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RESEARCH ARTICLE

Environmentally sustainable sand mining based on GIS based sediment yield estimation

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ABSTRACT

Rampant urbanization, which happens to be the major cause for sand demand is responsible for unsustainable extraction of sand from dried and sometimes even wet river beds. Demand for sand from construction sector in India is expected to grow from 630 million tonne in 2014 to 1.4 billion tonne in 2020 (material usage report). Out of different sources like, river sand, ocean sand, dessert sand, manufactured sand, the river sand is most preferred because of mineralogical properties and grain structure, easy local availability and low cost. This has led to rampant, regulated and unregulated, sand mining in most of the reservoirs and river beds. Though removal of sand/sediments from riverbeds and reservoir beds is essential to prevent shallowing and consequent widening of river bed and reduction of capacity of reservoir. In absence of yield estimation models sand mining leases are allotted where amount of sand mined is decided as 3m from river or 1 m above water table, whichever is less. This may not be environmentally sustainable and may lead of medium to long term changes in riverbed profile and consequent negative environmental impact.

KEY WORDS : Environmentally, Sustainable, Sand mining based, GIS

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INTRODUCTION

Sand mining apparently is a land degradation process, which disturbs soil profile, spoils surface configuration and considerably alters the topography of the land. Excessive mining is becoming an environmental threat (Sreebha, 2011) and (Padmalal, 2008). Formation of the sand is the result of soil erosion from upland and sediment yield at the outlet of watershed. Sediment yield is the process which can over a time restore this altered land profile.

Better approach will be determination of depth on the basis of sediment yield. For example as leases are allotted for five year period then zero effect mining activity can be carried out if depth of excavation is determined on the basis of average yield for five year period.

Sand is an important material which is excessively mined in growing economies like India. Excessive sand mining is degrading land profile and becoming an environmental threat. This degraded land profile gets leveled by the natural process of Sediment yield. ArcSWAT is modeling software which is used to find the quantity of the sediment yield. All the inputs like DEM file of the area, land use, soil type and weather conditions are taken. The result shows that variation of sediment yield depends on the precipitation of the watershed. Finding safety limit approach using GIS-based modeling technique does not seem feasible, but the acceptable degradation factor limit can be worked out.

Yield estimation model:

There are many approaches to find sediment yield. Since, estimation of sediment yield is related to soil erosion, so, it is important to measure soil erosion. Soil erosion of particular watershed can be estimated by the universal soil loss equation (USLE) (Wischmeier, 1965 and 1960). USLE was subsequently upgraded to revised universal soil loss equation (RUSLE) (Renard, 1997). There are five major factors that are used to calculate the soil loss for a given site. Each parameter is the arithmetic estimate of a specific condition that affects the severity of the soil erosion at a particular location (Angima, 2003). This was further modified to modified universal soil loss equation (MUSLE) (Williams, 1984). MUSLE had the capability to predict sediment yield by the equation:

$$\mathbf{Y = 11.8(Qq_p)^{0.56}RKLSCP}$$

where,

Y = Sediment yield in metric ton,

'Q' = Runoff volume in m^3,

'q_p' = Peak runoff rate in m^3/sec,

'R' = Rainfall-runoff erosivity factor

'K' = Soil erodibility factor,

'LS'= Slope length and degree,

'C' = Land-cover management factor and

'P' = Conservation practice factor.

The above formula calculates the sediment yield. We can calculate the above factors separately and then combine them to get appropriate result. The other approach is we can use an integrated hydrologic model such as soil and water assessment tool (SWAT) (Gassman, 2007). Land and water are the two most important natural resources. Watershed is considered to be the ideal unit for management of these natural resources. Modified universal soil loss equation (MUSLE) is utilized by SWAT to predict landscape sediment yield. In order to get the complete picture we will get the required results by the integrated hydrologic model SWAT (Almendinger, 2014). SWAT is designed in such a way that it can predict how water and sediment are impacted by land use and land management. Continuous simulation over long period can be carried out in this model, as it is process based and computationally efficient. Important components of model are hydrology, weather, soil temperature and properties, land management and plant growth. In SWAT, a watershed is the key unit on which all analysis is done. This watershed is then divided into multiple sub watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of same topographical characteristics, land use, management and soil characteristics (Foster, 1981).

