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# Effect of climate change on suspended sediment load in the Himalayan basin: A case study of Upper Kaligandaki River

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## Abstract

The effects of climate change on mountain hydrology are likely to have consequences for mountain people, particularly in terms of the water sources, vegetation, grazing land and other resources on which they are dependent. The Intergovernmental Panel on Climate Change (IPCC) has indicated that global warming is occurring relatively faster in recent decades, with the rate of temperature increase being greater in the high-altitude Himalaya than in lowland parts of Nepal (Shrestha *et al.*, 1999). One effect of the temperature rise is that glaciers are retreating faster than previously in the Himalayan region (International Centre for Integrated Mountain Development (ICIMOD), 2009; IPCC, 2001; 2007). This paper examines changes in river flows and sediment loads in the Himalayan region using the Upper Kaligandaki River basin as a case study. River flow and suspended sediment concentration data were collected at two locations and were analysed for the period 2011 to 2012. The two variables were found to have a positive correlation. Using historic river flow data, long-term annual average suspended sediment loads were then estimated for the period 1975 to 2011. The result showed a trend of increasing sediment load in the Upper Kaligandaki River. The increasing trend is likely to continue and will have detrimental consequences on the current landuse and infrastructure.

## Keywords

climate change, suspended sediment, Upper Kaligandaki, Himalayan region

## Introduction

The effects of climate change on mountain hydrology are likely to have consequences for mountain people, particularly in terms of the water sources, vegetation, grazing land and other resources on which they are dependent. IPCC reports (2001, 2007) have indicated that global warming is occurring relatively faster in recent decades, and the rate of temperature rise is generally higher in high altitude areas. For example, mean annual maximum temperatures were found to be increasing at a rate between 0.4°C and 0.9°C per decade across different ecological belts of Nepal, with the highest rate of increase occurring in the Trans-Himalayan region (Shrestha *et al.*, 1999). The temperature rise has been linked with an increased rate of snow and glacier melt in the Himalaya (ICIMOD, 2009). Retreating glaciers, melting of permafrost and annual fluctuation in snow cover areas have resulted in a change in sediment yields (ICIMOD, 2001; Inman *et al.*, 1999).

Climate change is primarily attributed to the increase in greenhouse gases (IPCC, 2007; 2001), but there are other causes of climate change such as natural variations in temperature, volcanic activity, changes in solar activity, urban heat effects and others. Whatever the cause, climate change is a major threat to snow covered areas, high mountain pastures and range lands, which support highland ecosystems. It is predicted that a one degree temperature rise at sea level will correspond to a two degree temperature rise in high altitude zones such as the Himalayas (IPCC, 2001; 2007). Hydrological impacts of climate change include altered precipitation patterns, increased occurrence of extreme weather events, increased glacial melting, and altered stream flows and river sediment transport.

The Himalayas, being geologically young, experience continuous denudation. Sediment production may vary significantly with long-term cycles in drainage system development and rejuvenation. The primary erosion processes are overland flow, channel degradation, bank cutting and erosion by wind currents. Other processes having an impact on sedimentation include debris flows, gully erosion and hill slope failures. Agricultural practices, such as grazing, and road construction activities have also enhanced sediment production in the Himalayan catchments. In rain-fed rivers, both river discharge and basin rainfall are the dominant variables for estimating suspended sediment concentration (Bhusal and Yogacharya, 1995).

Research on the impacts of climate change on river sedimentation and erosion in Himalayan catchments is limited. Erosion and sediment transport patterns are complex, but are likely to be directly influenced by changes in precipitation patterns. In this context, the present study seeks to examine trends in precipitation, runoff and suspended sediment transport in a Himalayan river basin, the Upper Kaligandaki River basin.

