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Estimation of the rate of erosion of valley fill deposits in a part of the NW Lesser Himalaya

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Depositional river terraces in tectonically active regions are used to determine the relative roles of tectonic and climatic changes in the landscape evolution of an area. Apart from providing evidences of tectonic and climatic shifts, these terraces over a long period act as a source of sediment, which is eroded from them. A terrace located in the Lesser Himalaya of known age and a small drainage network developed over it (indicating it to be the only source of erosion), was studied to estimate the rate of erosion. The rate of erosion was calculated by comparing the pre-erosion topography of the terrace modelled in this study by the present day topography of the terrace. Results show that these stored sediments in the form of a depositional terrace are being eroded at a rate of 190 tonnes/year. The results suggest that the rate at which these sediments are eroded is considerable and contributes significantly to the total sediment budget of the river.

Introduction

A thorough understanding of fluvial processes requires a comprehensive knowledge of the sediment budget of a river. Therefore, geologists study past fluvial processes by attempting to determine the rates of erosion and deposition on various time scales. These vary in time and space because of several natural factors such as: catchment geology, precipitation and river discharge, landslides, vegetation, slope (Slaymaker, 2004). Apart from these natural processes, anthropogenic activities such as: deforestation, cultivation, construction and mining also influence rates of erosion and deposition (Slaymaker, 2004).

The major Himalayan rivers (such as Ganga, Yamuna, Sutlej) flow through relatively wide valleys in the hinterland area. The amount of sediment produced throughout the Himalaya and the amount of sediment measured near the mountain exit of the Himalayan rivers show large differences (e.g. Wasson, 2003). One of the reasons for this difference is that the sediment generated gets trapped within the valleys, in places, as valley fill terraces, fans, slope debris (e.g. several such terraces could be observed in the Alaknanda valley, Fig. 1a). One of the important processes that cause dynamic changes in the sediment flux of a river is the climatic shift. During glacial periods, large amount of sediment is generated and as the glaciers wane due to onset of warm period, these sediments are exposed for erosion and transported mainly by the rivers to the downstream part causing

aggradation. As the discharge increases and sediment supply decreases, the rivers incise forming terraces. When considered over a long period, the sediment storage in the valleys become a source for sediment supply and may contribute a significant amount of the total sediment budget. An estimate made by mapping the area of the terraces and multiplying it with their thickness suggests ~ 4800 million tonnes of sediments is trapped between Pipalkoti and Devprayag in the Alaknanda valley (Fig. 1a). These terraces continuously get eroded by various processes such as gullying, undercutting by rivers and collapsing under the influence of gravity contributing to the adjacent rivers. Therefore, apart from the rate of erosion of the bedrock, it is essential to calculate the rates of erosion of such valley fill deposits and quantify the amount of sediment supplied by them to the river systems.

In this study, an attempt has been made to determine the rate of erosion by calculating the volume of sediment removed from a ~ 17 ka terrace located in NW Lesser Himalaya. River terraces (referred to as terraces from here onwards) form when a river becomes unstable and incises its bed (e.g. Schumm et al., 1987; Bridgland, 2000; Wegmann and Pazzaglia, 2009). Thus, terraces record the time of instability of the channel, making it an excellent geomorphic marker. Accordingly, terraces are commonly studied to identify tectonic and climatic events causing changes in the river dynamics in the geological past (e.g. Wegmann and Pazzaglia, 2009).

Study area

A requirement of this study was a terrace of known age with least interference from external processes such as anthropogenic activity or sediment supply on terrace surface by local stream, so that sediment volume of the terrace is only altered due to natural erosional processes. Thus, a terrace located in the Srinagar (Garhwal) region along the left bank of the Alaknanda River was chosen for the study (Figs. 1a,b) which fulfilled the above requirement. A village named Swit is located on top of the terrace under investigation, hence from here onwards this terrace is referred to as the Swit Terrace. It is located ~ 5 km ENE from the main Srinagar city (Figs. 1a,b). The elevation of the Swit terrace is ~ 655 m asl (above sea level) and covers an area of 0.6 km² and the elevation of its top from the river bed is ~ 100 m. A small stream originating from the adjacent valley walls, and locally called Swit *nala*, flows into the Alaknanda river. The local streams are seasonal and are fed mainly by the monsoon. The study area receives an average annual rainfall between 1000 mm to 1500 mm (Sati et al., 2007) with maximum rainfall occurring between mid-June to mid-September.

