deposited sediment and to corroborate the results from this study.

2. Intensive sediment sampling at Balehonnur on the lines described in this report should be done at Balehonnur after establishment of a gauging station at Balehonnur equipped with a water stage recorder and stilling well. Similarly permanent gauging stations with a stilling well and water stage recorder should be established at Bhagwathi and Nellibeedu.

3. The sediment deposition in the reservoir should be measured rigorously using depth sounding, hydrographic surveys, and remotely sensed data. This is long overdue after the baseline survey that was done in 1987 (Rao, 1987) and the remotely sensed data based survey, which was restricted to the upper levels (RRSSC, 1998). This will indicate the incremental sedimentation that has taken place in the reservoir at all depths after 1987.

A multi-disciplinary team and committee comprising of mining engineers, civil engineers, hydrologists, ecologists, wildlife biologists and forest officers should be empowered to oversee the restoration of the mined out area so that the slopes can be stabilized and vegetation reestablished which in turn will reduce sediment discharge as well as provide habitat for wildlife The reestablishment of the original Shola-grassland system after so many years of abuse by mining operations will be very challenging. It is clear that restoration at Kudremukh is a high priority activity to be preceded by controlled experiments using various techniques and this can be started as soon as KIOCL winds up its mining by 2005 and within this time period a restoration project can be launched.

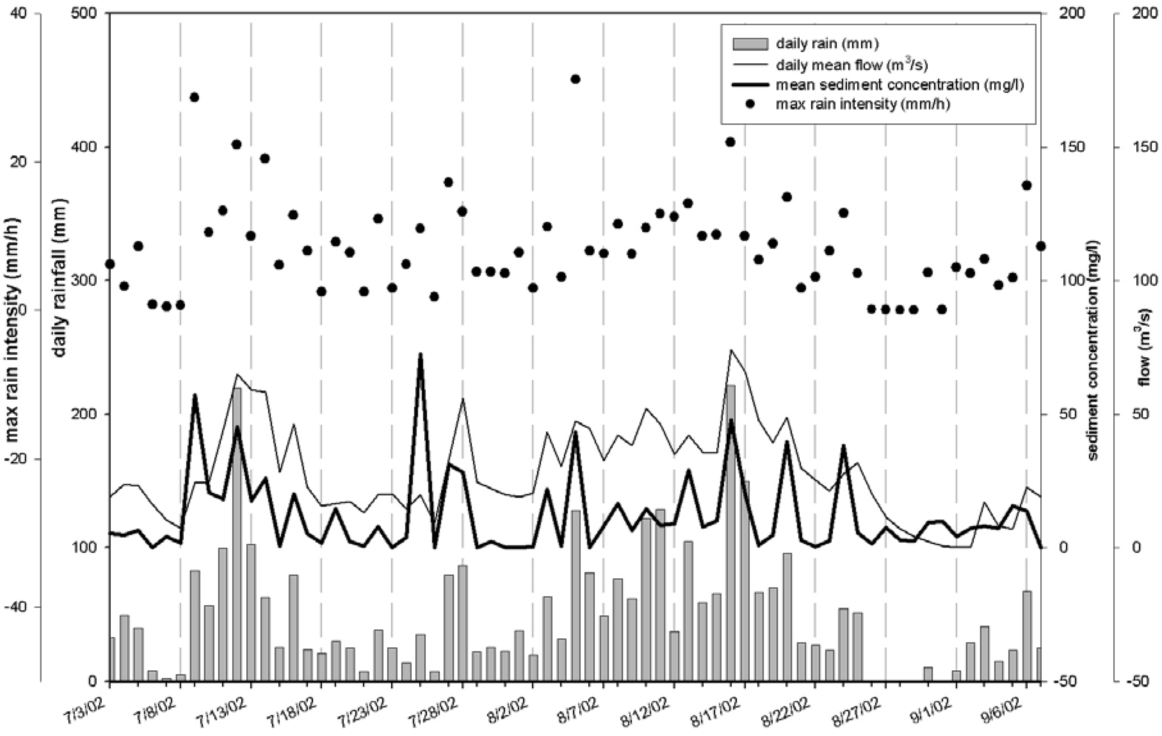


Figure 9: Rainfall, flow and sediment concentration (upstream)

