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ORIGINAL ARTICLE

Assessment of suspended particulate pollution in the Bhadra River catchment, Southern India: an environmental magnetic approach

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Abstract Open-cast mining generates sediment in river systems at globally significant scales. One of the challenges in attributing measured sediment loads to upstream mining activities is establishing the source of sediments that are a mixture of natural and mining-based materials. The environmental magnetic data (mass-specific magnetic susceptibility, anhysteretic remanent magnetisation, isothermal remanent magnetisation and inter-parametric ratios) on 57 samples of suspended sediment from the Bhadra River in the *Sahyadri* (the Western Ghat) of India have been used in this study. Samples were collected upstream, adjacent to and downstream of Kudremukh, a mountainous and high rainfall site where the largest mechanised open-cast mine in south Asia was located. Graphical and multivariate analyses and modelling of the data show that on average ~29% of the river suspended load downstream of the mine is derived from mining and allied activities at Kudremukh although the mine occupies less than 5% of the catchment. The contribution of primary ore is the maximum (18%), followed by transitional hard weathered ore (7%) and weathered ore (4%). The model has done a fairly good job of unmixing; the sum of errors is <1 for 40 samples, 1–4,254 for five samples and >71,000 for four samples. Modelling of samples with small mass seems to produce large errors. This investigation demonstrates the utility of environmental magnetic data, which can be obtained in a simple and rapid manner, and the unmixing of such data in identifying the contribution of mining activities to the total suspended sediment load.

Keywords Suspended particulate matter · Rock magnetism · Unmixing · Kudremukh · Southern India

Introduction

Open-cast mining, because of its very nature, and related activities release a large amount of particles of various sizes into terrestrial and aquatic ecosystems. On the global scale, the material movement through mineral extraction processes exceeds the annual riverine input of sediment to the oceans by a factor of almost three (Douglas and Lawson 2000). Coupled with the degradation of vegetative cover, the high rainfall in tropical regions can effectively transport these particles to streams and rivers and can produce anomalously high suspended particle- and river-bed-loads that can reduce the storage capacity of reservoirs downstream (Krishnaswamy et al. 2006).

The now defunct Kudremukh iron ore mine was the largest mechanised open-cast mine in India, located within hilly forest and grassland ecosystems where the annual rainfall can sometimes exceed 10,000 mm (Krishnaswamy et al. 2006). Mining operations began in 1976, but were closed in 2005 consequent upon a decision of the Supreme Court of India. The mine is located in the Aroli-Gangamula region of the *Sahyadri* (the Western Ghat) of Southern India (13°07′45″N; 75°15′20″E). It has an area of 46 km^2, and is characterised by evergreen forests and montane grasslands. The area receives an average annual rainfall of ~6,000 mm, about 82% of which is received during the SW monsoon (June–September). The iron ore here is banded magnetite quartzite with an average Fe content of

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36%. The geology of the area is predominantly gneiss belonging to the peninsular gneissic complex. Also present are conglomerates, meta-basalt including thin iron-stones, acid volcanics and iron formations (banded magnetite quartzite) which belong to the Bababudan Group of the Dharwar Supergroup. Deposits of haematite occur in a few places. The soils are deep, well drained, gravelly clays and clayey soils in the upper catchment. They are also partly sandy loam with local occurrences of laterite in the mining area. The elevation ranges from 100 to 1,890 masl.

Several investigations have documented the impact of Kudremukh iron ore mining on the river ecosystem. Reports from governmental agencies highlighted the increased sediment loading in the Bhadra River as a result of mining at Kudremukh (KERS 1987; KSPB 1987). Sediment source modelling of Bhadra river-bed sediments (Shankar et al. 1994) showed that ~47% is contributed by the Kudremukh mine. Studies have also reported the impact of Kudremukh mining on the Bhadra River ecology (CES 2001; Krishnamurthy 2003). Krishnaswamy and Mehta (2003) and Krishnaswamy et al. (2006) have shown that sediment load in the Bhadra River increased as mining operations progressed; despite occupying <1% of the catchment area, Kudremukh mine used to be the single largest source of suspended sediment (>50%) to the Bhadra River. They confirmed that mining and associated activities at Kudremukh are the principal source of sediment entering the Bhadra River, and that this river carries considerably more sediment now compared to pre-mining times, damaging the river ecosystem and disrupting downstream water resources. The impact of Kudremukh mining could extend to the Bhadra reservoir (catchment area = 1,986 km^2) located ~50 km downstream which irrigates ~1,000 km^2 of agricultural land. The enhanced sediment loading in the Bhadra River would result in rapid siltation and reduction in the water-bearing capacity of the reservoir.

Magnetic methods for pollution analysis are rapid and inexpensive compared to extensive chemical analysis, and can be applied to a wide range of environments (Hanesch and Scholger 2002). Chaparro Marcos et al. (2004, 2008), Petrovsky et al. (2000) and Knab et al. (2006) have combined rock magnetic and chemical analyses of river-bed sediments followed by statistical analysis to assess heavy metal pollution. They documented a good correlation between heavy metals (including Fe) and magnetic parameters. Yang et al. (2007) have found high values of magnetic parameters in surface sediment samples from the East Lake located close to the Wuhan Iron and Steel Company. However, all these studies were qualitative. Only a few have quantitatively addressed particulate pollution arising from iron ore mining.

This investigation attempts to quantitatively estimate the proportions of *natural* catchment soil particles and *anthropogenic* ore particles in the suspended particulate material (SPM) collected from the Bhadra River. Three stations were chosen: (1) Bilegal, located upstream of the Kudremukh mine; (2) Malleshwara, located adjacent to the mining area; and (3) Nellibeedu, located downstream of the mining area. As magnetic parameters are also influenced by the geology of the area, it is necessary to consider the background contribution to magnetic parameters before assessment of anthropogenic contribution (Knab et al. 2006). Bilegal samples are unaffected by mining activity, and hence, should reflect *natural* catchment soils and the natural background signal. Samples from Malleshwara should be a mixture of both *natural* and *anthropogenic* particles, and Nellibeedu samples must reflect particles contributed by mining and allied activities in addition to natural soil particles. A rock magnetic approach has been used which is suitable to address the problem at hand because the Kudremukh iron ore is largely magnetite, which is a strong ferrimagnet, whereas the catchment soils are weakly magnetic in relation to the ore. However, they are more strongly magnetic (because of a higher degree of pedogenesis which is typical of tropical regions) when compared to soils from temperate regions. Besides, the rock magnetic methodology can detect the presence of even minute concentrations (down to ppm level) of magnetite in samples. Rock magnetic studies have the advantage of being simple, sensitive, inexpensive, fast and non-destructive.