The ArcSWAT model is the integration of SWAT and ArcGIS, which gives the user friendly interface to integrate digital elevation model (DEM) file, land use and land cover practices, soil type and weather data which include rainfall, relative humidity, wind speed, solar radiation and temperature data of the study area. Digital elevation model (DEM) is the three dimensional model of terrain surface.

Thus, ArcSWAT can be the good modeling tool related to water and sediment yield. There are several legal and illegal sand mining sites under operation in dried river beds of India. Government authorities allot sand mines to the mining contractors keeping in view environmental impact assessment (EIA) guidelines. The paper by (Mitra, 2015) covers, uses of remote sensing GIS technique in surveying sand mining areas. Further it finds out legal and illegal sand mining by comparing it with maps available with mining department of the respective area.

EXPERIMENTAL PROCEDURE

– Preparation of the watershed contributing to the sediment yield at the point of sand mining from digital elevation map (DEM) file of that area using ArcSWAT.

– Incorporation of land use and land control (LULC) data, soil type data and weather station data for appropriate calculation and modeling of sediment yield at the sand mining area.

– Comparative study of the sediment yield data obtained by ArcSWAT modeling and actual rate of mining

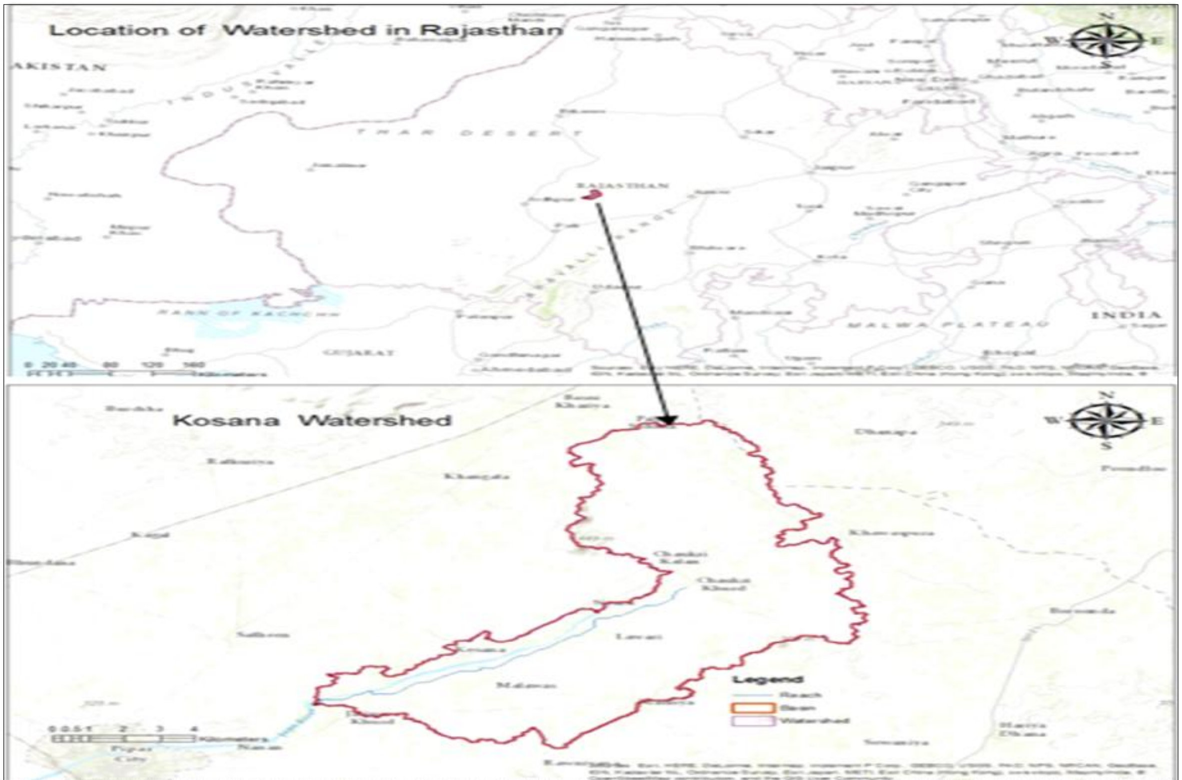

Fig. A : Study area watershed in Rajasthan state in India

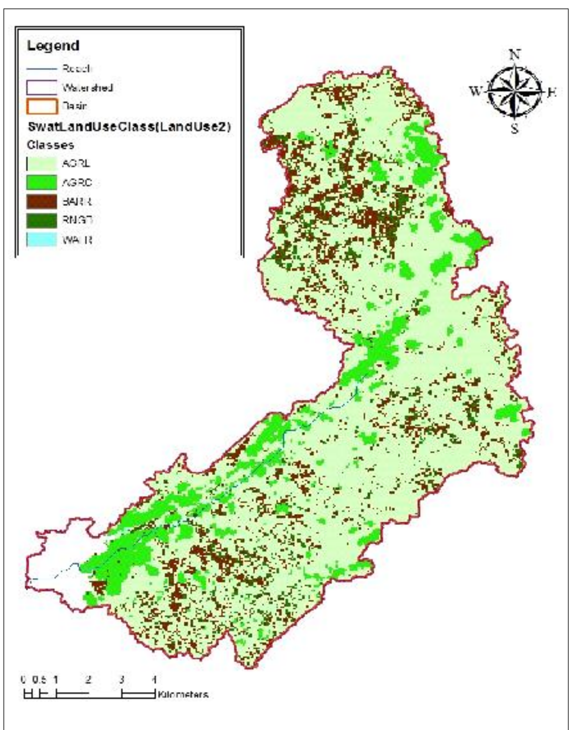