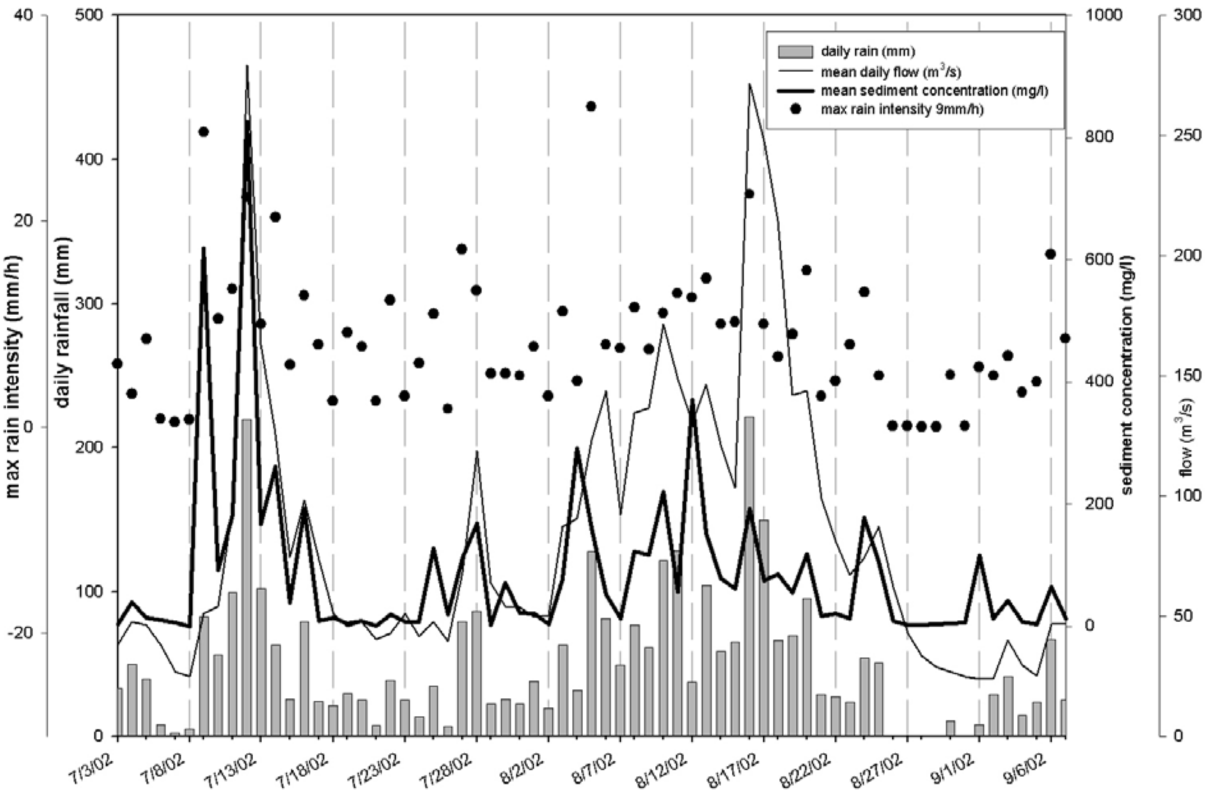


Figure 10: Rainfall, flow and sediment concentration (downstream)

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12. APPENDICES

APPENDIX 1: RAINFALL DATA

Considerable rainfall variability was observed within the study watershed during the sampling period of 67 days. A non-recording rain gauge was maintained for the entire period at Bilegal, the upstream sampling site. This rain gauge was used for rainfall intensity measurements, with rainfall amounts measured as frequently as possible within a day. Daily totals were calculated at 7am each day. The daily rainfall obtained at Bilegal was used in all analysis.
To gain some measure of the rainfall variability in the watershed, another rain gauge was sampled at Bhagawati nature camp, 3.5km upstream of Bilegal, for a period of 27 days. Additionally, rainfall data was obtained for the entire sampling period from the KIOCL at Malleswara, 6.75 km downstream of Bilegal.
Tables A1 and A2 show the rainfall totals for the three sites for corresponding time periods. Figure A1 shows the rainfall at the three sites for the 27 days that rainfall data was available at all three sites.
Note that in the entire Bhadra catchment, annual rainfall at the source of the river near Gangamoola is 575 cm, compared to 117cm at the dam site.

