Sediment Budgets 2 (Proceedings of symposium S1 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 292, 2005.

Estimation of soil erosion and sedimentation in Ramganga Reservoir (India) using remote sensing and GIS

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Abstract Accumulation of sediment reduces the storage capacity and the capability of a reservoir to conserve water for its intended purpose. To limit siltation, it is essential that soil conservation measures be undertaken in the drainage basin upstream of the reservoir. In this study, the catchment of the Ramganga Reservoir has been divided into nine sub-basins to determine which ones are prone to extensive soil erosion. Different parameters that influence soil erosion, such as slope, soil type and land use were analysed using a Geographic Information System (GIS). Siltation in Ramganga Reservoir has been assessed using multi-date remote sensing data. The revised capacity of the reservoir between 364.4 and 339.05 m water levels, due to siltation over a period of 12 years (1988–2000) was assessed to be 2391.63 × 10^6 m^3, which gives an average sedimentation rate of 4.28 × 10^6 m^3 $year^{-1}$. The average siltation rate, based on bathymetric surveys over a time period of (1974–1997), was 4.78 × 10^6 m^3 $year^{-1}$. Thus, the estimated siltation rate, obtained using both the methods gave fairly similar results. This agreement confirms that remote sensing is a viable, inexpensive, and fast alternative to conventional bathymetric surveys.

Key words sediment, reservoir, soil erosion, GIS, sedimentation rate

INTRODUCTION

Soil erosion is a process of land denudation involving both the detachment and transport of surface material. The detachment of soil occurs by such processes as sheet erosion, rill and gully erosion, and through mass wasting and the action of wind. It is a complex dynamic process by which productive surface soils are detached, transported and deposited at a distant place. It results in exposure of subsurface soil and the siltation of reservoirs and natural streams (Biswas, *et al.*, 1999; Jain & Dolezal, 2000). In India, 1 750 000 km^2 of the land out of a total area of 3 280 000 km^2 (about 53%) is prone to soil erosion (Narayan & Rambabu, 1983).

The major factors, that affect soil erosion and sediment yield, are related to land use and topography (Kothyari & Jain, 1997). Land use, as well as climate, geology and soil characteristics impact sediment yield. Vegetation or plant cover tends to reduce soil erosion, its effectiveness depending on the height and continuity of the canopy and the density of ground cover and roots. Generally, forests are most effective in reducing erosion because of their large canopies. Other factors such as topography or slope are also important in determining soil erosion.

If reservoir inflow is heavily laden with suspended sediment, it can lead to substantial reductions in storage capacity due to siltation, unless the incoming material is moved out of the reservoir. Reservoir sedimentation and consequent loss in storage capacity reduces the utilizable volume of water. To determine the useful life of an impoundment, it is essential to periodically assess the sedimentation rate in the reservoir. With a critical and timely knowledge of the sedimentary processes acting on a reservoir, remedial measures could be undertaken, and reservoir operational schedules adjusted, so that there could be optimum utilization of stored water.

Remote sensing, through its various spatial, spectral, and temporal attributes, can provide synoptic, repetitive, and timely information regarding the current water storage capacity of a reservoir. Digital analysis of satellite data could be applied to estimate temporal changes in the surface area of the reservoir. This information, along with elevation data collected from field surveys, can provide an estimate of the siltation rates in a reservoir. A number of studies, designed to assess reservoir sedimentation have been carried out using remote sensing (Goel & Jain, 1998, Jain, *et al.*, 2002)

THE STUDY AREA AND DATA USED

Ramganga Reservoir and its drainage basin were chosen for this study (Fig. 1). Ramganga was constructed across the Ramganga River, a tributary of the Ganga River, during 1974–1975. The main tributaries of the Ramganga River are the Mandalti and Sona Rivers. At full reservoir elevation (363.3 m), the surface area of the entrained water is 78.31 km^2. The Ramganga River transports large volumes of water and suspended sediment, the latter can be detrimental to the life of the reservoir.

To estimate sediment deposition in a reservoir using remote sensing, data about reservoir water level variations are needed. In the present case, the historical record of annual maximum and minimum observed levels were available. In the years 2000–2001, the maximum elevation of 364.4 m was observed on 28 September 2000. Subsequently, the reservoir level fell gradually with the minimum level of 339.05 m observed on 2 May 2001. In the present study, satellite data from the LISS-III sensor of the Indian Remote Sensing (IRS-1C) satellite were used. The study area is covered in Path 97, Row 50 of the satellite's orbit. The remote sensing data for the following dates were considered: 28 September 2000, 15 November 2000, 9 December 2000, 19 February 2001, 8 April 2001 and 2 May 2001. For the preparation of drainage and contour maps, Survey of India topographical maps 53-K/9, 10, 11, 13, 14, and 15, 53-O/1 and 2, at a scale of 1:50 000 were used.

