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Sediment Transport Studies in Punatsangchu River, Bhutan

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Abstract

Sediment transport pattern in the Himalayan River is complex and sediment sampling in these rivers are often difficult. Sediment load in the river varies largely from year to year. Major part of the sediment load is transported in the monsoon months. Reliable and consistent sediment rating equation is not found for the Himalayan Rivers. The change in the flow rate and suspended sediment concentration is very rapid and unpredictable. In Bhutan, there are no published records on sediment transport studies. There are four sediment sampling stations in the whole country. Bhutan being a mountainous country has a huge potential for hydropower development. The most common problem related to hydropower projects is the reservoir sedimentation. In this report, the sediment concentration and river flow data from one gauging station along Punatsangchu River is presented to increase the understanding of sediment transport pattern in this river.

Sediment transport in the Himalayan Rivers with regard to factors affecting sediment transport is addressed and some comparison is made with the Punatsangchu River. The factors affecting sediment transport are hydrology and climate, geology, land use and topography. The correlation between sediment concentration and river discharge for the year 2007 for Punatsangchhu River was found to be very good with an R^2 value of 0.8. The correlation of average discharge and concentration over the record period of 1993 and 1996 to 2008 was found to be 0.53. For some years the correlation was very poor with an R^2 value of 0.13. This shows that river discharge is not a reliable variable to predict the sediment concentration in Punatsangchu River. Most of the sediments are transported during the monsoon months which account for about 90% of the total load transported in a year. The bed load and suspended load are calculated using the formulae developed for alluvial rivers and the results were similar to the estimated load from the gauging station.

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Abbreviations

m.a.s.l: Meters above sea level
m: Meter(s)
m^3/s: cubic meter per second.
t/day: tonnes per day
mg/l: milligram per liter
km: Kilometer
km^2: Square kilometer
mm: Millimeters
MW: Mega Watt
ppm: Parts per million

Acronyms

GDP: Gross Domestic Product
GLOF: Glacier Lake Outburst Flood
CAPSD: Curriculum and Professional Support Division
WRMP: Water Resources Management Plan
WAPCOS: Water and Power Consultancy Services
PSMP: Power System Master Plan
IRI: The International Research Institute for Climate and Society
DoP: Department of Power
DoE: Department of Energy
BPC: Bhutan Power Corporation

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1 Introduction

1.1 Brief Background to the Project

The sediment supply and transport in the Himalayas is quite significant and is considered to be highest in the world. The Himalayas are characterized by a steep and rugged terrain in terms of topography which plays a significant role in the spatial distribution of rainfall, snow and snowmelt. A heavy rain in the catchment area results in an unusual stream flow event creating widespread slope instabilities, sediment transport and flooding.

Rivers in Bhutan have a high development potential for harnessing hydropower because of the mountainous terrain, climatic and other favorable (political, social, economic) conditions (Tamang, 2004). Bhutan has an estimated hydropower potential of 30 000 MW out of which 23 760 MW has been identified and assessed to be technically feasible. At present only 1.6% of the potential is harnessed (Tamang and Tshering, 2004).

Punatsangchhu river basin is one of the three major river basins in Bhutan. Previous studies in this river basin focused on hydropower development and hydrological studies. Despite a program to determine sediment data for Bhutan's rivers no information on sediment transport appears to have been published (DoE, 2003). Therefore, understanding the spatial and temporal patterns of the sediment transport and sediment yield in this basin is important for effective water resource development in Bhutan. The main concern with hydropower projects is their limited lifetime when the reservoir or head-pond becomes inoperative due to trapped sediments. Another problem associated with sediments in the hydropower plants is the wear of the turbines. This is caused by suspended sediments. It is therefore of interest to study the reservoir sedimentation and turbine wear for the new hydropower projects proposed in this basin. But these topics are not covered in this project because of lack of time and information.

It might also be interesting to study the transport rates so that the bridge designs can be carried out safely. In a nearby industrial town of Pasakha in south of Bhutan, a flooding event in 2001 along Amochhu River caused havoc in this area where the entire residential colony has been abandoned and the riverbeds and banks are completely covered by sediments. This event has led to the riverbeds being covered with sediments. If such flooding events become a frequent happening, the bridge will soon become un-functional. A good study on the sediment transport pattern could be useful for bridge design in such area in the future.