Fig. B : Land use data specific for the study watershed

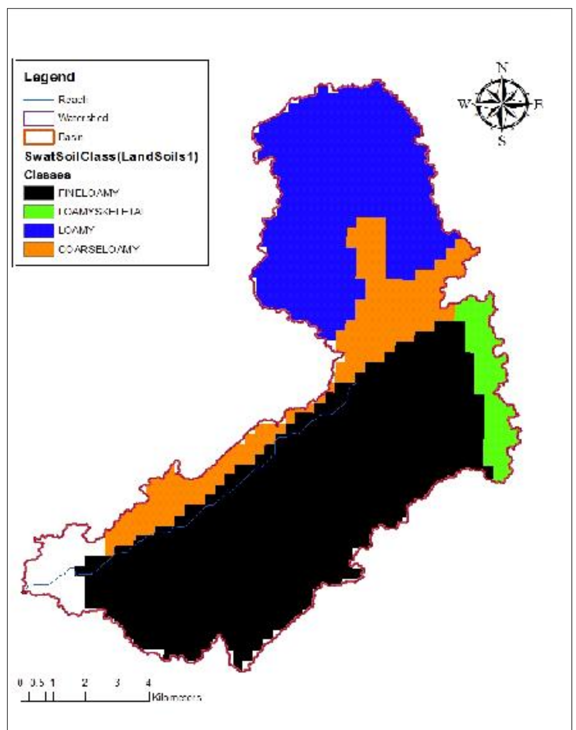

Fig. C : Soil data specific to study watershed

carried out at the sand mining area.

Study area profile:

The newly allotted sand mining site on Mithri tributary located between village Kosana and Malawas in Pipar tehsil in Jodhpur district is chosen as study area (Fig. A) for calculating sediment yield. The sand mining site is located at latitude 26.4389 North and longitude 73.62732 east on Mithri tributary. Mithri is the largest tributary of the Luni river in Rajasthan state in India. Both Mithri and Luni are non perennial seasonal rivers which have water flow only in case of heavy monsoon. As it is a seasonal river it is very difficult to find the origin point but as per Bing maps, it originates near Siyara village in Bhopalgarh tehsil of Jodhpur district and combines with Luni near Sangsani and Virami villages in Luni tehsil of Jodhpur district.

Tools, data and field observations :

– Software used – ArcGIS 10.3 with SWAT2012 known as ArcSWAT.

– Satellite digital elevation model file – Downloaded from NASA Aster Image available on *www.gdex.cr.usgs.gov/gdex*

– Land use land cover data – Collected from national bureau of soil survey and land utilization planning (NBSSLUP) regional centre, Udaipur.

– Soil classification data – Collected again from NBSSLUP regional centre, Udaipur.

– Weather data – Downloaded weather data of the weather stations falling in watershed and nearby weather stations from *www.globalweather.tamu.edu*.