Table A1: Rainfall at Bilegal and Malleswara for the sampling period (67 days)

Location	Total rainfall (mm)
Bilegal	3399.7
Malleswara	2917.0

Table A2: Rainfall at Bhagawati, Bilegal and Malleswara (27 days)

Location	Total rainfall (mm)
Bhagawati	1033.9
Bilegal	904.4
Malleswara	753.2

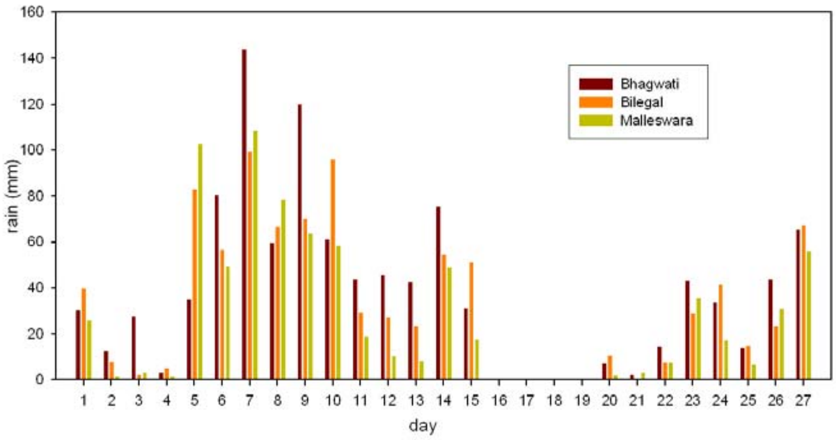


Figure A1.1: Daily rainfall at Bhagwati, Bilegal and Malleswara

It is evident from the tables and figures above, that rainfall is considerably variable within the watershed. While no consistent trend can be established from the limited time period available at all sites, it is interesting that the rainfall totals for the 27 days that it was available at all three sites is greatest for Bhagwati which is highest in the watershed, and least at Malleswara, which is furthest downstream.

Figure A2 (a)

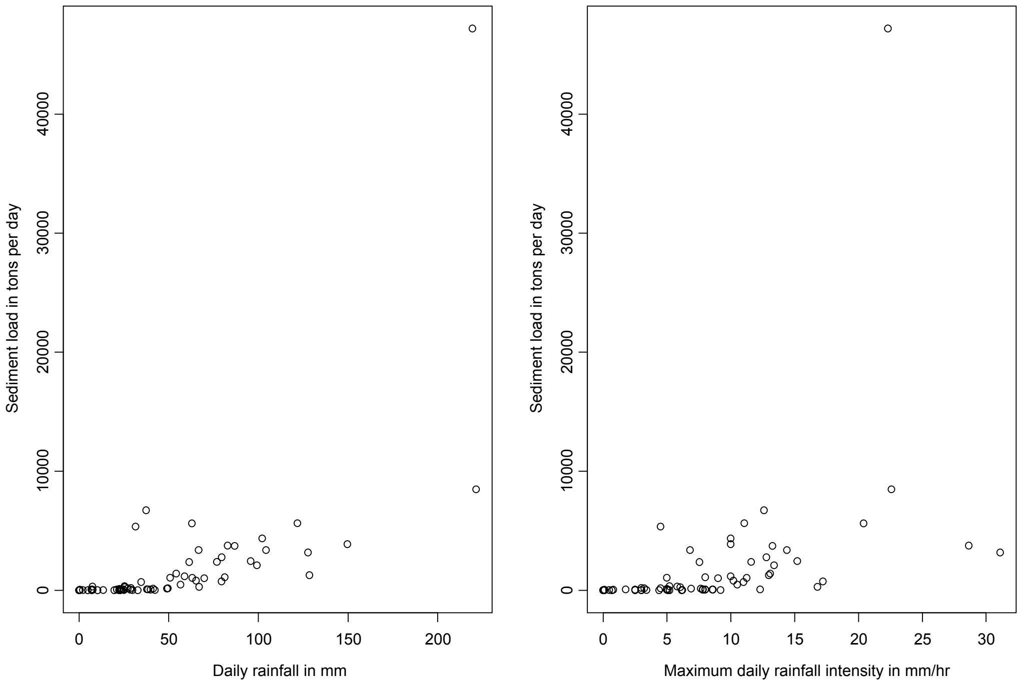


Figure A1.2: (a). Rainfall intensities

A LOESS model was fit between the daily rainfall and maximum hourly intensity data. Potentially this model could be used to estimate maximum rainfall intensities given daily rainfall. Figure A1.2 (b) provides initial indications that beyond a daily rainfall total of 100mm during this monsoon, the maximum rainfall intensities tends to level out.