In this report, the sediment and discharge data from Wangdi rapids gauging station is presented and this data is used to increase the understanding of sediment transport in Punatsangchhu River. Sediment transport studies in the Himalayan region are presented to make a comparison with the results from Punatsangchu River. The factors affecting sediment transport in general are addressed in this report but not quantified. The bedload and suspended load are calculated and compared to the load from the gauging station.

1.2 General background on Bhutan

Bhutan is a small land locked country in the eastern Himalaya, bordering China in the north and India in south, east and west as shown in Figure 1.1. It covers an area of 38 394 km^2 between the latitudes 26° 45’ N and 28° 10’ N and longitudes 88° 45’ E and 92°10’E (National Portal of Bhutan). Although the latitudes fall within the Northern hemisphere and between the equator and Tropic of Cancer, Bhutan does not have a typical tropical climate. The population of Bhutan is about 647 000 (2006). Developmental activities in Bhutan are guided by the philosophy of Gross National Happiness.

The economy of Bhutan is one of the world's smallest and least developed with a GDP (current price) per capita of 1414.3 USD (2006) (NSB, 2007). The land-use in Bhutan is dominated by forest cover of 72.5% while agricultural land makes up only 7.7% (NSB, 2007). The altitudes within this very small country vary largely from 97 meters above sea level (m.a.s.l.) in the southern sub-tropical region to 7553 m.a.s.l. in the Northern alpine region (Central Intelligence Agency).

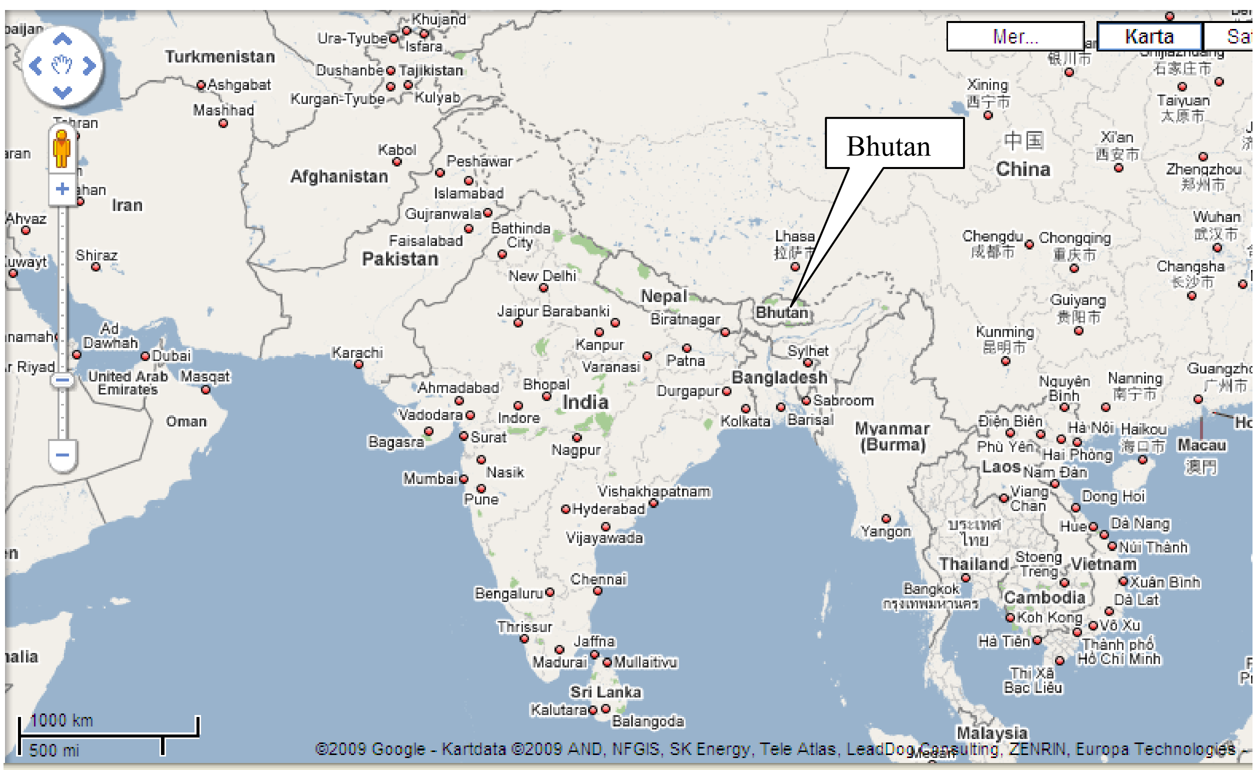

Figure 1.1: Asia map showing location of Bhutan (Google map, 2009)