## The study area

The Kaligandaki River is a glacier-fed antecedent river originating in the Nepal Himalayas. It runs from north to south in the higher Himalayan region, flows eastwardly through the lesser (or lower) Himalayan region, enters the Tarai plains of Nepal and ultimately joins the Ganges River in India. The study area, which covers a short stretch of Upper Kaligandaki River in the higher Himalaya, is located in the Trans-Himalayan region of Nepal (Fig. 1). Politico-administratively the area forms part of Mustang district, one of 16 mountain districts in the country (NTNC, 2008). The Upper Kaligandaki River has a catchment area of about 3500 $km^2$ and its elevation ranges from about 2900 m to 8137 m (at Dhaulagiri Peak). The landscape of the river basin is characterised by moraine deposits and debris fans, with pine and mixed shrub-type vegetation in the river valleys. The study area has a very low population density, with scattered settlements along the river terraces (NTNC, 2008).

Broadly, the basin can be divided into three climatic zones: 1) a cold temperate zone up to 3000 m; 2) an alpine zone between 3000 m and 4500 m and 3) a tundra zone above 4500 m (NTNC, 2008). The area above 5,000 m is either perpetually covered with snow or consists of vertical bare rocks. The basin falls under a rain shadow and has a dry, arid climate. The area around the basin outlet has an average annual rainfall of 785 mm whereas the Lo-Mangthang area, which lies further north, receives only about 200 mm of rainfall per year (DHM, 1999, 2008).

The Upper Kaligandaki River basin receives most (61%) of its precipitation during the monsoon (June to September), with winter (December to February) being the driest season (7% of annual precipitation). During winter most of the precipitation falls as snow. The average annual flow of Upper

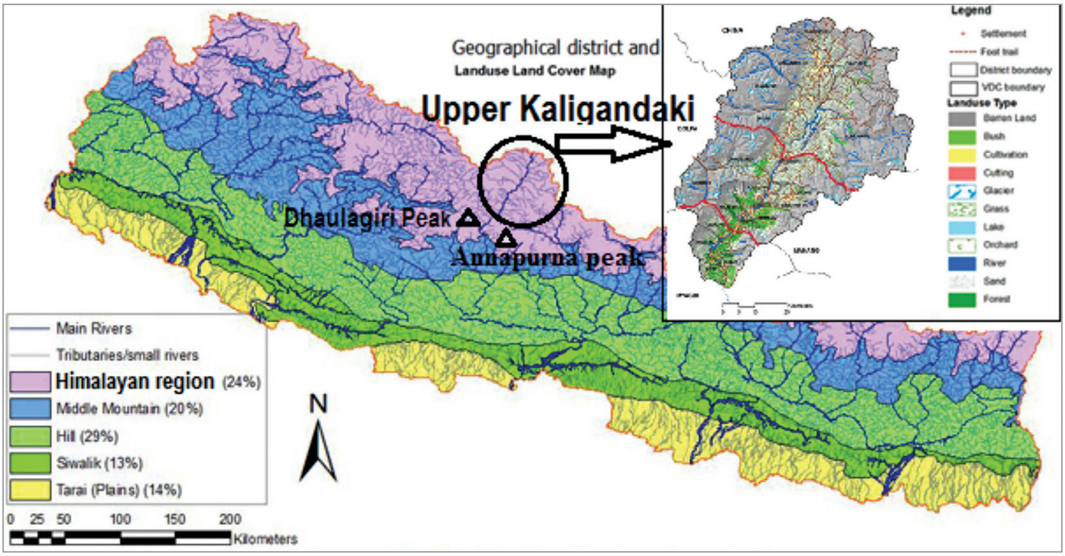


**Figure 1** – Location of the Upper Kaligandaki river basin within Nepal.

Kaligandaki River is 25 $m^3/s$ but there is large seasonal variability, with average flows in the monsoon season (June to September) and dry season (December to February) being 54.8 $m^3/s$ and 8.6 $m^3/s$, respectively. In general, the maximum flows occur in August and the minimum flows in March. The width of the river varies from 30 m to 150 m. The gradient of the river course varies from 3% to 16%, with an average of 7%. There are about 1,025 glaciers in this region (ICIMOD, 2001; 2009) and a multitude of glacier-fed streams enter the Upper Kaligandaki River.