METHODOLOGY

This study was focused on two issues: (1) watershed prioritization on the basis of soil erosion; and (2) reservoir siltation. The methodology for assessing these two issues is discussed in the following sections.

Computation of watershed prioritization

The drainage network and contours of the study area were converted into digital formats based on topographical maps (1:50 000 scale) from the Survey of India. For drainage networking, and development of a digital elevation model (DEM), the GIS

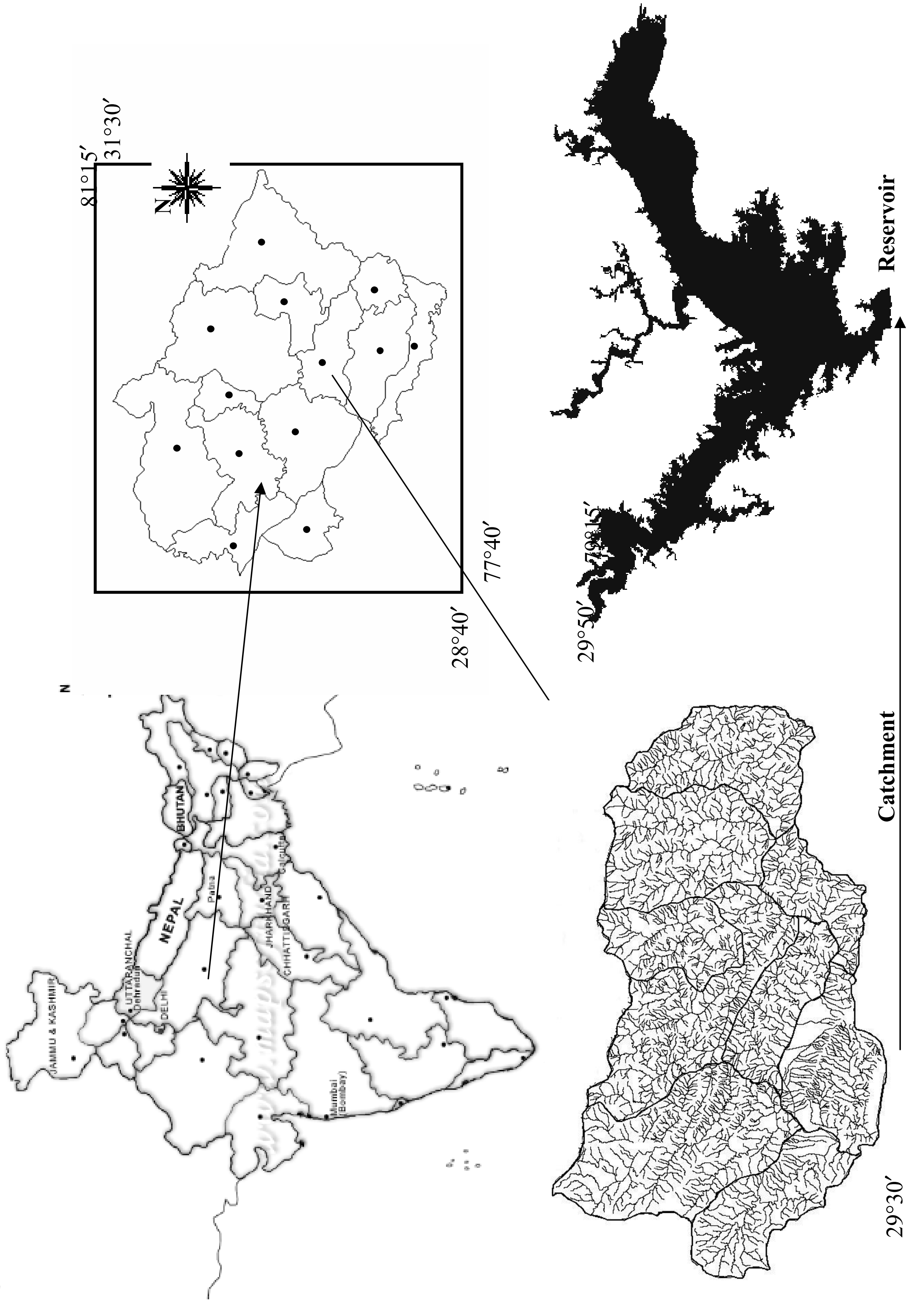

Fig. 1 Location of Ramganga drainage basin and reservoir.