Our a priori hypothesis is that the magnetic signature would show a clear pattern of increasing strength across the three sites in a downstream direction. In addition, it is also expected that magnetic signals in suspended sediment would *not* be positively related to the concentration of sediment as the exposed ore is not generated from the entire catchment, but is restricted to specific sites and reaches the river through a small sub-set of channels. If variability in magnetic signatures is *not* explained by a corresponding variability in suspended sediment concentration, this would suggest a point source of sediment rather than diffuse sources from throughout the catchment. Sediment source modelling using magnetic measurements offers the opportunity to quantify the relative proportions of riverine sediments contributed by different processes (Shankar et al. 1994; Yu and Oldfield 1989).

Materials and methods

Sample collection

Samples of the Bhadra River water along with suspended sediment were collected from Bilegal, Malleshwara and Nellibeedu (Fig. 1) during July and August of 2002 and

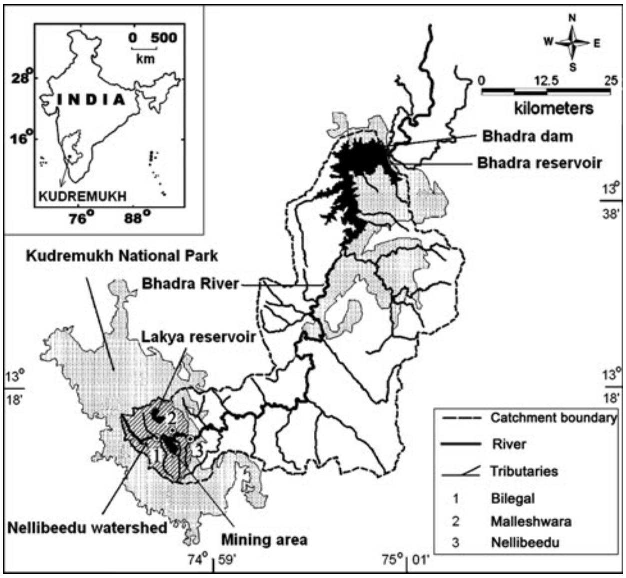

Fig. 1 Map showing the location of Kudremukh mining area and sampling sites. Bilegal is located upstream, Malleshwara adjacent to, and Nellibeedu downstream of the mining area

June, July, August and October of 2003. Some are water depth-integrated samples which were collected using a USDH-59 type hand-held sampler that was suspended from the middle of the bridge; the other samples were collected using the grab sample technique. The samples were filtered under pressure through 0.45 μm cellulose nitrate filters. The sediment-bearing filter papers were transferred to pre-weighed aluminium boats and oven-dried for 24 h. Details of sampling and sediment discharge are described in a previous paper (Krishnaswamy et al. 2006).

Source samples (primary ore, weathered ore and transitional hard weathered ore) from the Kudremukh mine were collected during September 2007. Only one sample each of the ore materials were chosen as they have magnetic parameter values that are much higher compared to Bilegal SPM. They were powdered and dispersed in distilled water. After about an hour, the suspension was filtered through 0.45 μm cellulose nitrate filter papers. The filter papers were dried at 40°C for 6 h. The procedure of dispersion of powdered ore and filtration was adopted so that the filtered ore material would be comparable with suspended sediment samples. It is true that this procedure changes both the magnetic grain size and particle size of the ore. But this is what happens when the ore is ground and powdered in a tube/ball mill for ore beneficiation.

Rock magnetic measurements

For rock magnetic measurements, the dried filter papers were folded and transferred to polythene covers which were tightly packed in 8 cm^3 cylindrical, non-magnetic plastic bottles. A range of magnetic parameters was determined on the samples (Walden 1999a; Thompson and Oldfield 1986).

Low- and high-frequency magnetic susceptibilities (χ_{lf} and χ_{hf} at 0.47 and 4.7 kHz) were determined on a Bartington Susceptibility Meter (Model MS2B) with a dual-frequency sensor. From χ_{lf} and χ_{hf} measurements, the frequency-dependent component of susceptibility (χ_{fd}) was calculated (Dearing 1999).

Anhysteretic remanent magnetisation (ARM) was grown in samples by steadily ramping down a mains frequency alternating field (AF) of 100 milliTesla (mT) while the sample was subjected to a steady field of 0.04 mT. An AF demagnetiser and an ARM attachment (both of Molspin make) were used for this purpose. The ARM thus grown was measured on a Molspin spinner fluxgate magnetometer. The calibration sample (a strip of magnetic tape embedded in a wooden cylinder) provided by the manufacturer was used to calibrate the magnetometer. The susceptibility of ARM (χ_{ARM}) was calculated by dividing the mass-specific ARM by the size of the biasing field ($0.04\ \mathrm{mT} = 31.84\ \mathrm{A\ m^{-1}}$) (Walden 1999b).

Isothermal remanent magnetisation (IRM) was grown in steps at different field strengths (20–1,000 mT) using a Molspin pulse magnetiser. The isothermal remanence grown in 1 T field (the maximum field attainable in the Environmental Magnetism Laboratory at Mangalore University) was considered as saturation isothermal remanent magnetisation (SIRM). Isothermal remanences and SIRM were measured using the Molspin spinner fluxgate magnetometer. To determine the mineralogy and grain size of the magnetic minerals present in the samples, inter-parametric ratios like *S* ratio, HIRM, $\chi_{\mathrm{ARM}}/\chi_{\mathrm{lf}}$, χ_{ARM}/SIRM and SIRM/χ_{lf} were calculated (Walden 1999b).

Table 1 gives the details of all the magnetic parameters studied and inter-parametric ratios, their units, interpretation and the instruments used.

Data analysis

The rock magnetic data were first analysed qualitatively using graphical and standard interpretation techniques (Thompson and Oldfield 1986; Oldfield 1991). In addition, box plots were used to compare the magnetic characteristics of suspended sediment samples from the three sites that represent a gradient of mining impacts from zero to maximum (upstream, adjacent to and further downstream of the mine). Two representative magnetic parameters, HIRM and IRM $_{\mathrm{500mT}}$, were chosen for this graphical comparison. Non-parametric Kruskal–Wallis tests were used to test the differences in the magnetic signature (IRM $_{\mathrm{500mT}}$, HIRM and *S* ratio) in suspended sediment samples between the three sites (Collins and Walling 2002; Carter et al. 2003).