The sediment-related risk is inherent in the Kaligandaki basin due to continuous uplifting and landscape evolution (Adhikari and Wagreich, 2008). A study in Lete and Ghansa (downstream of the present study area) indicated that there was an increase in suspended sediment loads by about 0.7% per year over a period of 30 years (Bhusal, 2010). Retreating glaciers, melting of permafrost and annual fluctuation in snow cover areas in the context of rising temperatures due to accelerated global and local warming were responsible for the changing rate of sediment yields (ICIMOD, 2001; Inman *et al.*, 1999).

## Data and Methodology

### Data sources

Historical precipitation, temperature and river flow data were sourced from the Department of Hydrology and Meteorology (DHM), Government of Nepal (DHM, 1999, 2008). DHM follows standard procedures of World Meteorological Organization as well as United States Geological Survey. Temperature readings are taken twice daily, normally at 08:45 and 17:45 Nepal Standard Time. Mean daily temperatures are computed by arithmetic mean of mean maximum temperature and mean minimum temperature. Maximum temperature readings are taken from mercury in-glass and minimum temperature readings from alcohol in-glass thermometers, sheltered in Stevenson screens with a bulb height of 1.25 m above the ground (DHM, 1999). Precipitation is measured using standard 8-inch diameter American-type rain gauges manufactured locally, installed at one metre above ground level. Readings are taken daily at 08:45 Nepal Standard Time.

The temperature data used in this study was from a site called Thakmarpha, located at an altitude of 2566 m in the lower part of

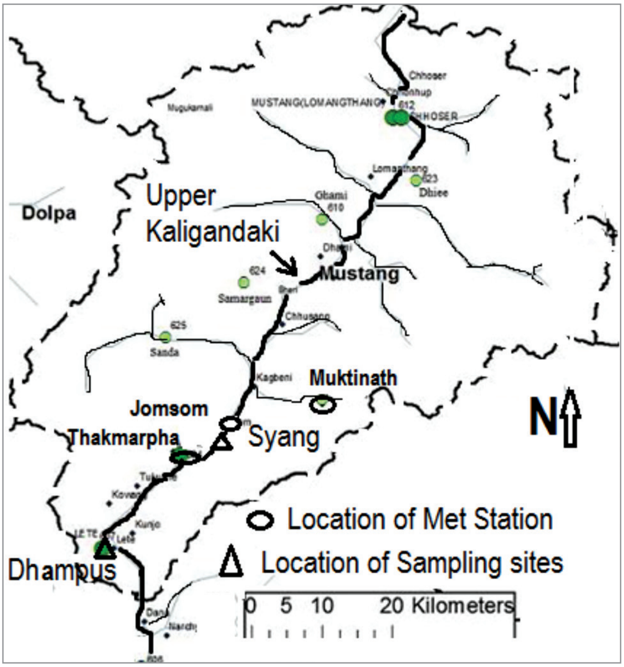


**Figure 2** – Location of hydro meteorological monitoring networks in the Upper Kaligandaki basin.

the Upper Kaligandaki catchment, for the period 1969 to 2012. Rainfall data was from three sites – Thakmarpha (2566 m), Jomsom (2744 m) and Muktinath (3609 m) – for the period 1975 to 2010. The monitoring locations are shown in Figure 2.

River flow data was obtained from two sites on the Upper Kaligandaki River, Syang (catchment area 3200 $km^2$) and Dhampus (catchment area 3500 $km^2$) (Fig. 2). Dhampus is 20 km downstream of Syang, and is generally representative of flow at the outlet of the Upper Kaligandaki basin (International Hydrological Programme (IHP) Nepal, 2011, RECHAM, 2013). The two sites are located at fairly stable locations with hard rock exposure at both banks. Mean daily river flows are computed from mean daily water level using established stage-discharge rating curves supported by frequent discharge measurements. Mean daily water level is the arithmetic mean of water levels manually noted three times daily, normally at 08:00, 12:00 and 16:00 Nepal Standard Time. Flow data for the site Syang is available for the periods 1975 to 2008 and 2011 to 2012; the site Dhampus has a shorter record, with flow data available for 2011 to 2013.