Method

A geomorphic map of the study area prepared by previous worker

Figure 1. (a) Location map of the study area shown by shaded relief ASTER image (black dots mark the boundary of the Alaknanda River basin); regional view of the area in the inset is shown by the Google Earth image; (b) Geomorphic map of the study area (modified after Sati et al., 2007). Note the Swit terrace located towards the east; (c) Detailed geological map of the study area (modified from Shekhar et al, 2006 and Jha, 1992). The contact between the Phyllite and the Quartzite is thrust, which resulted in reversal of stratigraphic succession in the area (Shekhar et al, 2006). The field succession starts with Koteswar quartzite (lowest unit) followed by slate and Marora limestone, and tectonically the Srinagar phyllite forms the top most unit (Shekhar et al., 2006).

(Sati et al., 2007) was modified using a Google Earth image, Survey of India topographic sheet (1:50,000 scale), and Shuttle Radar Thematic Mission (SRTM) image, followed by field checking. The Swit terrace was mapped using a total station in order to prepare a high resolution topographic map of the area. Contours of the area were then generated from this topography; these were smoothed to model the pre-erosion surface. The present day topography and the pre-erosion topography were then compared (subtracted in GIS environment) to calculate the total volume removed since the formation of the terrace. The volume was then used to compute other parameters such as mass of the eroded sediments and rate of erosion of the Swit terrace.

Geomorphic and Geological Setting

The predominant landforms in the Srinagar area are the well developed terraces present on the northern bank of the Alaknanda river (Fig.1b), suggesting that the river has incised several times in the past. Six levels of terraces have been identified in this region by previous workers (e.g. Sundriyal et al., 2007; Sati et al., 2007; Ray and Srivastava, 2010; Juyal et al., 2010). The highest terrace i.e., T-6 is equivalent of the Swit Terrace as both these occur at a similar elevation i.e., ~ 100 m from the river bed.

The lithology consists of phyllite, quartzite, limestone, and slate of Chandpur Formation (Figs. 1c) (Srivastava and Ahmad, 1979). Phyllite is the dominant lithology which is folded in many places (Shekhar et al. 2006). Another important lithology in the area is quartzite. The Precambrian Garhwal Group is represented by Marora limestone, Garhwal slate and Koteswar quartzite associated with Chamdhar Metabasic. The valley is surrounded by mountains ranging in elevation from ~ 700 m to ~ 1700 m. Several small streams originate in these mountains and constitute the source of sediment supply to the Alaknanda River in this segment. The mountains are mostly composed of phyllites, thus phyllite gravels and fine grained sediments are the chief constituents of the local streams. On the other hand, the Alaknanda drains quartzites upstream of the Srinagar valley, therefore, well-rounded to sub-rounded clasts of quartzite and grey micaceous sand dominate the Alaknanda sediments. Therefore, depositional terraces are often composed of clasts of quartzite deposited by the Alaknanda River and phyllite deposited by the local streams.

Lower order landforms include channel bars and point bars. Thick deposits of sand are present along the banks of the Alakananda River in this stretch. Some landslides contribute sediments directly to the Alaknanda River (not marked on the geomorphic map). A fan-like surface over which Supana village is located is identified in the northeastern part of the study area (Fig.1b).

The terrace is located within the Lesser Himalaya bounded by the North Almora Thrust (NAT) in the north (Fig. 1c). The dip of the NAT or Srinagar fault (Kumar and Agarwal, 1975; Valdiya, 1980) is debated; most of the authors are of the opinion that this thrust dips southward and downstream side of the river is the upthrown block of the thrust whereas, few authors believe that the NAT dips northward (Srivastava and Ahmad, 1979; Ahmad et al., 2000). Two transverse faults have displaced the rocks to the north of NAT (Fig. 1c) (Shekhar et al., 2006). Kirtinagar fault (Sati et al., 2007), Sumari thrust, Koteswar fault and Barkot fault (Shekhar et al., 2006) are the other identified small scale structures. However, these structures do not influence the Swit terrace.