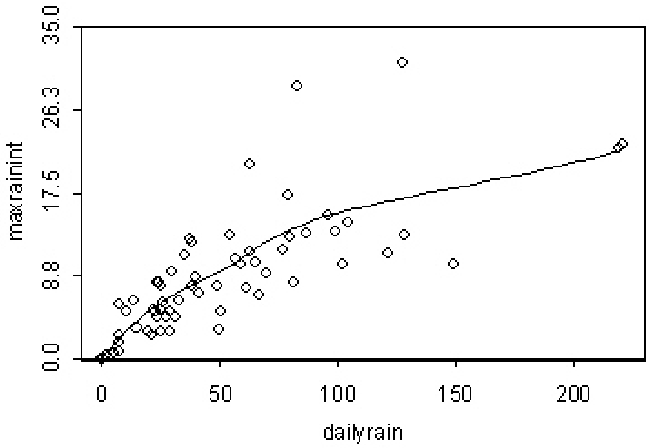


Figure A1.2 (b). LOESS model of maximum hourly rainfall intensity and daily rainfall

APPENDIX 2: STAGE-FLOW RATING CURVES

Simultaneous measurements of stage and streamflow were conducted to establish stage-flow relationships both upstream (Bilegal) and downstream (Nellibeedu). For each stage reading, streamflow was calculated using the velocity-area method, with stream velocity measured using a current meter. Stream velocity was measured at two depths at each of three points along the stream cross-section. At higher stream stages, the float method was used to determine stream velocity. A polynomial stage-flow rating curve was determined for each site. These rating curves were then applied on the instantaneous stage readings taken throughout the sampling period. Daily mean flows were derived from the instantaneous streamflows as explained in Appendix 3.

b) BILEGAL

At Bilegal, after careful consideration of data, only float method readings were used in deriving a final stage-flow rating curve. A generalized linear model was used to fit the data.

$Q=31.8690681401 + (0.4359344271*S) – (0.0007976037*(S^2)$……………(Eq. A2.1)

Where; Q = Stream flow in m^3/s,
S = Stream Stage in cm.

```
       *** Generalized Linear Model Details***

Coefficients:
                     Value  Std. Error   t value
(Intercept)  31.8690681401 1.108315415  28.75451
      Stage   0.4359344271 0.022847568  19.08012
 I (stage^2)  -0.0007976037 0.000315206  -2.53042

(Dispersion Parameter for Gaussian family taken to be 7.812354 )

    Null Deviance: 4452.819 on 10 degrees of freedom

Residual Deviance: 62.49883 on 8 degrees of freedom
```

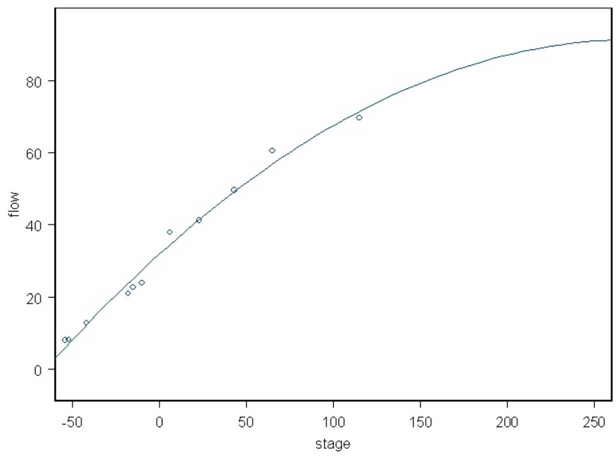


Figure A2.1: Stage-Flow Rating curve at Bilegal

b) NELLIBEEDU
At Nellibeedu, a combination of current meter and float method readings were used in deriving a final stage-flow rating curve. A generalized linear model was used to fit the data.

$$Q=17.83296 + (66.49190*S) + (22.80239*(S^2)) \quad \text{(Eq. A2.2)}$$

Where; Q = Stream flow in m^3/s,
S = Stream Stage in m.

```
      *** Generalized Linear Model Details***

Coefficients:
                 Value Std. Error  t value
  (Intercept) 17.83296    4.14926 4.297865
     newstage 66.49190   17.03430 3.903412
I(newstage^2) 22.80239   14.83092 1.537490

(Dispersion Parameter for Gaussian family taken to be 25.85982)

    Null Deviance: 9249.43 on 13 degrees of freedom

Residual Deviance: 284.458 on 11 degrees of freedom
```