Suspended sediment concentration was measured at the two flow monitoring locations: 1) Syang, over the period March 2011 to March 2012 (IHP Nepal, 2011) and 2) Dhampus, over the period 2011 to 2013 (RECHAM, 2013).

A depth integrating sampler (US DH-48) was used for sediment sample collection. During sampling, the intake nozzle is orientated into the current and held in a horizontal position while the sample is lowered at a uniform rate from the water surface to the bottom of the stream and then raised again to the water surface at a uniform rate. The sampler continues to take its sample throughout the time of submergence. Sediment concentrations (weight by weight) were determined by filtration and evaporation.

### Data analysis

Linear trend analysis was carried out on temperature data from the site Thakmarpha (1969 to 2012); specifically to assess trends in the maximum temperatures during April, May, June, July, and August as well as annual maximum and annual minimum temperatures.

Average annual and seasonal precipitation over the basin was computed by the arithmetic mean of rainfall totals at the three rainfall stations (Thakmarpha, Jomsom and Muktinath). Linear trend analysis was then carried out on the basin-average precipitations for the period 1975 to 2011.

Similarly, linear trend analysis was carried out on annual runoff from the basin for the period 1975 to 2008 and 2011/12 using flow data from the site Syang.

Instantaneous measurements of suspended sediment and river flow were correlated to develop sediment-flow rating curves. Several iterations were carried out to get the best fitting sediment-discharge rating curves at both locations by separating data sets at different categories; i.e., monthly, seasonal (rainy period and winter) and yearly. Annual estimated suspended sediment yields were then generated from annual river flow series.

## Results and discussion

### Trends in temperature, precipitation and runoff

Previous studies have indicated an annual temperature rise in Nepal varying roughly from 0.04°C to over 0.06°C (Shrestha *et al.*, 1999; Baidya *et al.*, 2008). This rise in annual mean temperature has generally occurred throughout Nepal except for in a few isolated places (Karmacharya *et al.*, 2007; Practical Action, 2009). The maximum temperature recorded in summer at river valleys in the lower part of the Upper Kaligandaki basin is 26ºC, and has been previously found to be rising at a rate of about 0.02ºC per year (Baidya *et al.*, 2008).

Analysis of temperature trends for 1969 to 2012 at the site Thakmarpha, conducted as part of this study, found that the average maximum temperature (April to August) and average minimum temperature (January to March) increased at a rate of 0.019ºC and 0.004ºC per year, respectively. The maximum temperatures for May, July and August increased at a rate of 0.03ºC per year (Table 1). Hence, based on present and previous trend analysis, the warming is evident over the study basin.

The average annual rainfalls in the basin and in overall western regions of Nepal show an increasing trend (Baidya *et al.*, 2008). Analysis of annual precipitation data for this study indicated that the lower part of the study basin, which is the wetter part, displayed an increase in annual precipitation over the period 1975 to 2011 whereas the northern part of the basin, which is the lowest precipitation region of Nepal, had a decreasing trend. Overall, the Upper Kaligandaki basin was found to have had an increase in annual precipitation of

**Table 1** – Results of maximum temperature trend analysis for the Upper Kaligandaki basin, 1969 to 2012.

| Temperature [Maximum(Max) Minimum (Min)] | Rate of change of temperature | Correlation coefficient | 95% Confidence Interval for Rate of change of temperature | |
|---|---|---|---|---|
| | | | Lower Bound | Upper Bound |
| Annual max | 0.009 | 0.583 | – 0.023 | 0.041 |
| Annual min | 0.002 | 0.936 | – 0.059 | 0.064 |
| Average max (Apr–Aug) | 0.019 | 0.037 | 0.001 | 0.037 |
| April max | 0.011 | 0.559 | – 0.027 | 0.049 |
| May max | 0.033 | 0.053 | 0.000 | 0.067 |
| June max | 0.005 | 0.772 | – 0.029 | 0.039 |
| July max | 0.034 | 0.028 | 0.004 | 0.064 |
| August max | 0.028 | 0.110 | – 0.007 | 0.063 |