Table 1 Magnetic measurements, their interpretation and instrumentation (Thompson and Oldfield 1986; Oldfield 1991; Maher 1988)

Magnetic measurements and their units	Interpretation	Instruments used
Low- and high-frequency susceptibility χ_{lf} and χ_{hf} (10^{-8} m^3 kg^{-1})	Proportional to the concentration of magnetic minerals	Susceptibility sensors
Frequency-dependant susceptibility χ_{fd} (10^{-8} m^3 kg^{-1})	Proportional to the concentration of superparamagnetic minerals	Susceptibility meter with a dual-frequency sensor
Susceptibility of anhysteretic remanent magnetisation (ARM) χ_{ARM} (10^{-5} m^3 kg^{-1})	Proportional to the concentration of magnetic minerals of stable single domain size range	AF-demagnetiser, ARM attachment and fluxgate magnetometer
Isothermal remanent magnetisation and saturation isothermal remanent magnetisation IRM and SIRM (10^{-5} A m^2 kg^{-1})	Proportional to the concentration of magnetic minerals	Pulse magnetiser and fluxgate magnetometer
Hard isothermal remanent magnetisation HIRM (SIRM-IRM$_{300\mathrm{mT}}$) (10^{-5} A m^2 kg^{-1})	Proportional to the concentration of magnetically 'hard' minerals like haematite and goethite	
$\chi_{\mathrm{ARM}}/\chi_{\mathrm{lf}}$	Indicative of magnetic grain size of ferrimagnetic minerals	
χ_{ARM}/SIRM	Indicative of magnetic grain size	
SIRM/χ_{lf}	Indicative of magnetic grain size	
S ratio (IRM$_{300\mathrm{mT}}$/SIRM)	Relative proportions of ferrimagnetic and anti-ferromagnetic minerals (high ratio = relatively high proportion of magnetite)	

This was followed by factor analysis which is used to explore multivariate relationships between data sets and to group associated variables into a small number of factors. Simultaneous R- and Q-mode factor analysis was carried out on rock magnetic data using SPSS 16.0 for Windows (Walden et al. 1992, 1997; Booth et al. 2005). Linearly additive parameters, namely χ_{lf}, IRM $_{500\mathrm{mT}}$, SIRM and HIRM, for the suspended sediment samples and source samples were used. Factors were extracted using principal component analysis and redistributed using varimax rotation.

Unmixing procedure

Sediment source unmixing models have successfully been employed for sediment source identification and quantification using geochemical (Douglas et al. 2003, 2009; Caitcheon et al. 2006), environmental magnetic (Jenkins et al. 2002; Caitcheon 1998; Peters and Turner 1999), magnetic and radioactive (Shankar et al. 1994), sedimentological (Holz et al. 2004) and isotopic (Fox and Papanicolaou 2007) properties. The linear unmixing model (Weltje 1997) used in this study is similar to that employed by Walden et al. (1997) to determine the proportions of end members (sources) in suspended sediment samples using environmental magnetic properties. The Bhadra River suspended matter from Malleshwara and Nellibeedu are assumed to be conservative mixtures of source materials in the catchment. The source materials are (a) naturally weathered and eroded material comprising particles of catchment soils and (b) *anthropogenic* material derived from the Kudremukh mining area, comprising particles of primary ore, weathered ore and transitional hard weathered ore. Based on the magnetic data, the Bhadra River suspended particles were unmixed into the proportions of the two source components. To this end, the Solver "add in" component of Microsoft Excel spreadsheet was used (Walden et al. 1997). The magnetic parameter values of four source materials were provided to the Solver "add in" component together with properties of 49 suspended sediment samples, which had to be unmixed, and the initial proportions of each source. The optimisation process found the best solution from these values (Thompson 1986). For convenience, the proportions are expressed as percentages.

Results and discussion

Rock magnetic data

The mean values of magnetic parameters and inter-parametric ratios for the four types of source materials (Bilegal SPM, primary ore, transitional hard weathered ore and weathered ore) in the catchment are given in Table 2, and represented as bar diagrams in Fig. 2.

The dominant magnetic mineral in all the source materials is magnetite as indicated by the high *S* ratio (>0.80) and by the IRM acquisition curves (Fig. 3) which show that most samples saturate by a field of 300 mT. However, the transitional hard weathered ore seems to have some haematite content as suggested by a lower *S* ratio of 0.80 and the samples not being saturated even at 1T field. Being

Table 2 Magnetic parameters and ratios of source materials and suspended sediment samples

Magnetic parameters and ratios	Source materials				Suspended sediment samples	
	Bilegal SPM average ($n = 8$)	Primary ore	Weathered ore (highly oxidised)	Transitional hard weathered ore (partially oxidised)	Malleshwara SPM average ($n = 5$)	Nellibeedu SPM average ($n = 44$)
χ_{lf} (10^{-8} m^3 kg^{-1})	728	3,680	22,342	7,613	2,305	2,687
χ_{fd} (10^{-8} m^3 kg^{-1})	36	39	1,957	168	83	49
χ_{fd}%	5	1	9	2	3.8	2.3
χ_{ARM} (10^{-5} m^3 kg^{-1})	2	5	12	7	2.9	3.7
IRM$_{20\mathrm{mT}}$ (10^{-5} A m^2 kg^{-1})	502	5,150	9,130	17,943	882	996
IRM$_{60\mathrm{mT}}$ (10^{-5} A m^2 kg^{-1})	3,432	45,991	48,174	95,874	11,264	12,543
IRM$_{100\mathrm{mT}}$ (10^{-5} A m^2 kg^{-1})	5,910	65,266	66,858	108,344	21,476	22,257
IRM$_{300\mathrm{mT}}$ (10^{-5} A m^2 kg^{-1})	8,000	77,496	92,811	140,090	29,836	33,704
IRM$_{500\mathrm{mT}}$ (10^{-5} A m^2 kg^{-1})	8,594	78,611	95,991	71,678	29,836	35,160
SIRM (10^{-5} A m^2 kg^{-1})	8,928	78,981	97,753	174,541	31,972	37,155
S ratio	0.94	0.98	0.95	0.80	0.93	0.91
HIRM (10^{-5} A m^2 kg^{-1})	741	1,485	4,942	34,451	2,136	3,451
$\chi_{\mathrm{ARM}}/\chi_{\mathrm{lf}}$	3.23	1.29	0.54	0.89	1.3	1.8
χ_{ARM}/SIRM (10^{-5} m A^{-1})	25.54	5.99	12.41	3.86	9.2	13.54
SIRM/χ_{lf} (10^3 A m)	12.63	21.46	4.38	22.93	13.89	14.29