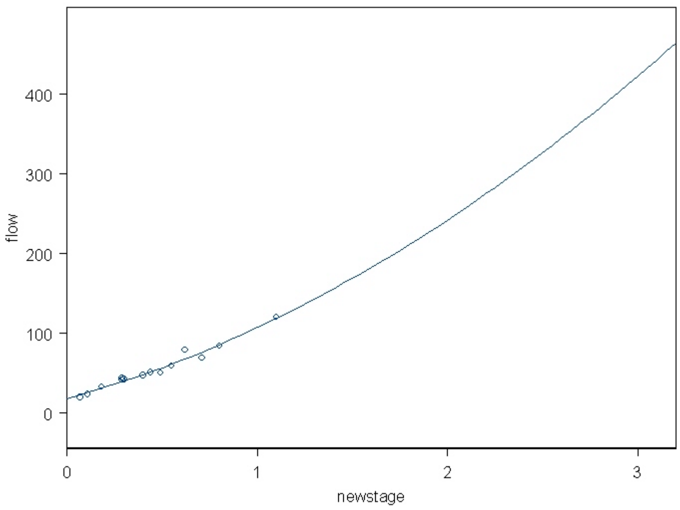


Figure A2.2: Stage-Flow Rating curve at Nellibeedu

APPENDIX 3: SUSPENDED SEDIMENT LOAD ESTIMATION

Estimates of suspended sediment load rely on flow as well as sediment concentration measurements. The original dataset consists of instantaneous stage measurements corresponding to the sediment sampling, with a total of 276 samples upstream and 339 samples downstream for the 67 day sampling period. Depth integrated suspended sediment samples were taken using a hand-held USDH-59 sampler. Water samples were collected at least twice a day at each site, with more intensive sampling during rain events. During intensive sampling, grab samples were sometimes taken in lieu of depth-integrated samples.

A second dataset consisted of intensively recorded stage readings for a subset of the sampling period, with 583 stage readings (Aug 6^{th} to Sept 2^{nd}) upstream and 993 stage readings (July 14^{th}-Sept 1^{st}) downstream. Two estimates of daily suspended sediment load were derived utilizing these two datasets.

a) DAILY MEAN FLOW

Stage-flow relationships as described in Appendix 2 were applied on the original instantaneous stage readings to estimate instantaneous flows, which were then compiled into a daily mean flow data set. However, since sampling was more frequent during rain events, it is possible that the daily mean flow derived would be biased towards higher flows. Therefore, a second dataset of mean daily flow was calculated from the intensively sampled stage readings, which were taken on a subset of the sampling period. A linear regression was run on the two daily mean flow data sets, and applied on the remaining period when the intensive stage sampling was not available. The derived daily mean flow was used for all further analysis and load estimations. Figure A3.1 shows the linear regression models used upstream and downstream.