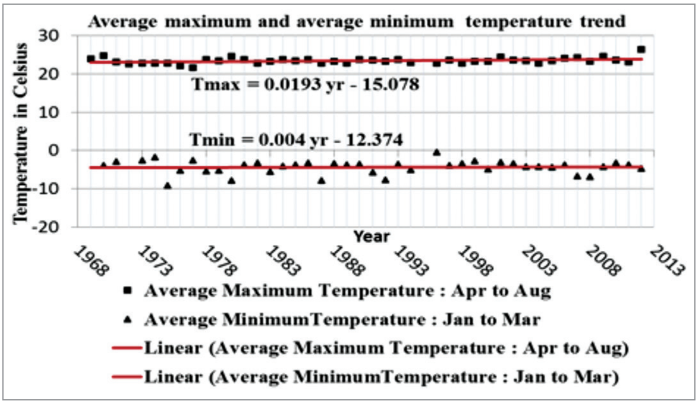


**Figure 3** – Trends in average maximum and average minimum temperatures at the monitoring site Thakmarpha in the Upper Kaligandaki basin, 1969 to 2012.

1.8 mm/year over the period 1975 to 2011; however, this rate of change is not statistically significant (at the 95% confidence level) (Fig. 4). The mean, standard deviation and coefficient of variation of annual precipitation are 327 mm, 67.6 mm and 21% respectively.

The annual runoff from the basin increased at a rate of 2.3 mm/year over the period 1975 to 2011 (Fig. 4), and this increase is statistically significant (the 95% confidence interval is 1.01 to 3.60 mm/year). Similarly, the mean, standard deviation and coefficient of variation of runoff is 264 mm, 45.2 mm and 17%, respectively.

The increase in runoff from the basin is likely to be linked to the increase in temperature and changes in precipitation. While the increase in precipitation was not statistically significant, snowfall was found to have decreased, indicating that more precipitation is occurring as rainfall. A study carried out in Kosi River catchment, Eastern Nepal, found there is about 8.5% contribution to annual flow from snow and glacier melt, a maximum monthly contribution of 22.5% in May and a minimum monthly contribution of 1.9% in January (WWF, 2009). An assessment made on Upper Kaligandaki river basin indicated that the snow melt contribution could reach up to 40% (Bhusal and Chapagain 2011). These results indicate that river flows could decrease by 40% if all snow and glacier melt contribution ceases (Bhusal, 2010).

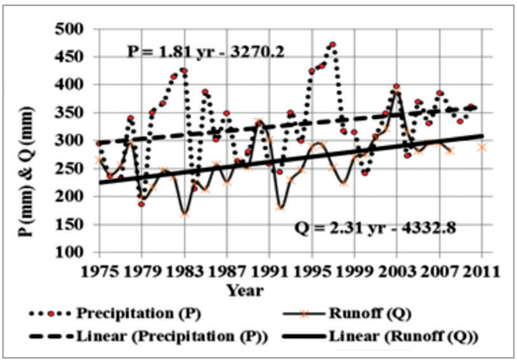


**Figure 4** – Trends in annual precipitation and runoff in the Upper Kaligandaki basin, 1975 to 2011.

## Changes in sediment load in the river

The daily suspended sediment load and daily river flow, for the two monitoring locations in the Upper Kaligandaki River, were strongly correlated, ie correlation coefficients of 0.88 and 0.86 for the sites Syang and Dhampus, respectively. The correlation between river flows and suspended sediment transport is largely due to the sediment load being suspended, which reflects the sediment characteristics of the basin (Fig. 1). The correlations were then used to estimate the daily suspended sediment load (Figs. 5 to 8).