located upstream of the Kudremukh mine, Bilegal is not affected by the mining activity. Hence, the SPM samples from this location represent *natural* material derived from the weathering of catchment rocks. This fact is borne out by rock magnetic data which are distinctively different from those for the three types of ore studied, which are *anthropogenic* catchment materials contributed by the mining and allied activities at Kudremukh. Bilegal samples have a moderate value of 5 for χ_{fd}%, a parameter that is a measure of the concentration of ultra-fine magnetic grains in the SP or SSD size range that are produced during pedogenesis (Maher and Taylor 1988; Dearing et al. 1996; Geiss and Zanner 2006; Geiss et al. 2008). Hence, it may be inferred that the Bilegal SPM is derived principally from *natural* sources, i.e., catchment soils. They also have low mean values (Table 2) of concentration-dependent parameters, namely χ_{lf} (728×10^{-8} m^3 kg^{-1}), IRM$_{20\mathrm{mT}}$ or soft IRM (502×10^{-5} A m^2 kg^{-1}) and SIRM ($8{,}928.22 \times 10^{-5}$ A m^2 kg^{-1}). IRM acquisition curves plot at the bottom of Fig. 3, again indicating a low concentration of magnetic minerals. This is a confirmation that Bilegal samples do not have any contribution from *anthropogenic* sources.

The ratios $\chi_{\mathrm{ARM}}/\chi_{\mathrm{lf}}$ and χ_{ARM}/SIRM may be interpreted in terms of magnetic grain size. Higher ratios indicate finer grain size and vice versa (King et al. 1982; Dearing et al. 1997). Thresholds of χ_{ARM}/SIRM for certain modal grain sizes can be estimated from Maher's (1988) magnetotelluric data for known grain sizes of magnetite/maghemite. A χ_{ARM}/SIRM value of $<20 \times 10^{-5}$ A m^{-1} indicates MD + PSD grains. Values between 20 and 90×10^{-5} A m^{-1} suggest coarse SSD grains (Dearing et al. 1997). Bilegal samples have a χ_{ARM}/SIRM ratio of $>20 \times 10^{-5}$ A m^{-1}, indicating a higher contribution of coarse SSD grains. A plot of χ_{fd}% versus χ_{ARM}/SIRM with superimposed threshold values allows estimates to be made of the proportions of frequency-dependent SP and non-SP grains (Fig. 4). The generally coarse SSD nature and the high SP proportion of Bilegal samples are apparent from Fig. 4.

In contrast, the *anthropogenic* source materials (primary ore and transitional hard weathered ore) expectedly have low χ_{fd}% (1 and 2%; Table 2; Fig. 2). However, the weathered ore has a high value (9%) because more SP grains are produced during weathering. Being ores, the three *anthropogenic* source materials have high mean values of concentration-dependent parameters, χ_{lf} (3,680, 22,342 and $7{,}613 \times 10^{-8}$ m^3 kg^{-1}), soft IRM (5,150, 9,130 and $17{,}943 \times 10^{-5}$ A m^2 kg^{-1}) and SIRM (78,981, 97,753 and $174{,}541 \times 10^{-5}$ A m^2 kg^{-1}). The χ_{ARM}/SIRM ratio is $<20 \times 10^{-5}$ A m^{-1}, suggesting an MD + PSD grain size. Generally, magnetite in iron ore deposits has an MD + PSD grain size (Alva-Valdivia and Urrutia-Fucugauchi 1998; Alva-Valdivia et al. 2003). Yang et al. (2007) too have found iron oxide particles in the MD + PSD grain size range in contaminated surficial sediment samples of a lake near an iron and steel factory. It may be noted that the weathered ore has a higher χ_{ARM}/SIRM (12.41×10^{-5} A m^{-1}) because of the weathering it has undergone, but the value still suggests MD + PSD grain size.

The aforesaid observations suggest that the two broad categories (*natural* and *anthropogenic*) in particular and