1.3 Climate of Bhutan

The climate in Bhutan is governed by altitude, orientation of mountain ranges, vegetation and the monsoons that bring between 60 and 90 percent of the region's rainfall. The climate is humid and subtropical in the southern plains and foothills, temperate in the inner Himalayan valleys of the southern and central regions, and sub-alpine to alpine in the north, with year-round snow on the main Himalayan summits. Temperatures vary according to elevation. The subtropical climate in the southern part of Bhutan has a mean monthly temperature of 15 degree Celsius in the winter and 30 degree Celsius in the summer. In the temperate region, the average daily temperature varies from 5-15 degree Celsius in the winters and 15-30 degree Celsius in the summer. The alpine region is the coldest part in Bhutan with a mean annual temperature of 8 degree Celsius (CAPSD, 1994).

Annual precipitation ranges widely in various parts of the country. Bhutan receives fair amount of annual rainfall varying from 500 mm in the North to above 2000 mm in the South. (CAPSD, 1994) Table 1.1 gives the rainfall and temperature variation with altitude.

Table 1.1: Rainfall (snowfall not recorded) and temperature variation with altitude in Bhutan (Pradhan, 2008)

Zone	**Altitude(m)**	**Average Temperature ^{0}C**			**Rainfall mm**
		Max	Min	Mean	
Wet Sub-Tropical	150-600	35	12	24	2500-5500
Humid Sub-tropical	600-1200	33	5	20	1200-1500
Dry Sub-tropical	1200-1800	29	3	17	850-1200
Warm Temperate	1800-2500	26	1	13	650-850
Cool temperate	2500-3500	22	1	10	650-850
Alpine	>3500	12	-1	5.5	<650

It can be seen from Table 1.1 that the rainfall decreases with increase in altitude. The reason for this could be that snowfall is not recorded and only rainfall is considered. The places above an altitude of 3500 m are covered by snow for most part of the year and precipitation in this region occurs mostly in form of snow which is not measured. The permanent snowline is found at an altitude above 4800m (CAPSD, 1994). These places are inaccessible in the winter. Another reason for this decreasing trend of rainfall with increasing altitude is because as the altitude increases, the air becomes thinner and also there is less pollution in the higher altitude area, this results in less condensation and hence the rainfall becomes lesser with increased altitude.

Precipitation in Bhutan is characterized by heavy rainfall in the summer months and heavy snowfall in winter in the higher altitude regions. During summer, moist air comes from Bay of Bengal crossing a short distance over Bangladesh and India and enters into the southern parts of Bhutan and then rises over the hills. As the moist air rises up, the temperature starts falling down and the moisture starts condensing and rains heavily in the lower parts. The air loses most of its moisture content by the time it reaches in the higher parts so there is less rainfall in the higher parts. During winter the winds come from China, passes over a large land mass and have very less moisture content. These winds enter into the higher parts of Bhutan and cool down very fast and come down in the form of snow.

1.4 River system in Bhutan

Bhutan has three major river systems: the Drangmechhu; the Punatsangchhu, also called the Sankosh and the Wangchhu. Rivers in Bhutan are generally fed by rainfall, snow melt and glacier melt and ultimately drains into the Brahmaputra River in India. Glaciers in northern Bhutan covering a total surface area of about 10% of the total country area are an important renewable source of water for Bhutan's rivers. The rivers of Bhutan generally have steep gradients and narrow steep-sided valleys, which occasionally open up to give small areas of flat land for cultivation. They carry large volumes of flow and sediment during the monsoon season and significant snowmelt at the end of the dry season. Short rain-fed tributaries descend even more steeply from east or west to join these major rivers. Figure 1.2 shows the river system in Bhutan. Punatsangchhu River basin is marked with grey lines showing the basin boundary roughly.