The site with the slightly stronger correlation between flow and suspended sediment, Syang, is the only site with historical flow data available. The correlation equation shown on Figure 5 was applied to the annual river flow data from Syang to

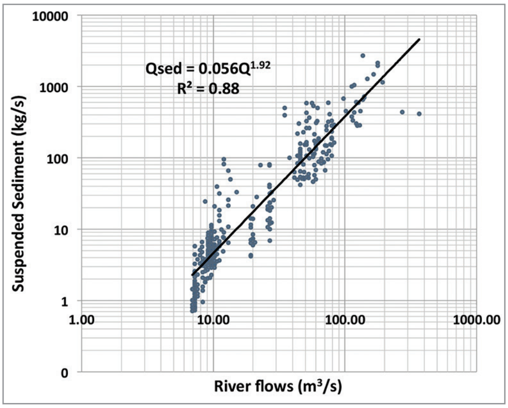


**Figure 5** – Suspended sediment-discharge rating curve for the monitoring site Syang.

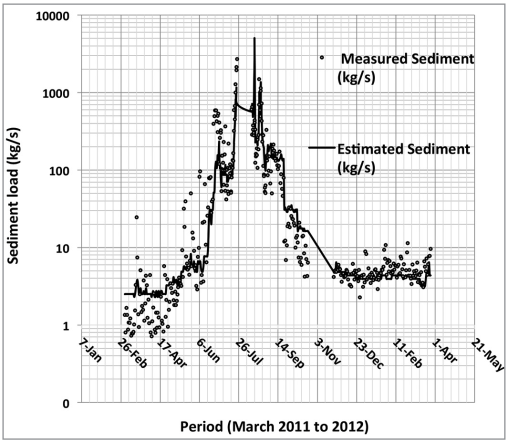


**Figure 6** – Observed and estimated suspended sediment load at Syang, 2011 to 2012. Estimated values were derived using the rating curve equation shown on Figure 5.

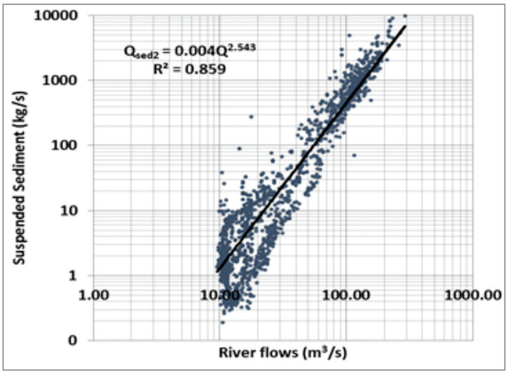


**Figure 7** – Suspended sediment-discharge rating curve for the monitoring site Dhampus.

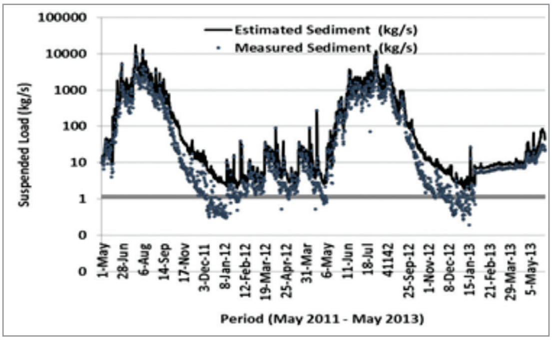


**Figure 8** – Observed and estimated suspended sediment load at Dhampus, 2011 to 2013. Estimated values were derived using the rating curve equation shown on Figure 7.

estimate the annual suspended sediment loads for 1975 to 2008 and 2011 to 2012. The results indicated sediment load in the river increased on average by 23 thousand tonnes per year, although there is a high variability in annual load. The rate of increase of the annual sediment load was between 0.006 and 0.04 megatonnes (Mt) per year (95% confidence limits). The long-term average sediment load is 1.8 Mt but the year-to-year variations are large (annual sediment load varies from -54% to +37% of the average).

During the periods 1975 to 2008 and 2011 to 2012, extreme rainfall events (and consequently floods) occurred occasionally. The lowest annual precipitation within the study period occurred in 1975, yet the lowest estimated annual sediment load occurred in 1992. The highest annual sediment load occurred in 2003, despite the highest annual precipitation occurring in 1997. The precipitation in 2003 was 0.85 times the precipitation in 1997 whereas sediment load in 2003 was 2 times the load in 1997.