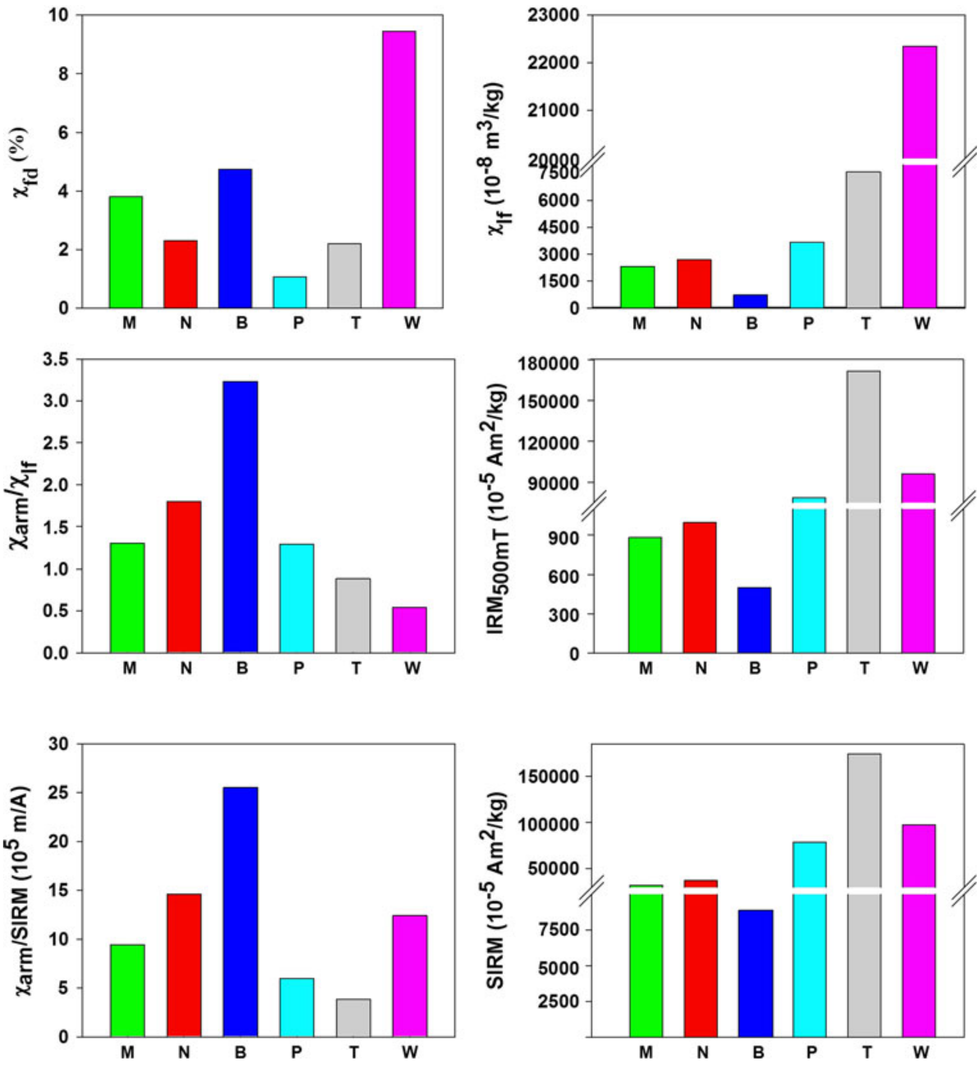

Fig. 2 Bar diagrams showing the mean values of magnetic parameters and inter-parametric ratios for Bhadra River suspended sediment samples [from Malleshwara (*M*) and Nellibeedu (*N*)] and source materials [Bilegal suspended sediment (*B*), primary ore (*P*), transitional hard weathered ore (*T*) and weathered ore (*W*)]. Bilegal samples (upstream of the mining area) have distinctly low values compared to the three types of ore material; Malleshwara and Nellibeedu samples exhibit intermediate values

the four types of catchment source materials in general have marked differences in their magnetic properties, which would be helpful in unmixing the SPM samples.

Rock magnetic data for the SPM samples collected from Malleshwara and Nellibeedu are also given in Table 2, and represented as bar diagrams in Fig. 2. By virtue of being located adjacent to and downstream of the mining area, they consist of both *natural* particles of catchment soil and *anthropogenic* particles of ore materials. This can be seen from the mean values of magnetic parameters which lie between those for *natural* (Bilegal SPM) and *anthropogenic* (ore materials) sources of particles. The question is: what are the proportions of the four source materials in each of the SPM samples? An attempt has been made to answer this question through (a) qualitative analysis, (b) statistical analysis and (c) modelling of the magnetic data.

Figure 5 shows that suspended sediment samples show a clear pattern of increasing magnetic strength from Bilegal to Nellibeedu, consistent with our a priori hypothesis of

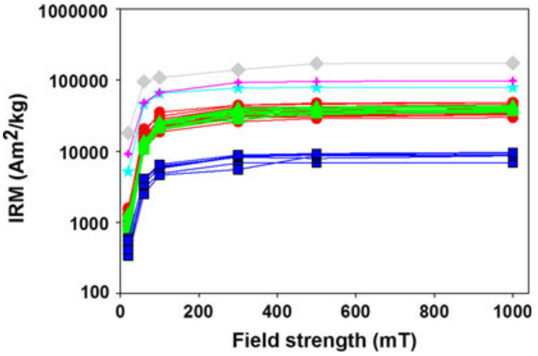

Fig. 3 IRM acquisition curves for Bhadra River suspended sediment samples [Bilegal (*filled squares*), Malleshwara (*filled triangles*), Nellibeedu (*filled circles*), primary ore (*asterisks*), weathered ore (*pluses*) and transitional hard weathered ore (*filled diamonds*)]. Bilegal samples have low IRM values compared to Malleshwara and Nellibeedu samples, implying that the former are pristine, whereas the latter have contributions from the mining area. Some of the Nellibeedu samples are not saturated even at 1,000 mT and show an increasing trend, suggesting the presence of haematite

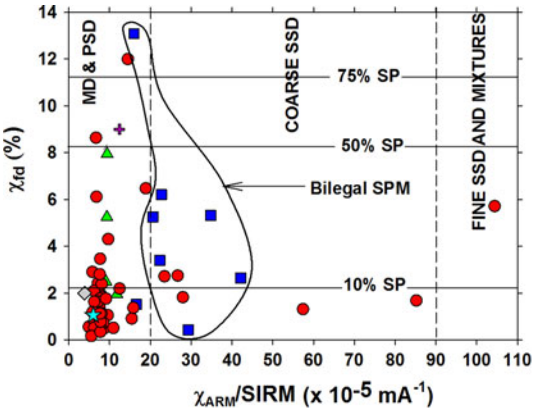

Fig. 4 χ_{fd}% versus χ_{ARM}/SIRM for Bhadra River suspended sediment samples from Bilegal (*filled squares*), Malleshwara (*filled triangles*), Nellibeedu (*filled circles*), primary ore (*asterisk*), weathered ore (*plus*) and transitional hard weathered ore (*filled diamond*) with superimposed threshold values (Maher and Taylor 1988; Dearing et al. 1997). Magnetic minerals of most of the Bilegal samples have a coarse SSD grain size, whereas Malleshwara and Nellibeedu samples, being contaminated by ore materials, have a coarser (MD and PSD) grain size. Bilegal samples have a relatively higher percentage of SP grains (a pedogenic characteristic) compared to Malleshwara and Nellibeedu samples

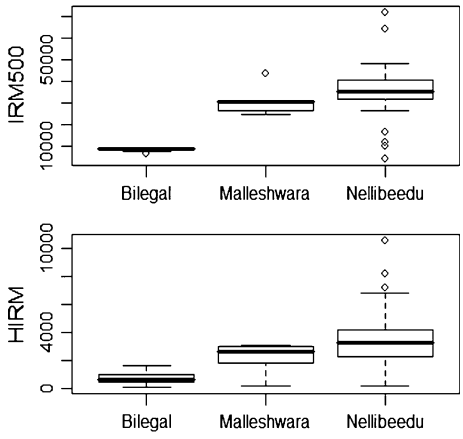

Fig. 5 Boxplots showing central tendency (*median*) and dispersion (*inter-quartile range*, *whiskers* and *outliers*) in magnetic parameters across the three sites: Bilegal upstream of mining, Malleshwara and Nellibeedu, respectively, adjacent to and downstream of the mining area. The pattern is consistent with increasing contribution of mined ore to the suspended sediment load from upstream (of the mine) to downstream sites