a) Upstream

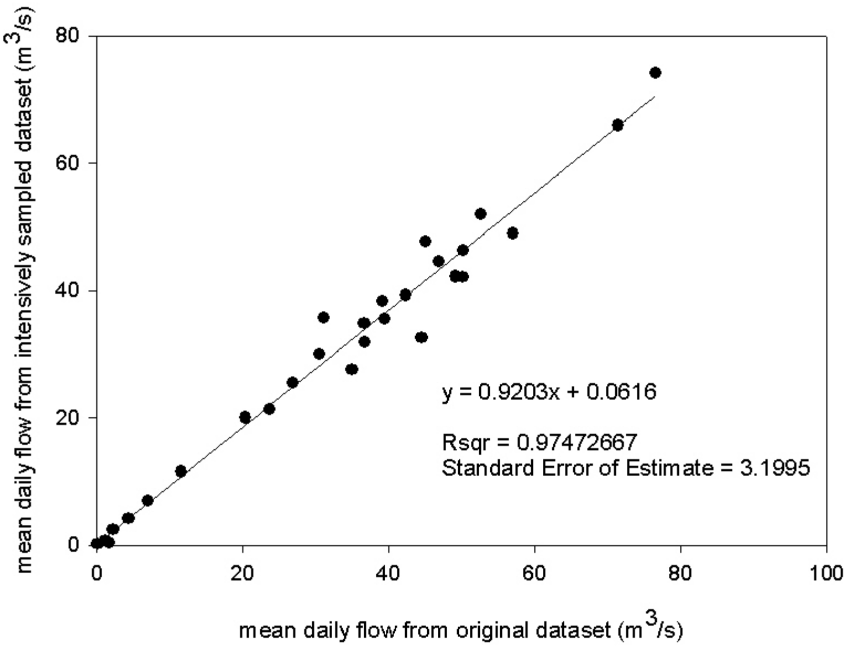


Figure A3.1: Linear regression to derive a final mean daily flow dataset

b) Downstream

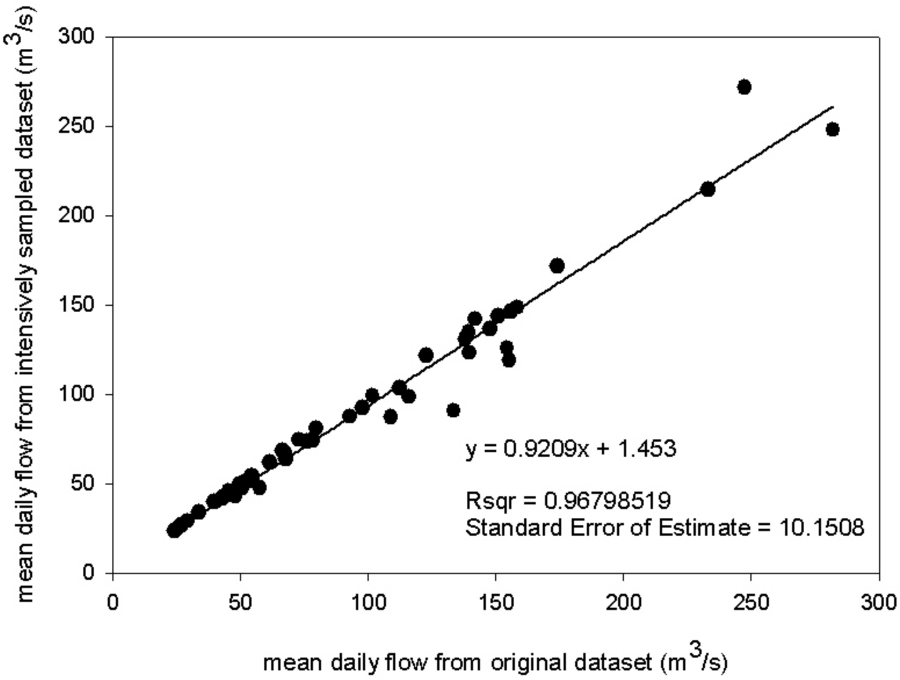
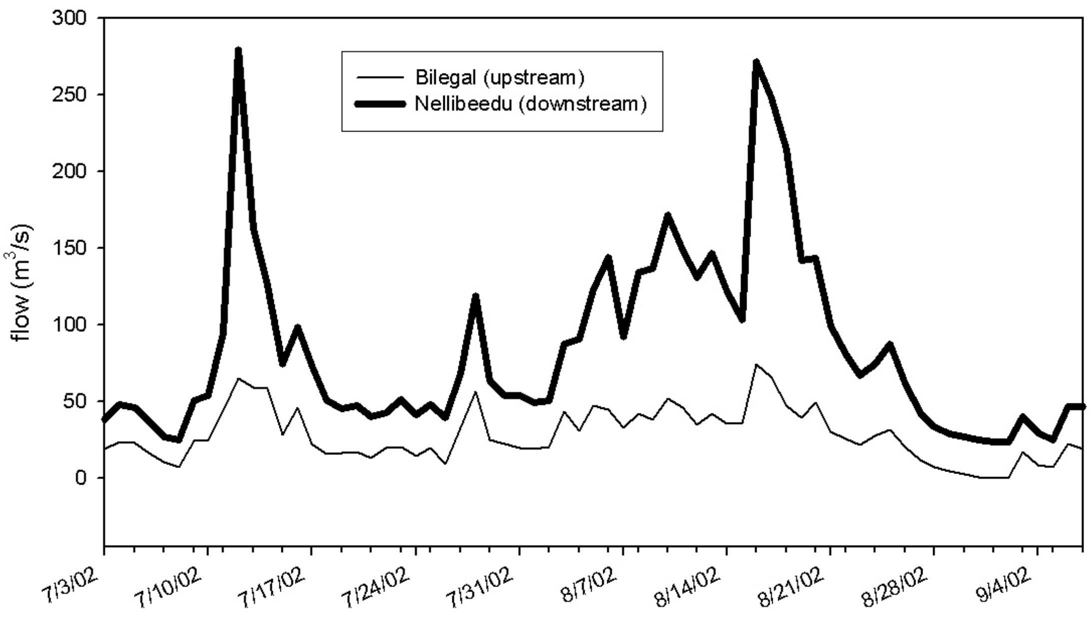