Model working:

Working of the model mainly depends on the GIS DEM file, land use and land cover (LULC) practices, soil properties and weather conditions of the watershed. The watershed is divided into basins, sub-basins and then to HRUs. Then overlaying of land use, land cover and soil properties with slope is done. The driving force behind the entire SWAT model is the water balance because it impacts soil erosion, plant growth and the movement of sediments (Arnold, 2012). Modeling of watershed hydrology is separated in land phase, which controls the amount of water and sediments loading into the main channels from each subbasin into instreams. Climatic conditions drive the water balance as they provide moisture and energy inputs, such as solar radiation, wind speed, daily precipitation, air temperature and relative humidity. Hydrologic processes simulated by SWAT include evapotranspiration, surface runoff, infiltration, lateral flow, tile drainage and redistribution of water in the soil profile. Plant growth model is utilized in SWAT to simulate all types of land cover. It is used to find removal of water, nutrients, biomass and sediments (Arnold, 2012). SWAT uses the MUSLE equation to calculate erosion and the sediment yield from the landscape (Winchell, 2007 and 2013). After determination of the main channel, the loading are routed and deposited to outlet point.

EXPERIMENTAL FINDINGS AND ANALYSIS

After running swat model, swat output was read and analyzed. The desired data was imported in the database and then read and analyzed. The sub basin data was very important which gave the idea of the sediment yield in the watershed. This data is copied from database and further analyzed and the results of sediment yield are as shown in Table 1 to 5 and Fig. 1 to 5.

The total per hectare sediment yield of 17.5 years *i.e.* from year 1997 to 2014 is 323.206 tons per hectare as shown in the Table 5. So, the average sediment yield is 323.206/17.5 ≈18.469 tons per hectare.

The chosen sand mining site is roughly 2 km in length and 200 m wide. So, approximate area of the sand mining site is 0.4 km^2 or 40 hectares. Now, the average total sediment yield of this area is 40x18.469= 738.757 tons per year. The average extraction of the sand mining from the site is approximately 50,000 tons per year from the site based on the random surveys. The rate of extraction is very high compared to the replenishment by sediment yield. The amount of sand mined in one year will be replenished in 50,000/738.757 ≈ 66 years, if the same weather conditions and LULC practices are used.

The fact is that a sand mining site is allotted for generally 5 years and in this complete span of time a total of 2,50,000 tons or even more sand will be mined from the area and it will take on the average more than 333 years to regain the same profile if the same environment conditions exist.

It can be seen from the graphs above surface runoff and sediment yield are dependent on precipitation. More precipitation results in more surface runoff and in turn more sediment yield at sand mining site.

From the monthly average graphs it can be clearly seen that precipitation is more in the month of July, August and September months, which are the months when this area receives most of its monsoon rainfalls.

Table 1: Precipitation in mm

Years	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Grand total
1997	0.8	0	7.9	2.9	18.2	29.9	206.4	112.7	77.3	28.3	10.9	1.1	496.4
1998	0	26.1	3.2	26.5	0	80.8	118.8	42	65.8	6.3	1.6	0	371.1
1999	3.8	16.9	0	0	55.4	18.4	82.4	32.3	0.2	14.4	0	0	223.8
2000	0	3.8	0	0	5.6	0.1	152.7	59.8	5.6	0	0	0	227.6
2001	0	0	0	0.5	1.5	64.5	95	260.2	1.5	19.9	0	0	443.1
2002	0.5	0	0	0.5	1.6	53.4	8.4	111.3	10.4	0	1.4	30.3	217.8
2003	6.2	3.4	0	0.1	0	67.7	572.6	387.5	7.1	0	0	0	1044.6
2004	1.5	0	0	1	32.7	2.4	1.3	13.8	10.6	79.7	0	0	143
2005	10.1	0.1	1	12.5	0	1.9	59.4	5.1	46.9	0	0	0	137
2006	0	0	1.5	0	0	29.3	14.3	31.6	5.5	0	0	0	82.2
2007	3.7	3.2	31.3	0	0	22.8	36.5	29.9	5.6	0	0	0.5	133.5
2008	0	0.2	3.6	8.4	85.9	75.4	76.8	228.4	140.6	0	0	0.1	619.4
2009	0	0	0	0	0	28.1	230.5	49	3.8	1.2	0.2	0	312.8
2010	3.8	0	0	0.2	0	2.6	81.4	147	52.8	0.1	53.2	0.7	341.8
2011	0	18.3	1.9	1	0.3	3	94.5	270.1	214.6	0	0	0	603.7
2012	0	0	0	4.1	1.8	3.6	89.2	104.8	46.3	0	0	0	249.8
2013	6.6	11.2	0.7	0.4	0.1	4	162.7	268.6	138.8	23.2	0.4	0	616.7
2014	0.1	0	0.4	0.3	8.5	11.9	81.3						102.5