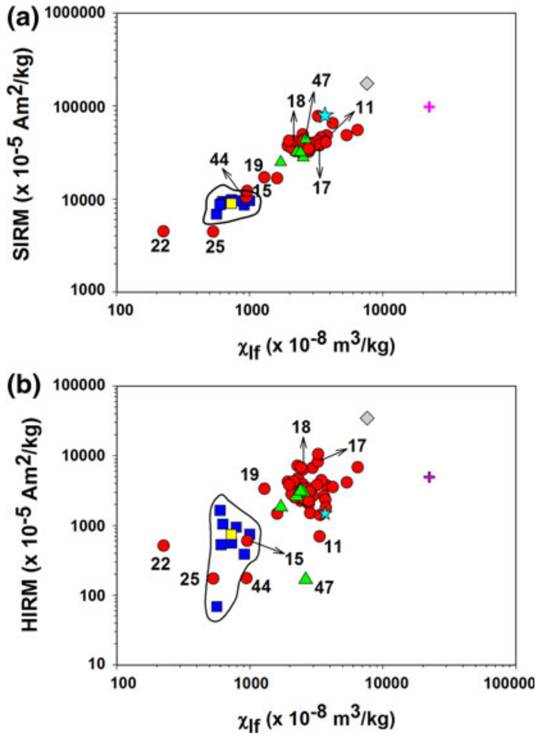

Fig. 6 Biplots for Bhadra River suspended sediment samples and source materials. **a** SIRM versus χ_{lf}. **b** HIRM versus χ_{lf} [Bilegal (*filled squares*), Bilegal average (*filled squares*), Malleshwara (*filled triangles*), Nellibeedu (*filled circles*), primary ore (*asterisks*), weathered ore (*pluses*) and transitional hard weathered ore (*filled diamonds*)]. Bilegal SPM and the ore materials plot separately. Most of the Nellibeedu and Malleshwara samples plot between the two types of source materials—*natural* catchment material (Bilegal) and *anthropogenic* ore materials (primary ore, transitional hard weathered ore and weathered ore)

increasing mobilisation of mined materials into the Bhadra River as one goes from upstream to downstream of the entire mine and mining affected area. In addition, the Kruskal–Wallis tests for IRM$_{500\ mT}$ and HIRM indicate significant ($p < 0.01$) differences across the sites.

In addition, the linear regression of the magnetic parameters (IRM$_{500\ mT}$, HIRM and S ratio) with suspended sediment concentration as a covariate did not yield any significant relationship ($p > 0.05$, $R^2 < 0.05$), suggesting that the magnetic strength of suspended sediment is derived from intermittent contributions from mining effluents through specific channels coming from a restricted area rather than from hydrologic processes that influence the entire catchment.

Graphical analysis

The SIRM (a measure of the concentration of all remanence-carrying magnetic minerals) versus χ_{lf} (a measure of the concentration of ferrimagnetic minerals) and HIRM (a measure of the concentration of anti-ferromagnetic minerals) versus χ_{lf} are plotted in Fig. 6a, b. Samples of the four source materials plot separately; the magnetic mineral assemblages within each of the four source materials seem to have distinct differences. However, the way they plot suggests that they are, to some extent, “numerical multiples” of one another. Such situations are likely encountered in many, or perhaps a majority, of natural field settings (Walden et al.1997). Except six, all Malleshwara and

Nellibeedu SPM samples plot between the four source materials, indicating that it is feasible and possible to mathematically unmix them in terms of the four source materials chosen. The six samples that plot outside of the area covered by the four source materials would pose difficulty in modelling as they may have some contribution from a source that has not been identified.

Malleshwara samples plot more or less as a cluster, which is close to the primary ore plot. This is in agreement with the field set-up (Fig. 1): Malleshwara samples come from close to the mining area. In contrast, Nellibeedu samples are more spread out perhaps because they have contributions from other catchment soils also. Figure 6a, plotted on a log scale, suggests that the highest contribution must be from the Bilegal type of source material as most samples plot closest to it. Figure 6a, b indicates that of the three *anthropogenic* source materials, the primary ore contributes the maximum to the SPM samples, and that the contributions from transitional and weathered ores are minimal.

Multivariate analysis

Q- and R-mode factor analysis was carried out on linearly additive magnetic parameters (χ_{lf}, IRM$_{300\mathrm{mT}}$, SIRM and HIRM) for the source materials and Malleshwara and Nellibeedu SPM samples. The sample and variable loadings obtained are plotted in Fig. 7. Only one factor was extracted with an eigen value of >1 (3.16); it accounts for 78.91% of the variance in the data set. As the second factor has an eigen value of 0.67, only one dominant factor which is loaded on SIRM is inferred, suggesting that this is the magnetic mineral factor. If two factors are extracted, the variance explained is >95%. Such a high value indicates lack of dimensionality in the data, and it is usually so for rock magnetic data sets (Lees 1994). It appears that factor 1 is controlled by magnetic mineral concentration, but is more influenced by magnetically "hard" minerals (represented by HIRM) and factor 2 by χ_{lf}, a parameter that is significantly influenced by magnetic minerals of SP grain size.

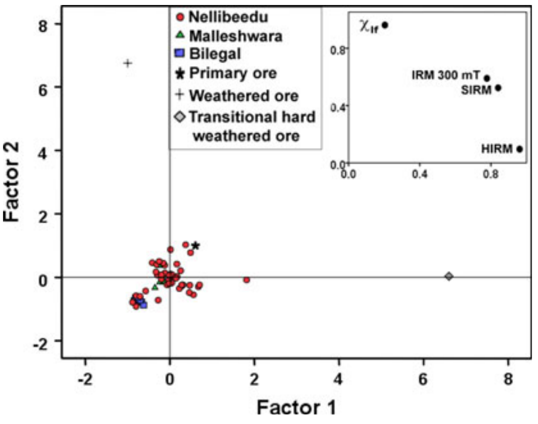

Fig. 7 Sample and variable (*inset*) factor loadings for Bhadra River suspended sediment samples and source materials [Bilegal (*filled squares*), Malleshwara (*filled triangles*), Nellibeedu (*filled circles*), primary ore (*asterisk*), weathered ore (*plus*) and transitional hard weathered ore (*filled diamond*)]

The inferences drawn from qualitative data analysis are confirmed by factor analysis: The four source materials plot separately, indicating that they can be distinguished on the basis of the magnetic parameters chosen for this analysis (Fig. 7). Most of the Malleshwara and Nellibeedu samples plot in the factor space covered by the four source samples. Of the three *anthropogenic* sources, primary ore contributes the most, as SPM samples exhibit a close affinity to primary ore. The transitional and weathered ores plot indeed far away from the SPM samples, indicating their minimal contributions to the make-up of the latter.