Field Investigation

The field investigation was first carried out to ascertain that no anthropogenic factors (contributing to addition or removal of sediments at rapid rate) or local stream (by adding sediment on top of the terrace) influences the sediment budget of the terrace. Mainly processes such as mining of the terrace for gravels, cutting of terrace for constructional purposes such as dams, a stream terminating on the terrace surface (depositing sediments on top of it), were considered as influencing factors in this study. The surface of the Swit terrace is under cultivation and no other processes seem to influence its surface. Therefore, it was concluded that the terrace is suitable for this study.

Terrace Lithology

The deposits of the terrace are mainly composed of gravels, sand, and silt. The phyllite bedrock attains an elevation of ~45 m from the river bed (Figs. 2 a,b). The bedrock is overlain by a mica rich sandy layer. The sandy layer varies in color as well as grain size (Fig.2c); the buff sandy layer is finer than the grey sand. This sandy layer ~ 60 cm thick is overlain by a thin (~ 30 cm) silty-sand stratum. These strata are overlain by a pebbly layer (~ 32 cm), alternating layers of silty-clay and silty-sand, a quartzite clast dominated bed, and layers of silty clay and coarse sand (Fig.2d). These strata are further overlain by a thick pebbly stratum which is covered by a thick layer that is quartzite clast rich.

The terrace deposits suggest intercalation of deposits from the Alaknanda River and a local stream. The Alaknanda River deposits could be easily differentiated as they consist mostly of sub-rounded to well-rounded clasts of quartzite and grey micaceous sand, whereas deposits of the local stream consist of pebbles of phyllite and fine grained silty-sand to silty-mud deposits. Previous workers (Sundriyal et al., 2007) suggest that the fine grained sediments have been deposited because of the formation of landslide-dammed lakes in the Alaknanda basin.

Total Station Survey

A Total station survey of the Swit terrace was carried out in order to prepare a high resolution Digital Elevation Model (DEM). The total station data were georeferenced in the field using a Global Positioning System (GPS). The data recorded by the instrument was downloaded from the Total Station to a computer and then imported to Arc GIS. The data were then used to prepare a high quality topographic map using various interpolation techniques. The total station used in this study was used with a standard prism and has an accuracy of ± 5 mm. The main focus during the survey was to take dense points around the drainage network developed on the terrace. However, it was difficult to collect points at the drainage heads due to dense vegetation. As there is not much change in the slope of the stream and points were collected in the downstream part (not far away from the drainage head), it did not affect the overall quality of the data. Several points were also collected from the top of the terrace as well as from its slopes. Data were also collected to mark the boundary between the bedrock and the overlying sedimentary strata. On the whole, 342 individual topographic data points were collected enveloping the entire terrace.

Figure 2. (a) Photograph showing bedrock overlain by thick sedimentary cover in Swit terrace; (b) Photograph showing relationship between the bedrock and the Alaknanda River. This photograph is taken from the top of the Swit terrace; c) Alternating layers of buff and grey color sand; d) Outcrop towards the top of the terrace showing alternating layers of the silty-sand and coarse sand overlain by clast rich deposit.

Results

The data points collected were used to generate the modern topography of the terrace. Contours were also generated from the modern modelled topography and these were smoothed to generate the pre-erosion topography of the area.

Recent topographic modelling

The data points were imported in Arc GIS in shape file format and overlaid on the image of the study area (Fig.3a). Using *surfacing* under *create surface* module in the ERDAS software, the topography of the present day terrace surface was created (Fig.3c). The interpolation technique used was *Linear Rubber Sheeting* because the points were closely spaced, hence covering all the prominent breaks in slope on the surface.

Pre-erosion topographic modelling

The pre-erosion surface of the area was prepared by manually modifying the contours as shown in Fig. 3d, e. Due to the large width of the eroded basin it was found that removing points within the basin and preparing the surface without supervision through software yielded erroneous results. Hence, the contours were generated from the present day modelled topography and then these contours were smoothed; while smoothing of the contours the slope of the non-eroded terrace was also taken into account. These contours were then used to prepare a pre-erosion topography using *surfacing* under the *create surface* module of ERDAS software.