Figure A3.2: Daily mean flows upstream and downstream

b) Daily suspended sediment Load Estimates



Daily suspended sediment load estimates were derived by multiplying the daily flow with the daily sediment concentration. Two estimates were calculated, using the same estimate of daily flow, but different estimates of sediment concentration.

Load = Q * SEDCONC *86400/1000000……………………….(Eq. A3.1)

Where; Load = daily suspended sediment load (tons/day),

Q = daily mean flow (m^3/s),

SEDCONC = daily mean sediment concentration (mg/l).

First Estimate of Sediment Load

A daily mean sediment concentration was calculated from the original instantaneous sediment concentration measurements over the entire sampling period. This was used to calculate sediment loads using Equation A3.1.

Alternate estimate of Sediment Load

To derive an alternate estimate of sediment load based on an alternate estimate of daily mean sediment concentration, predictive models of instantaneous flow-sediment from the original dataset were applied to the intensively sampled stage-flow readings during the subset period to predict instantaneous sediment concentrations for that subset period, and daily mean sediment concentrations were calculated for the same. To fill in the daily sediment concentrations for the remaining time periods, a predictive model was developed between daily mean flows and mean sediment concentrations calculated from the original dataset. The model was then run on the final daily mean flows for the remaining time periods to estimate the daily mean sediment concentrations. The models used for these two steps are described below.

a) INSTANTANEOUS SEDIMENT CONCENTRATION MODEL

A generalized additive model was developed to predict sediment concentrations. Three potential predictor variables – flow, rainfall intensity, and rainfall were tested. For both upstream and downstream sites, flow was found to be the most robust predictor for instantaneous sediment concentration. Figure A3.3 below shows the graphs for the models at Bilegal and Nellibeedu.

Bilegal

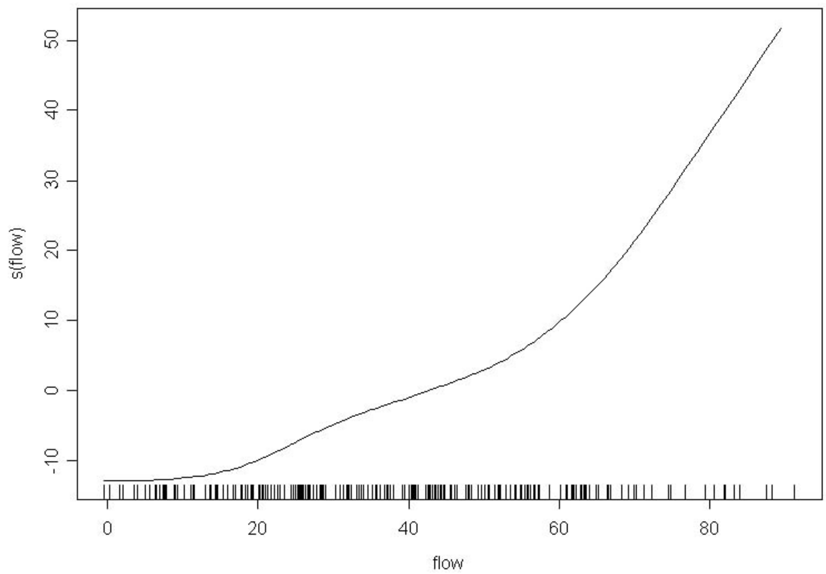
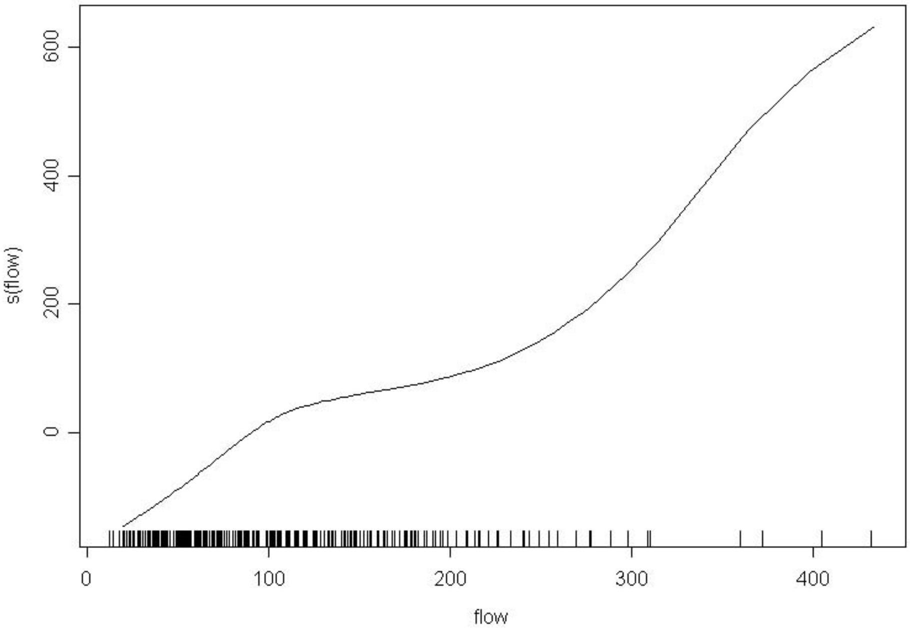