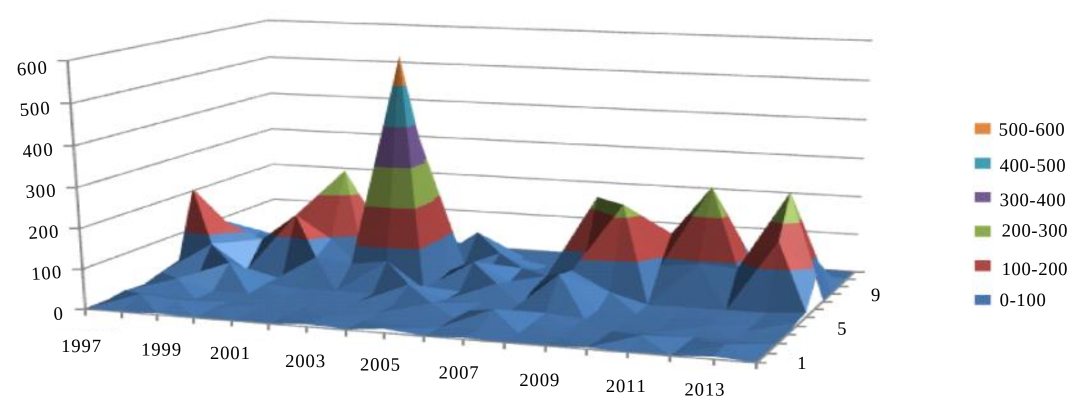

Fig. 1 : Graphical representation of precipitation in mm

Table 2 : Surface runoff in mm

Year	1	2	3	4	5	6	7	8	9	10	11	12	Grand total
1997	0	0	0	0	0.003	0.277	48.512	14.799	16.541	0.319	0	0	80.451
1998	0	1.596	0	0.026	0	5.406	19.476	12.397	6.232	0	0	0	45.133
1999	0	0.044	0	0	10.256	0.776	10.945	4.665	0	0.101	0	0	26.787
2000	0	0	0	0	0	0	29.564	2.467	0	0	0	0	32.031
2001	0	0	0	0	0	9.585	5.976	85.403	0	1.018	0	0	101.982
2002	0	0	0	0	0	5.295	0.027	14.12	0	0	0	4.164	23.606
2003	0.255	0	0	0	0	9.354	237.943	162.824	0.253	0	0	0	410.629
2004	0	0	0	0	1.437	0	0	0	0	19.042	0	0	20.479
2005	0.001	0	0	0.043	0	0	4.15	0	2.531	0	0	0	6.725
2006	0	0	0	0	0	0.206	0	0.885	0	0	0	0	1.091
2007	0	0	1.719	0	0	0	1.223	0.012	0	0	0	0	2.954
2008	0	0	0	0.003	4.526	3.443	9.745	73.536	71.664	0	0	0	162.917
2009	0	0	0	0	0	0.171	98.456	4.143	0.04	0	0	0	102.81
2010	0	0	0	0	0	0	4.734	20.064	7.04	0	2.35	0	34.188
2011	0	0.139	0	0	0	0	10.535	61.581	56.18	0	0	0	128.435
2012	0	0	0	0	0	0	9.374	12.38	2.88	0	0	0	24.634
2013	0	0	0	0	0	0	32.885	93.773	34.769	2.649	0	0	164.076
2014	0	0	0	0	0	0.001	8.181						8.182