Computation of Volume and Rate of Erosion

The pre-erosion surface was compared with the present day

Figure 3. (a) Location of data points (marked by black dots) collected during total station survey; (b) 3-D view of the drainage network developed over the Swit terrace; (c) Contours of the present day surface; (d) Contours after manual modification showing pre-erosion surface; (e) Example showing how the contours were smoothed manually. The red contours show contours of pre-erosion topography.

topography to produce a volumetric estimate of the sediment eroded through the process of gully erosion and drainage development on the terrace. The shape of the basin and lack of major anthropogenic activity on the terrace surface suggest the erosion to be primarily caused by natural processes (Fig. 3b). It should be noted that in the present study erosion through the processes of gully and drainage development is only taken into account, as the objective was to estimate the erosion only through natural processes (i.e., erosion because of cultivation has not been estimated).

The rate of erosion was estimated considering the time of terrace formation to be the same as T6 of Srinagar valley. There is however ambiguity over the time of formation of T6. Two different dates have been obtained by previous workers: Ray and Srivastava, (2010)

suggested T6 to have formed at 26 ± 4 ka whereas Juyal et al., (2010) suggested it to have formed at 17 ± 2 ka. Since Juyal et al., (2010) have dated two samples from this unit and the ages of both samples are in good agreement with each other, their age was followed in this study.

Volume estimation of eroded sediments

DEMs of the pre-erosion surface and eroded surface were compared and the difference was calculated in ERDAS using the *function* module under *utilities*. The outcome of this analysis was a raster image that had cell values containing the 'elevation-difference' of the two images. This raster image was then used to calculate the volume via the *surface volume key* in the Arc 3D analyst. This amount

was calculated to be 1709972 m^3 ($\sim 1.71 \times 10^6$) for a drainage area of 57013 m^2 .

Mass estimation of eroded sediments

Mass of the sediment removed from the drainage basin on the terrace was calculated considering density of the sediments to be 1.9 g/cc ; since quartz (density = 2.65 g/cm^3) is the dominant mineral in the terrace sediments and considering the average porosity of the sediments to be $\sim 30\%$, the sediment density was approximated to 1.9 g/cm^3 .

$$\text{Volume of the sediment eroded} = 1.710 \times 10^6 \text{ m}^3$$

$$\text{Density} = 1.9 \text{ g/cc} = 1900 \text{ kg/m}^3$$

$$\text{Mass} = \text{Density} \times \text{Volume}$$

$$= 1900 \times 1710000$$

$$= 3249000000 \text{ kg or } \sim 3.25 \text{ million tonnes}$$

Therefore, the total mass of the sediment removed from the terrace since its formation 17,000 yrs ago is 3.25 million tonnes.

Rate of erosion

The sediments removed from a terrace per year is:

$$\begin{aligned} \text{Mass of the sediment eroded per year} &= \frac{\text{mass of the total sediment eroded}}{\text{Total time}} \\ &= \frac{3249000}{17,000} \\ &= 191.12 \text{ t/yr} \gg 190 \text{ t/yr} \end{aligned}$$

The rate of erosion can be thus calculated from the above data as:

$$\begin{aligned} \text{The specific sediment yield} &= \frac{(\text{Mass of the sediment eroded} / \text{Surface area of the basin})}{\text{total time}} \\ &= \frac{(3249000 / 57013)}{17000} \\ &= 56.987 / 17000 \\ &= 0.00335 \text{ ton/m}^2/\text{yr} \\ &= 3.35 \text{ kg/m}^2/\text{yr or } 3350 \text{ t/km}^2/\text{yr} \end{aligned}$$

Discussion

River Terrace

The study of terraces in tectonically active areas such as the Himalaya is very important to identify significant tectonic and climatic events (e.g. Lave and Avouac, 2000; Singh et al., 2008; Sinha et al., 2010; Ray and Srivastava, 2010). In tectonically active terrains, the origin of terraces could result from complex interaction between tectonics and climate (e.g. Wegmann and Pazzaglia, 2009; Sinha et al., 2010) and often it is difficult to attribute the origin of a terrace to any one factor.

Terraces can be classified into erosional (or strath) and depositional; they can be paired and unpaired as well. Depositional terraces form when a river aggrades and then entrenches the alluvium (Goudie, 2004). The depositional terrace usually does not get preserved for long period, because they are easily erodible, whereas the preservation potential of the strath terrace is comparatively much higher (for e.g. terraces as old as $\sim 500 \text{ ka}$ have been identified along the Wind River in NW Wyoming by Hancock et al., 1999). The Swit

terrace is a depositional (or a valley fill) terrace and due to continuous incision by the Alaknanda River, bedrock at the base is exposed. For sediment budgeting it is essential to know the residence time of these sediments stored within the hinterland. In the Himalaya not enough data is available on the residence time of the valley fill sediments and Swit terrace provided a suitable location to compute residence time of these sediments.