Figure A3.3: GAM model for instantaneous sediment concentration

Nellibeedu



b) DAILY MEAN SEDIMENT CONCENTRATION MODEL

A generalized additive model was developed to predict sediment concentrations. Three potential predictor variables – daily mean flow, maximum rainfall intensity, and rainfall were tested. At Bilegal, the maximum rainfall intensity was found to be the most robust predictor for daily mean sediment concentration. At Nellibeedu, the mean daily flow was the best predictor. Figure A3.4 below shows the graphs for the models at Bilegal and Nellibeedu.

Bilegal

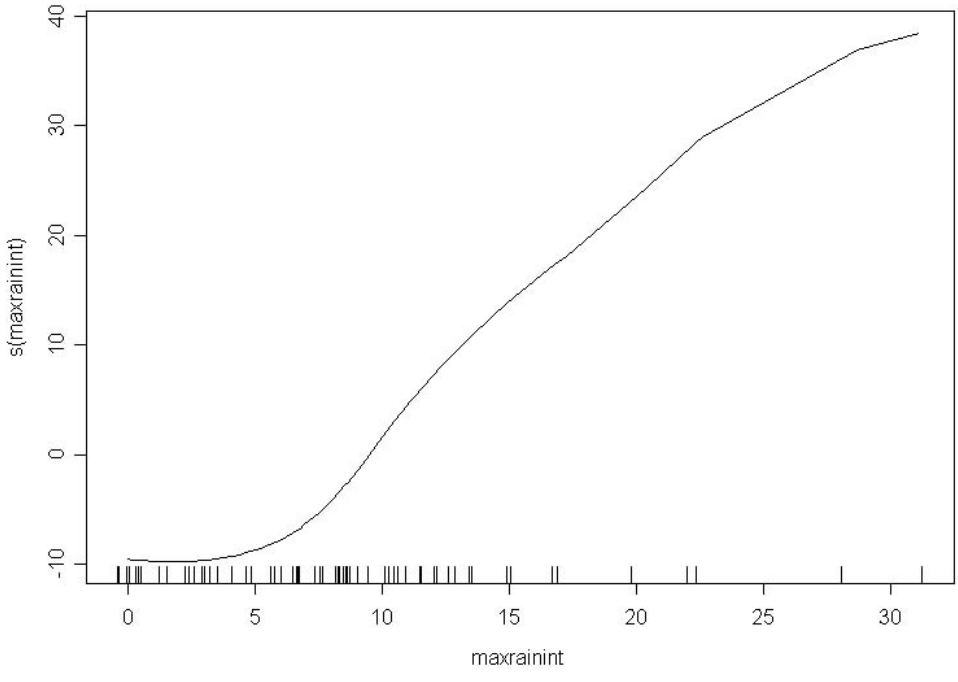


Figure A3.4: Daily mean sediment concentration models

Nellibeedu