Sediment source unmixing

The satisfactory working of the model was tested using ten hypothetical source mixtures; these mixtures were computed taking different proportions of each of the four source materials in terms of the mean values of their χ_{lf}, IRM$_{300\ \mathrm{mT}}$, SIRM and HIRM. The model successfully unmixed the hypothetical mixtures in the correct proportions. Hence, it is reasonable to presume that the model is capable of effectively unmixing mixtures.

In a similar way, 49 samples of SPM collected from the Bhadra River at Malleshwara and Nellibeedu were unmixed. Table 3 provides the magnetic parameters of suspended sediment samples used for modelling and the percentages of the four source materials ascribed by the unmixing model. The model has done a fair job of unmixing; the sum of errors being <1 for a majority of the samples ($n = 40$), between 1 and 4,254 for five samples and >71,000 for four samples. Overall, the Malleshwara and Nellibeedu SPM samples have an average of 29% of total ore material. To this, the primary ore contributes the most (18%) followed by transitional hard weathered ore (7%) and weathered ore (4%). If the samples with large errors (IG13, DG321, DD37, DG34, DD164, DG18 and DD237) are ignored, the average percentage of ore material is 32%, of which the primary ore contribution is 20%; the contributions of transitional hard weathered ore and weathered ore are 7 and 5%, respectively. These results are in tandem with the features exhibited by Fig. 6 in which the primary ore plots close to, and the transitional and weathered ores at greater distances from, SPM samples.

Four samples (DG34, DG321, DD37 and IG13) have been modelled with rather large errors. All have been ascribed 0% ore and 100% Bilegal SPM. An indication of

Table 3 Magnetic parameters of suspended sediment samples used for modelling and the percentages of the four source materials ascribed by the unmixing model

Sample ID	Location	Date of collection	χ_{lf} (10^{-8} m^3 kg^{-1})	IRM $_{300\ mT}$ (10^{-5} A m^2 kg^{-1})	SIRM (10^{-5} A m^2 kg^{-1})	HIRM (10^{-5} A m^2 kg^{-1})	Modelled percentages					Sum of squares[a]
							PO	WO	TO	Total ore	Bilegal average	
DD39	Nellibeedu	12-07-2002	3,788	44,460	48,200	3,740	29	8	7	44	56	0
DD40	Nellibeedu	12-07-2002	3,446	41,636	46,085	4,449	22	6	10	38	62	0
DD41	Nellibeedu	12-07-2002	2,957	33,326	40,025	6,698	0	5	17	22	78	15
DD42	Nellibeedu	12-07-2002	2,657	33,708	35,952	2,244	25	4	3	33	67	0
DD44	Nellibeedu	12-07-2002	2,500	25,996	29,882	3,886	3	5	9	17	83	0
DD45	Nellibeedu	12-07-2002	3,602	38,244	40,885	2,642	25	9	4	38	62	0
DD46	Nellibeedu	12-07-2002	2,974	34,811	37,472	2,661	23	6	4	33	67	0
DD47	Nellibeedu	12-07-2002	2,786	35,680	39,056	3,376	22	4	7	33	67	0
DD48	Nellibeedu	12-07-2002	2,404	30,556	32,822	2,265	21	4	3	28	72	0
DD73	Nellibeedu	16-07-2002	4,201	61,859	65,423	3,564	58	6	6	70	30	0
DD164	Nellibeedu	05-08-2002	3,344	36,997	37,694	697	39	0	0	39	61	4,254
DD165	Nellibeedu	05-08-2002	3,695	39,289	41,633	2,343	28	9	3	40	60	0
DG16	Nellibeedu	05-08-2002	2,466	39,082	41,502	2,419	35	2	4	41	59	0
DD189	Nellibeedu	10-08-2002	5,360	44,325	48,473	4,148	17	17	8	42	58	0
DG18	Nellibeedu	10-08-2002	957	11,589	12,191	602	5	0	0	05	95	932
DD199	Nellibeedu	12-08-2009	3,192	34,388	38,165	3,778	15	7	8	30	70	0
DD235	Nellibeedu	12-08-2009	3,245	33,628	41,858	8,230	0	5	19	24	76	293
DD236	Nellibeedu	12-08-2009	2,281	29,966	37,162	7,197	0	1	17	18	82	136
DD237	Nellibeedu	12-08-2009	1,287	13,704	17,068	3,364	0	0	6	06	94	796
DD238	Nellibeedu	12-08-2009	3,371	36,913	38,325	1,412	31	8	1	40	60	0
DD239	Nellibeedu	12-08-2009	3,723	38,855	40,660	1,804	31	9	1	41	59	0
DG34	Nellibeedu	20-08-2002	225	3,975	4,489	514	0	0	0	0	100	71,961
DG6	Nellibeedu	22-05-2002	1,605	15,224	16,701	1,477	3	3	2	08	92	1
DG14	Nellibeedu	23-05-2003	1,931	33,165	37,394	4,230	17	0	10	27	73	0
DG17	Nellibeedu	23-05-2003	2,183	34,728	37,250	2,521	28	1	5	34	66	026
DG19	Nellibeedu	23-05-2003	6,467	48,310	55,154	6,844	3	21	15	39	61	027
DD77	Nellibeedu	12-07-2003	2,501	43,086	49,399	6,313	19	1	16	36	64	0
DG26	Nellibeedu	12-07-2003	2,054	32,735	35,561	2,826	24	1	5	30	70	0
DD80	Nellibeedu	12-07-2003	2,134	37,622	41,904	4,281	24	0	10	34	66	0
DD82	Nellibeedu	12-07-2003	1,974	38,413	42,245	3,833	26	0	9	35	65	44
DG30	Nellibeedu	15-07-2003	2,541	40,599	43,071	2,472	37	2	4	43	57	0
DG31	Nellibeedu	15-07-2003	2,559	40,553	43,830	3,276	32	2	6	40	60	0
DD98	Nellibeedu	15-07-2003	2,424	29,060	35,866	6,805	0	2	16	18	82	154
DD101	Nellibeedu	06-08-2003	2,511	38,369	41,789	3,420	28	2	7	37	63	0