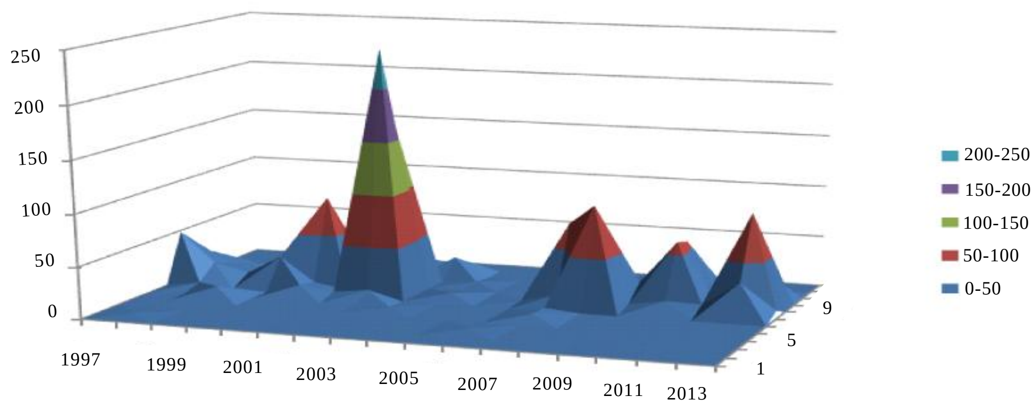

Fig. 2 : Graphical representation of surface runoff in mm

Also from the yearly graphs we can see that more runoff and sediment yield are observed when precipitation in the year is more.

Conclusion :

ArcSWAT is a good tool which takes care of the various parameters of watershed. The sediment yield result given by ArcSWAT are given in tons/hectare/year is convenient to use. More work on this subject can be done to achieve more appropriate results. The limit defining of extent of sand mining does not seem feasible economically, but a maximum acceptable degradation factor of land can be worked out by this approach and limit only upto that extent can be fixed. The replenishment approach does not work completely on our study area and probably the reason is that precipitation of this area is very less. But at the places where sediment yield is more due to slopes and precipitation, this approach can be tried. So, this approach is better if permitted extraction rates are based on new deposition that

Table 3 : Sediment yield in tons per ha

Years	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Grand total
1997	0	0	0	0	0	0.037	4.861	1.68	2.672	0.192	0	0	9.442
1998	0	0.168	0	0.004	0	2.131	2.606	0.857	1.053	0	0	0	6.819
1999	0	0.011	0	0	1.401	0.064	2.656	0.244	0	0.008	0	0	4.384
2000	0	0	0	0	0	0	5.488	0.246	0	0	0	0	5.734
2001	0	0	0	0	0	0.815	0.389	17.656	0	0.114	0	0	18.974
2002	0	0	0	0	0	0.767	0	1.851	0	0	0	0.702	3.32
2003	0	0	0	0	0	2.07	56.271	60.322	0.005	0	0	0	118.668
2004	0	0	0	0	0.13	0	0	0	0	3.41	0	0	3.54
2005	0	0	0	0.004	0	0	0.444	0	0.099	0	0	0	0.547
2006	0	0	0	0	0	0.156	0	0.111	0	0	0	0	0.267
2007	0	0	0.24	0	0	0	0.071	0.001	0	0	0	0	0.312
2008	0	0	0	0	0.946	0.294	0.986	16.086	27.327	0	0	0	45.639
2009	0	0	0	0	0	0.103	43.503	0.972	0	0	0	0	44.578
2010	0	0	0	0	0	0	0.565	1.891	1.377	0	0.603	0	4.436
2011	0	0.066	0	0	0	0	1.067	6.924	6.194	0	0	0	14.251
2012	0	0	0	0	0	0	0.871	1.312	0.137	0	0	0	2.32
2013	0	0	0	0	0	0	10.548	23.574	4.961	0.122	0	0	39.205
2014	0	0	0	0	0	0	0.77						0.77

Table 4 : Monthly average of precipitation, surface runoff and sediment yield in tons per hectare

Months	Average of SURQmm	Average of SYLDt_ha	Average of PRECIPmm
1	00.01422222	0	2.06111111
2	00.09883333	0.013611111	4.62222222
3	00.09550000	0.013333333	2.86111111
4	00.00400000	0.000444444	3.24444444
5	00.90122222	0.137611111	11.75555556
6	01.91744444	0.357611111	27.76666667
7	29.54033333	7.283111111	120.233333333
8	33.12052941	7.866294118	126.711764700
9	11.65470588	2.577941176	49.02352941
10	1.360529412	0.226235294	10.18235294
11	0.138235294	0.035470588	3.98235294
12	0.244941176	0.041294118	1.92352941