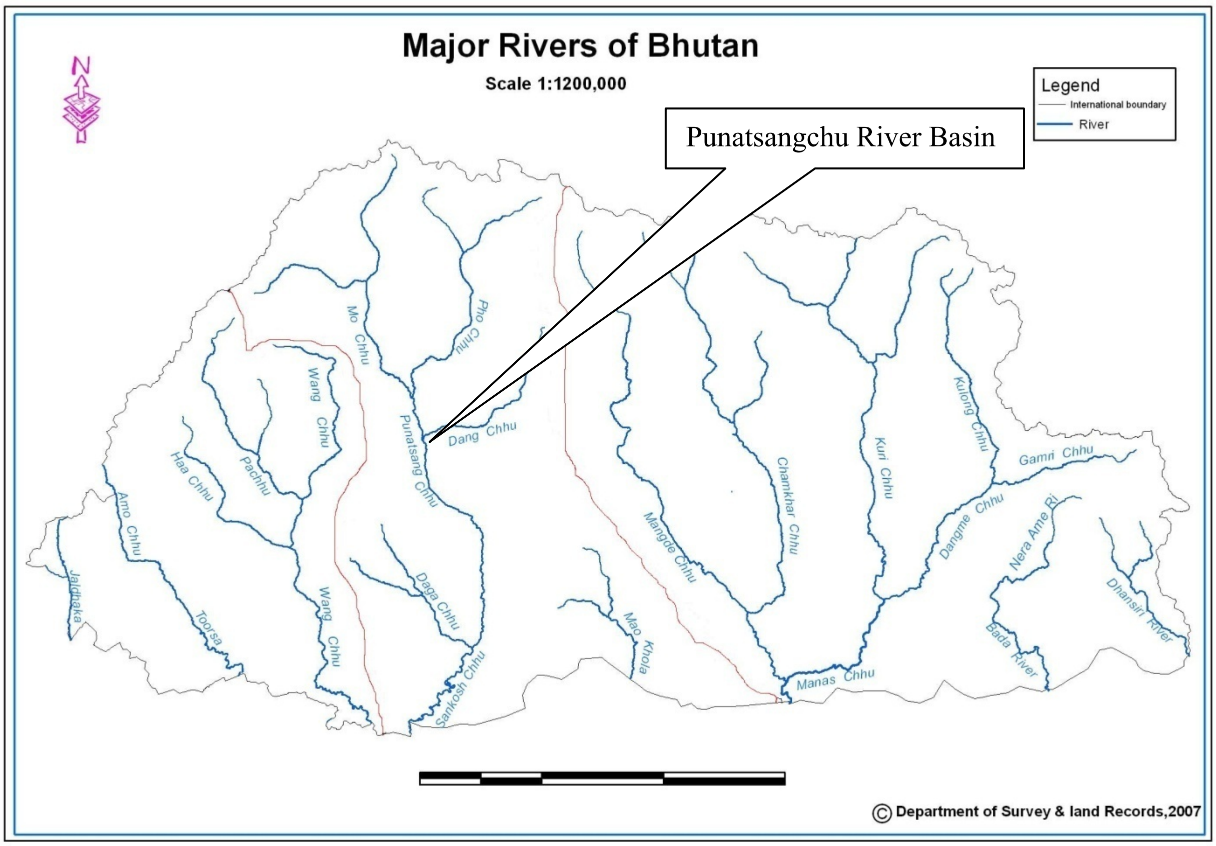

Figure 1.2: River system of Bhutan. (Survey of Bhutan, 2007)

1.5 Hydropower Development in Bhutan

Hydropower is an important entity to the Bhutanese economy. The Government's decision to exploit water resources for production of electricity has improved the economy over the recent years. Due to the topographic and geographical features of Bhutan, the country has a huge potential for hydropower development. Most of Bhutan's already built and proposed hydropower plants are run-of-the-river schemes with no impact or minimal impact to the environment. Bhutan has an estimated hydropower potential of 30 000 MW out of which 23 760 MW has been identified and assessed to be technically feasible. At present only 1.6% of the potential is harnessed (Tamang and Tshering, 2004). As per the Power System Master Plan (2003) of Bhutan, 17 hydropower projects are identified in the Punatsangchhu River basin with the power potential of approximately 8 000 MW.