software ILWIS (Integrated Land and Water Information System) was used. ILWIS integrates image processing capabilities, tabular databases, and conventional GIS characteristics. This software was developed at the International Institute for Geo-Information Science and Earth Observation (ITC) (www.itc.nl). The reservoir catchment was divided into nine sub-basins based on the drainage network. The two parameters considered were: (1) the greenness index, to study the effect of vegetation; and (2) the brightness index, to study the effect of soil and slope. The function *interpolation from iso-lines* in ILIWS was applied to each rasterized contour map to generate the DEM. Using the DEM, the slope for each sub-basin was estimated. For computation of other parameters, such as the greenness and soil brightness indices, tasselled cap transformation in the ERDAS IMAGINE software was applied.

Tasselled cap transformation

Numerous methods are available for enhancing the spectral information content of satellite data. The tasselled cap transform compresses the total information into three bands: greenness, brightness and wetness. Besides displaying a large image variability within three bands, tasselled cap bands could be directly related to the physical characteristics of a scene. Brightness is a weighted sum of all bands defined in the direction of the principal variation in soil reflectance. Greenness is orthogonal to brightness, a contrast between the near-infrared and visible bands, and is strongly related to the amount of green vegetation in the scene. Wetness relates to canopy and soil moisture (Crist & Kauth, 1986). The coefficients to convert the data into brightness, greenness, and wetness are not available for IRS LISSIII. Therefore the coefficients available for IRS LISSII and Landsat TM have been applied to the LISSIII data (Crist & Cicone, 1984; ERDAS Field Guide, 1999). These three indices have been calculated using two sensor coefficients for the corresponding wavelength regions. It was found that the results obtained using the coefficients for Landsat TM were better. For the Landsat TM, the coefficients for brightness, greenness, and wetness functions are (Crist & Cicone, 1984, ERDAS Field Guide, 1999):

TM Band	1	2	3	4	5	7
Brightness	0.3037	0.2793	0.4743	0.5585	0.5082	0.1863
Greenness	–0.2848	–0.2435	–0.5436	0.7243	0.0840	–0.1800
Wetness	0.1509	0.1793	0.3299	0.3406	0.306	–0.4572

In this study, the above coefficients were used for IRS LISSIII data for the corresponding wavelength regions. After applying a tasselled cap transformation to an image, three layers are obtained which represent greenness, brightness, and wetness, respectively.

ASSESSMENT OF RESERVOIR SEDIMENTATION

For the quantification of the volume of sediments deposited in the reservoir, the basic information extracted from the satellite data are the reservoir surface areas at different water surface elevations. With the deposition of sediment in submerged areas of the reservoir, the area enclosed by an individual contour, at any elevation, decreases. Greater deposition of sediment causes greater decreases in the contour area. Using the synoptic satellite data and image interpretation techniques, the surface area of the reservoir at the instant of satellite overpass is determined. The incremental change in reservoir capacity between two consecutive levels is computed using the prismoidal formula (Patra, 2001). The overall reduction in capacity between the lowest and the highest observed water levels can be obtained by adding the incremental capacity at various levels. It is important to note that the amount of sediment deposited below the lowest observed level cannot be determined using remote sensing data. It is only possible to calculate the sedimentation rate within the particular zone of the reservoir. Hence, the volume of the reservoir below the lowest observed level is assumed to be the same before and after sedimentation.

Identification of water pixels

Although the spectral signatures of water are quite distinct from other land covers such as vegetation, built-up areas, and soil surfaces, identification of water pixels at the water/soil interface can be difficult, and depends upon the interpretive ability of the analyst. Deep-water bodies have a quite distinct and clear representation in the imagery. However, shallow water can be mistaken for soil, while saturated soil can be mistaken for water pixels, especially along the periphery of a reservoir. Secondly, it also is possible that a pixel at the soil/water interface will represent mixed conditions. McFeeters (1996) developed an index similar to the Normalized Difference Vegetation Index (*NDVI*), which is called the Normalized Difference Water Index (*NDWI*). The *NDWI* is calculated as follows:

$$NDWI = \frac{(GREEN - NIR)}{(GREEN + NIR)} \tag{1}$$

where *GREEN* is a band that encompasses reflected green light, and *NIR* represents reflected near-infrared radiation. When equation (1) is used to process a multi-spectral satellite image that contains reflected visible green and *NIR* bands, water features have positive values of *NDWI*; whereas soil and terrestrial vegetative features have zero or negative values, owing to their typically higher reflectance of *NIR* than green light.