**Table 2** – Estimated annual suspended sediment load (Mt) for the Upper Kaligandaki River, 1975 to 2011, based on a correlation between river flow and suspended sediment concentration.

| Year | Annual | Jun-Sept | Oct-May |
|---|---|---|---|
| | Mt | Mt | Mt |
| 1975 | 1.859 | 1.727 | 0.132 |
| 1976 | 1.498 | 1.392 | 0.106 |
| 1977 | 1.783 | 1.660 | 0.123 |
| 1978 | 2.076 | 1.914 | 0.162 |
| 1979 | 0.987 | 0.894 | 0.093 |
| 1980 | 1.349 | 1.237 | 0.112 |
| 1981 | 1.572 | 1.435 | 0.137 |
| 1982 | 1.295 | 1.176 | 0.119 |
| 1983 | 0.923 | 0.882 | 0.041 |
| 1984 | 1.376 | 1.316 | 0.059 |
| 1985 | 1.544 | 1.506 | 0.038 |
| 1986 | 2.096 | 2.040 | 0.056 |
| 1987 | 1.321 | 1.223 | 0.097 |
| 1988 | 1.564 | 1.378 | 0.186 |
| 1989 | 1.358 | 1.151 | 0.206 |
| 1990 | 2.975 | 2.817 | 0.159 |
| 1991 | 2.710 | 2.599 | 0.111 |
| 1992 | 0.851 | 0.775 | 0.076 |
| 1993 | 1.335 | 1.236 | 0.099 |
| 1994 | 1.638 | 1.548 | 0.089 |
| 1995 | 2.069 | 1.931 | 0.137 |
| 1996 | 2.099 | 1.944 | 0.155 |
| 1997 | 1.606 | 1.488 | 0.118 |
| 1998 | 1.198 | 1.048 | 0.149 |
| 1999 | 1.812 | 1.679 | 0.133 |
| 2000 | 1.899 | 1.759 | 0.140 |
| 2001 | 2.349 | 2.151 | 0.198 |
| 2002 | 2.561 | 2.348 | 0.213 |
| 2003 | 3.222 | 2.813 | 0.409 |
| 2004 | 2.325 | 2.089 | 0.236 |
| 2005 | 1.782 | 1.574 | 0.208 |
| 2006 | 2.096 | 1.919 | 0.177 |
| 2007 | 2.108 | 1.920 | 0.188 |
| 2008 | 1.868 | 1.678 | 0.190 |
| 2011 | 2.140 | 1.981 | 0.159 |
| Mean | 1.807 | 1.664 | 0.143 |
| Max | 3.222 | 2.817 | 0.409 |

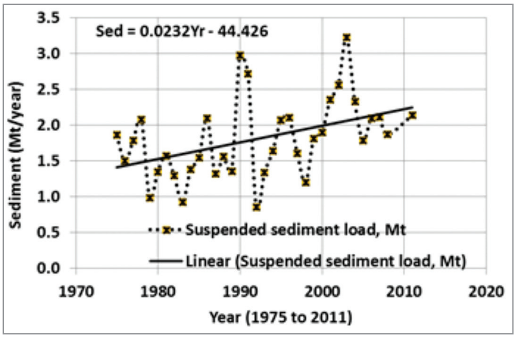


**Figure 9** – Estimated annual suspended sediment loads in the Upper Kaligandaki River at Syang, 1975 to 2011. A linear trend is overplotted with the equation of the line shown.

## Conclusion

The present study indicated an increasing trend in runoff and sediment load in the Upper Kaligandaki River in the Himalayan basin. The study, along with previous research, also indicated that the basin is warming. This warming trend is likely a result of climate change in the Himalayas, and the effects are melting of covered ice over loose soils, melting of permafrost and glacier lake outburst floods, all of which have accelerated erosion processes in the region. In addition, the increase in extreme rainfalls has also further contributed to increased sediment production in the basin. The gradually rising trend in the annual suspended load is likely to be continued in the future. Such changes, and related changes in soil and river bank erosion and landslides will impact the local inhabitants, their landuse practices and their infrastructure.

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