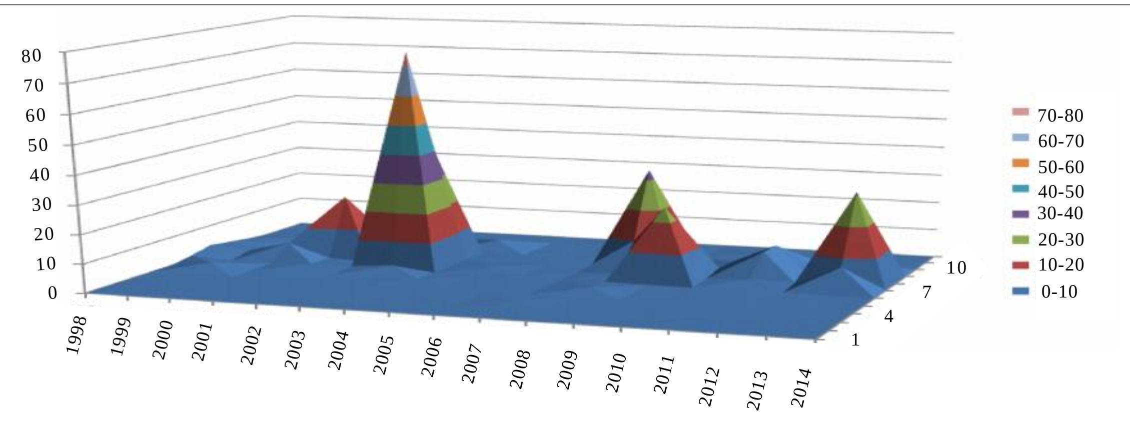

Fig. 3 : Sediment yield in tons per hectare

Table 5 : Year wise sum of surface runoff, sediment yield and precipitation

Years	Sum of SURQmm	Sum of SYLDt_ha	Sum of PRECIPmm
1997	80.451	9.442	496.4
1998	45.133	6.819	371.1
1999	26.787	4.384	223.8
2000	32.031	5.734	227.6
2001	101.982	18.974	443.1
2002	23.606	3.32	217.8
2003	410.629	118.668	1044.6
2004	20.479	3.54	143
2005	6.725	0.547	137
2006	1.091	0.267	82.2
2007	2.954	0.312	133.5
2008	162.917	45.639	619.4
2009	102.81	44.578	312.8
2010	34.188	4.436	341.8
2011	128.435	14.251	603.7
2012	24.634	2.32	249.8
2013	164.076	39.205	616.7
2014	8.182	0.77	102.5
Grand total	1377.11	323.206	6366.8

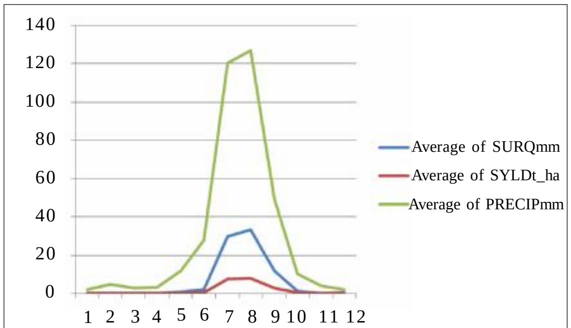

Fig. 4 : Monthly average of precipitation, surface runoff and sediment yield in tons per hectare

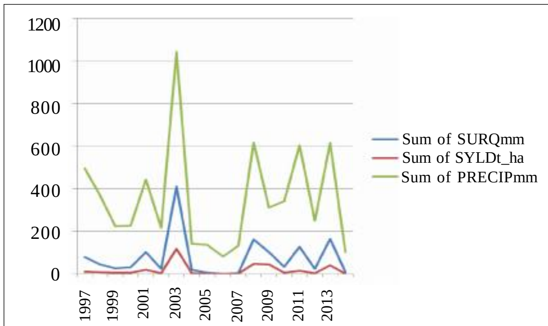

Fig. 5 : Year wise sum of surface runoff, sediment yield and precipitaion

year rather than long term average bed load yield. Yet this GIS based approach if judicially implemented can address many environmental problems. In spite of the fact that this site is quite far-off site from urban areas and quite under exploited site compared to other site, the situation seems alarming. As per the data published the requirement of sand in India by year 2020 will be as high as 140 crore tones, we are bound to look for the alternative of natural sand for construction in order to save our environment.

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