RESULTS AND DISCUSSION

All the parameters required for watershed prioritization have been computed as described above. The output data have different values for each pixel; therefore area-weighted values have been calculated for each watershed. The Area Weighted Vegetation (*AWV*) was calculated by finding the sum of the product of the area of each vegetation category and its weight, divided by the total area of the watershed (equation (2)):

$$AWV = \frac{A1 \times wV1 + A2 \times wV2 + A3 \times wV3 + A4 \times wV4 + A5 \times wV5}{A1 + A2 + A3 + A4 + A5} \tag{2}$$

where AWV is area weighted vegetation, $A1$, …, $A5$ are the areas under each vegetation category, and $wV1$, …, $wV5$ are the weights for each vegetation category. After calculating the area-weighted vegetation for each watershed, the range of AWV was broken down into one of four classes (1–4). High AWV is given the lowest weight and *vice versa*. This is based on the reasoning that a watershed with higher amounts of vegetation will have less erosion. Thus, a watershed with higher vegetation must be given low priority for treatment and *vice versa*. Table 1 gives the AWV and the vegetation related weights for all nine sub-basins for purposes of prioritization. Brightness was treated in a similar fashion, Area Weighted Soil ($AWSo$) values were calculated for all the sub-basins. After calculating the $AWSo$, this too was broken down into four classes (1–4). High $AWSo$ was given the higher weight and *vice versa*. The $AWSo$ values for the different sub-basins, and the corresponding prioritizations, have been tabulated in Table 2.

Since a watershed contains many slope categories, area weighted slope (AWS) was calculated for each sub-basin using the following equation:

$$AWS = \frac{A1 \times wS1 + A2 \times wS2 + A3 \times wS3 + A4 \times wS4 + A5 \times wS5}{A1 + A2 + A3 + A4 + A5} \tag{3}$$

where AWS is area weighted slope, A1, …, A5 are the areas under each slope category,

Table 1 Weighted greenness values and weights for all nine sub-basins.

S. no.	Sub-watershed	Area (km^2)	Weighted greenness value	Weights
1	Maidari	181.66	6.48	4
2	Badangarh	213.29	7.04	4
3	Kalli	115.15	8.10	3
4	Mandalti	229.31	8.88	3
5	Banjadevi	301.63	9.46	2
6	Adnala	152.09	9.76	2
7	Palain	126.67	7.92	3
8	Chuka Nala	165.36	11.06	1
9	Dhulwarao	92.25	9.17	2

Table 2 Brightness values and weights for all nine sub-basins.

S. no.	Sub-watershed	Area weighted brightness value	Weights
1	Maidari	99.59	4
2	Badangarh	102.90	4
3	Kalli	101.47	4
4	Mandalti	94.64	3
5	Banjadevi	92.61	2
6	Adnala	94.54	3
7	Palain	91.13	2
8	Chuka Nala	89.38	1
9	Dhulwarao		2

and $wS1$, …, $wS5$ are the weights for each slope category. Then the slope image was classified into different categories, and the number of pixels in each category noted (Table 3). The slope ranges were further divided into four classes. The area weighted slope values and corresponding weights are given in Table 3. Higher slope causes greater erosion; hence it is given a higher weight and prioritization.

To account for the integrated effects of all three parameters, the individual weights of all the parameters were added. Here it is implicitly assumed that the relative influence of the weights of the different categories ,on soil erosion, are identical. The sum of the weights was also subdivided into four categories for purposes of prioritization. Watersheds with higher weight sums were considered to be more vulnerable to soil erosion and *vice versa*. Thus, the watershed with the highest weight must be given the highest priority for purposes of watershed treatment and for adopting soil conservation measures (Table 4). Hence, based on the summed weights, sub-basins 1, 2 and 3 should be given the highest priority for implementing soil conservation measures.