In tectonically active terrain, preservation of valley fill terraces is difficult because the area is continuously uplifting and the river constantly incises, thus, steepening the slopes of the valley walls, which in turn facilitates the erosion of the terraces. Further, the depositional terraces in mountains are also a type of sediment storing body, quantification of which is important for calculating effective sediment budgets of a valley (e.g., Straumann and Korup, 2009). Thus, the present study also contributes partially towards understanding of the sediment budget in the area.

Residence period of the Swit terrace

Sediment residence period in a valley is a function of various factors (discussed later). Within the limitation we attempt a boundary condition for the residence period of the Swit terrace. The total volume of the sediment trapped in the Swit terrace was calculated as $\sim 3.8 \times 10^7 \text{ m}^3$ (Area - $607700 \text{ m}^2 \times$ Average thickness of the sediment - 64 m). Assuming average density for the sediments as 1900 kg/m^3 the mass of the sediment stored in the Swit terrace is calculated as $\sim 7.22 \times 10^{10} \text{ kg}$. Given the amount of sediment removed from the terrace is $3.25 \times 10^9 \text{ kg}$, the amount of sediment left is $6.895 \times 10^{10} \text{ kg}$. With the erosion rate of 190 t yr^{-1} , the remaining volume of the sediments could be removed from the terrace in next $\sim 363 \text{ ka}$. Adding up the depositional age of the Swit terrace i.e. $\sim 17 \text{ ka}$, therefore the residence period of the terrace is calculated as $\sim 380 \text{ ka}$.

Indeed, the residence time of $\sim 380 \text{ ka}$ appears to be sufficiently high compared to reported ages in the area; the ages of oldest terraces in the Alaknanda valley is only $\sim 49 \pm 4 \text{ ka}$ (Ray and Srivastava, 2010). This anomaly in calculated age of the Swit valley raises the question of how large can be the span of sediment residence in a valley? In fact, the period for which sediments remain stored in a valley depends on factors such as (a) the amount of sediment accumulated, (b) amount of rainfall, (c) bed level and lateral shifting of the trunk river towards the terrace, and (d) rate of tectonic uplift in the area. In the present case, the calculated value provides only the upper bound for the residence period. Reason behind this may be due to: (a) use of average rate of erosion for a period of 17 ka in the estimation, which is believed to increase with the growth of drainages on the surface of the terrace, thus, reducing the residence time of the sediments, (b) incision and/or lateral shifting of the Alaknanda River towards the Swit terrace could also increase the rate of erosion by several folds, and (c) the uplift of the terrace which would also enhance the rate of erosion (Shroder and Bishop, 1998). It is felt that further refining in the estimated residence time can be done by taking into account all the factors to get an actual robust value.

Comparison with the previous studies and its implication

Wasson (2003) summarized the sediment yields of catchments in the Himalaya (refer to Table 2 of Wasson, 2003) which showed that mass movements, rockfall, rock glaciers, glaciers and glacial outwash

yield most sediment. Studies have also shown that the cultivated and terraced landforms of less than 1 km² yields about 250 - 6440 t km⁻² yr⁻¹ of sediments (Narayana and Babu, 1983; Bruijnzeel and Bremmer, 1989). Furthermore, the calculation of sediment production on cultivated land in the Chamoli district, Garhwal, shows 519 - 6410 t km⁻² of sediment being produced per year (Wasson, 2003).

The value obtained in the present study suggests a high *average rate of erosion* from a very small area. The values calculated in the present study falls within the range (250 - 6440 t km⁻² yr⁻¹) measured by previous workers (Narayana and Babu, 1983; Bruijnzeel and Bremmer, 1989) for cultivated and terraced land.

Conclusion and Future Directions

The present study demonstrates that valley fill deposits may be a significant source of sediment supply and sediments can be eroded at a rate of ~3350 t/km²/yr⁻¹ in the Lesser Himalaya. If this rate applies to the other valley fill deposits of the Lesser Himalaya, then the total sediment supplied to the rivers from the erosion of terraces may form a significant part of the sediment budget. It should be noted that these values are preliminary from one area, and in order to develop robust estimate, more such data with rigorous and detailed field mapping would be required.

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