Table 3 continued

Sample ID	Location	Date of collection	χ_{lf} (10^{-8} m^3 kg^{-1})	IRM $_{300\ \mathrm{mT}}$ (10^{-5} A m^2 kg^{-1})	SIRM (10^{-5} A m^2 kg^{-1})	HIRM (10^{-5} A m^2 kg^{-1})	Modelled percentages					Sum of squares[a]
							PO	WO	TO	Total ore	Bilegal average	
DG321	Nellibeedu	05-08-2002	531	4,275	4,448	173	0	0	0	0	100	126,229
DD163	Nellibeedu	05-08-2002	2,817	35,871	38,911	3,041	23	5	6	34	66	0
DD302	Nellibeedu	22-08-2003	2,761	32,673	34,923	2,250	23	5	3	31	69	0
DD398	Nellibeedu	02-10-2003	3,260	67,219	77,782	10,562	28	0	28	56	44	78
DD26	Nellibeedu	09-07-2002	2,196	29,463	32,673	3,209	15	3	6	24	76	0
DD27	Nellibeedu	09-07-2002	2,449	31,173	34,992	3,819	13	4	8	25	75	0
DD28	Nellibeedu	09-07-2002	2,307	34,371	39,136	4,765	14	2	11	27	73	0
DG1	Nellibeedu	11-07-2002	2,778	30,208	32,242	2,034	19	6	3	28	72	0
DG4	Nellibeedu	11-07-2002	2,840	32,589	34,093	1,505	26	6	1	33	67	0
DD37	Nellibeedu	11-07-2002	944	10,289	10,465	176	0	0	0	0	100	104,705
	Average		2,687	33,704	37,156	3,451	19	4	7	30	70	
IG1	Malleshwara	10-07-2002	1,712	22,984	24,815	1,831	14	2	3	19	81	0
IG5	Malleshwara	06-07-2002	2,525	24,976	27,954	2,978	7	6	6	18	82	0
IG13	Malleshwara	22-07-2002	2,628	43,398	43,566	167	0	0	0	0	100	135,631
IG14	Malleshwara	25-07-2002	2,251	29,224	31,839	2,615	18	3	5	25	75	0
IG27	Malleshwara	08-08-2002	2,407	28,598	31,687	3,089	13	4	6	23	77	0
	Average		2,305	29,836	31,972	2,136	10	3	4	17	83	

Values less than 1 are shown as zero

PO primary ore; *WO* weathered ore; *TO* transitional hard weathered ore

[a] Sum of the squares of differences between actual and modelled values expressed as percentage of the actual values

this effect was already given by Figs. 4 and 6a, b. They plot either outside the area bounded by the four source materials or close to the value represented by the source materials. Incidentally, they have small sample masses when compared with the average sample mass of 0.11 g for Malleshwara and Nellibeedu samples: the largest error-sample (135,631) has a mass of 0.03 g, the fourth largest error-sample (71,961) a mass of 0.08 g and the two samples in between (126, 229 and 104,705) a mass of 0.04 g each. It is known that small sample mass can be a critical factor in magnetic measurements, leading to large errors. The huge errors on the model output for these four samples may simply reflect the sensitivity of rock magnetic instrumentation to abnormally low sample mass. Alternatively, it is possible that the small sample mass resulted because of low velocity flow conditions, when more of low specific gravity soil particles, and less of high specific gravity ore particles if any, are contributed to the suspended load of a river. In addition, low velocity conditions may preferentially bring in fine, rather than coarse, particles. The next five largest error-samples (DD164, DG18, DD237, DD235 and DD98) have errors of 4,254, 932, 796, 293 and 154, respectively. They have been ascribed 0% of one or two types of ore materials.

The modelling results show that the high suspended sediment loading in the Bhadra River downstream of the mining area is undoubtedly from mining and allied activities. The proportion of *anthropogenic* material deduced from this study is less (29%) compared to ~50–85% in Bhadra riverbed sediments (Shankar et al. 1994) at locations close to Malleshwara and Nellibeedu. This may probably be because of the high specific gravity of the ore particles which makes them settle faster and become part of the bed-load when compared to *natural* catchment soil particles which are more likely to be transported as suspended load.

Future investigations of similar nature should (1) address the issue of small sample mass by adopting suitable sampling techniques, (2) consider selective transport of particles of different sizes and specific gravity and (3) combine sampling of bed- and suspended sediment-loads to better analyse the impacts of mining (and its closure) on the total sediment load. Future attempts at sediment source modelling must also address the relationship between particle size and magnetic parameters for both river sediments and source materials (Yu and Oldfield 1989).

Conclusions

Rock magnetic data for the Bhadra River suspended sediment samples from three stations suggest that Bilegal samples are principally derived from catchment soils. As they were collected upstream of the mine site, they do not contain materials resulting from mining and related activities. On the other hand, samples from Malleshwara (which is located close to the mine site) contain a significantly high proportion of sediment particles derived from mining and related activities at Kudremukh. Samples from Nellibeedu, located downstream of the mine site, also contain a high proportion of particles derived from mining and allied activities. In addition, the Nellibeedu samples also contain a larger proportion of haematite, which is an alteration product of magnetite. The magnetic grain size of the Bilegal samples is finer (coarse stable single domain) compared to Nellibeedu and Malleshwara samples (multidomain + pseudo-single domain).

The rock magnetic data obtained in this study provide ample evidence of particulate pollution of the Bhadra River as a result of Kudremukh mining and allied operations. Graphical analysis of the data highlights four source samples: The Bilegal SPM, primary ore, weathered ore and transitional hard weathered ore plot separately in the SIRM versus χ_{lf} and HIRM versus χ_{lf} diagrams; the Nellibeedu and Malleshwara samples plot in between. Of the three *anthropogenic* sources, primary ore contributes the most as suspended particulate samples exhibit a close affinity to it. This is further corroborated by factor analysis. Modelling of the data shows that on average ~29% of the river suspended load downstream of the mine is derived from mining and allied activities at Kudremukh. The contribution of primary ore is the maximum (18%), followed by transitional hard weathered ore (7%) and weathered ore (4%). Environmental magnetic data and their statistical analysis constitute a simple, rapid and inexpensive tool to assess and quantify the sources of the suspended particulate load of the Bhadra River.

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