Reservoir sedimentation

The surface areas, and their corresponding elevations are presented in Table 5 for the year 2000/01. The reservoir capacity between two consecutive reservoir elevations is computed using the trapezoidal formula (equation (4)):

Table 3 Area weighted slope and weights for all nine sub-basins.

S. no.	Sub-watershed	Area weighted slope (%)	Weights
1	Maidari	36.17	4
2	Badangarh	35.24	4
3	Kalli	39.12	4
4	Mandalti	30.07	3
5	Banjadevi	30.32	3
6	Adnala	18.31	2
7	Palain	16.20	2
8	Chuka Nala	12.01	1
9	Dhulwarao	32.33	3

Table 4 Weights and priorities for all nine sub-basins.

S. no.	Sub-watershed	Weights	Priority
1	Maidari	12	I
2	Badangarh	12	I
3	Kalli	11	I
4	Mandalti	9	II
5	Banjadevi	7	III
6	Adnala	7	III
7	Palain	7	III
8	Chuka Nala	3	IV
9	Dhulwarao	7	III

Table 5 Elevations and revised surface areas for the Ramganga Reservoir on the dates of various satellite passes.

Date of pass	Number of water pixels	Reservoir elevation (m)	Water spread area estimated using remote sensing (Mm^2)
28 September 2000	141476	364.40	78.13
15 November 2000	139231	363.78	76.89
09 December 2000	133599	362.35	73.78
19 February 2001	106745	352.14	58.95
08 April 2001	80761	342.51	44.60
02 May 2001	76686	339.05	42.35

Table 6 Estimates of sediment deposition in Ramganga Reservoir using remote sensing data for the year 2000–2001.

Date of satellite pass	Reservoir water level (m)	Surface area using remote sensing	Capacity using remote sensing (Mm^3)	Cumulative Capacity using Bathymetric survey (Mm^3)	Cumulative Capacity using remote sensing (Mm^3)
28 September 2000	364.40	78.13	48.05	2442.43	2391.63
15 November 2000	363.78	76.89	107.72	2398.00	2343.62
09 December 2000	362.35	73.78	676.18	2292.06	2235.91
19 February 2001	352.14	58.95	496.51	1660.90	1559.72
08 April 2001	342.51	44.60	115.49	1075.52	1063.20

$$V = H\,(A_1 + A_2 + \sqrt{(A_1 \times A_2)})\,/3 \tag{4}$$

where V is the volume between two consecutive levels; A_1 is the surface area at elevation 1; A_2 is the surface area at elevation 2, and H is the difference between elevations 1 and 2. Calculation of sediment deposition in Ramganga Reservoir is presented in Table 6.

The results show that the volume of sediment deposited between 1988 and 2000/01 (12 years) between the maximum and minimum observed levels (364.4 m and 339.05 m) was 50.8×10^6 m^3. If a uniform sedimentation rate is assumed, then the average in the zone (364.4 and 339.05 m) is 4.23×10^6 m^3 year^{-1}. Reservoir bathymetric surveys were carried out by the Irrigation Research Institute (IRI), Roorkee, India; their results are (IRI, 1997):

Year	1974	1988	1997	Sedimentation rate, 1974–1997 ($\times 10^6$ m^3)	Sedimentation rate, 1988–1997 ($\times 10^6$ m^3)
Capacity of reservoir ($\times 10^6$ m^3)	2590.72	2508.01	2480.25	4.80	3.08

Thus, the average sedimentation rates based on bathymetric surveys, and remote sensing techniques, are in reasonable agreement.

CONCLUSIONS

In the present study, watershed prioritization and reservoir siltation have been estimated using remote sensing data in conjunction with GIS techniques. A weighted index is derived from the maps of vegetation, soil, and land-use. This index represents the relative level of soil erosion likely to occur in a particular sub-basin. While there is no rigorous theoretical derivation for this index, it is intuitively appealing, and is helpful in identifying areas where soil conservation measures need to be employed, on a priority basis. Also average sedimentation rates in the reservoir have been assessed using remote sensing for the period 1988–2000 (4.28×10^6 m^3 $year^{-1}$). This is in reasonable agreement with the average sedimentation rate calculated from recurrent bathymetric surveys, (4.80×10^6 m^3 $year^{-1}$). As such, remote sensing techniques represent an economical as well as a practical alternative to the much more expensive and tedious bathymetric surveys. As a result of siltation, the reservoir appears to be losing, on average of 0.15% of its initial capacity every year; this is within the normal range of loss.

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