1.6 Sediment Transport and Related Problems

There are no records of sediment transport studies in Bhutan. In the whole country there are only four sediment sampling stations along the rivers. The biggest problem related to hydropower projects is the reservoir sedimentation. Other than reservoir sedimentation, the suspended sediment also has an adverse effect on the turbines of the hydropower plants which reduces the efficiency of the turbine and hence reduces electricity generation.

1.7 Objectives and Methodology

The objectives of this study are:

- To present the sediment transport information about the Punatsangchu River from the sediment data available for this river for a record period of 17 years.
- To use this data to increase the understanding of sediment transport pattern for this river.
- To gather and present information on factors affecting sediment transport and about sediment transport in the other Himalayan region.
- Finally, the information from the sediment data for this river is to be correlated to the factors affecting the sediment transport pattern and compared to other Himalayan region.

This study was done by reviewing literature related to sediment transport mainly in the Himalayan region. The sediment data available for Punatsangchhu River for a period of 17 year was used to study the pattern of sediment transport in this river. Various plots and statistical analysis were made from the data to see some trend in the sediment transport pattern. The bedload and suspended load are calculated using the formulae developed for use in rivers and compared with the loads from the gauging station. Factors affecting sediment transport in general is addressed and sediment transport studies in the Himalayan region are also discussed to make a comparison with the sediment transport in Punatsangchhu River.

1.8 Limitations

Getting data was a big problem for this study. Hence the study is limited to certain assumptions. Because of the lack of data and time, the factors affecting the sediment transport in Punatsangchhu River could not be quantified. This study is based on literature available on similar rivers in the Himalayas and measurements from one principal gauging station along this river which measures the daily sediment concentration and discharge for a record period of 17 years out of which 14 years data are selected. The conclusions drawn from this report is entirely based on sediment and flow data from one gauging station for a record period of 14 year.

2 Factors affecting sediment transport

2.1 Overview

Sediments are basically fragments of rocks and minerals that come from the weathering of rock and are carried and deposited by wind, water, or ice. When the rain falls, materials are dislodged and these materials are transported on the land surface, streams and rivers act as passage for the movement of sediments and when there is not enough energy to transport the sediments, deposition occurs (Larry, W., 1999). Rivers and streams carry sediment as they flow depending on the sediment supply along their course. When the eroded particles are carried by water in motion, sediment transport occurs. Depending on the settling velocity and the drag and lift force, these sediments are carried along the river in either suspended form or bedload. The greater the discharge and flow rate, the higher the capacity for sediment transport. Rivers or streams erode soil particles along their courses and cause erosion.

The change in the trends of the suspended sediment loads in any river is persistently altered not only by human actions but also by various environmental variables. One of the reasons for increase in the sediment concentration is soil erosion. Erosion usually increases the sediment discharge from streams coming from the catchment; but it should be noted that not all erosion immediately shows up as sediments. Much of it moves into various temporary storages in the watershed.

Glazyrin and Tashmetov (1995) and Evans (1997) have stressed the importance of additional factors in sediment generation in mountainous regions to include tectonics and seismic activity, glacial area, proportion of snow and basin area. Ali and Boer (2007) found out that a number of environmental variables such as topography, hydro-climatology, lithology, land use and soil erodibility affect sediment yield. Sediment transport is governed by the river flow, the particle size distribution, the river cross section and temperature. Therefore, the factors affecting sediment transport can be broadly classified as;

- Hydrology
- Climate
- Geology
- Topography and
- Land use

Based on sediment transport capacity and the sediment supply, a river can be classified into reaches as shown in Table 2.1

Table 2.1: Classification of river reaches (Lysne et.al, 2003)

Reach of the river	**Sediment supply situation**
Erosion	Transport capacity > sediment supply
Transport/Regime	Transport capacity = sediment supply
Deposition	Transport capacity < sediment supply
Delta	Transport capacity << sediment supply

Most of the rivers in Bhutan fall into the first type of river reach i.e. erosion. In the southern plains where the river leaves Bhutan to join the bigger rivers in India, the reaches of river are in transport/regime and deposition.

2.2 Hydrology and Climate

Sediment load is dependent on the river discharge. Other than discharge, variables like rainfall and snow melt also contributes to the sediment load. The river discharge is dependent on the rainfall. Discharge of the river does not necessarily indicate proportionate sediment load. An example of this is the Amazon River; this river has very high flow but still carries very little sediments, this is because Amazon River gets most of its sediments from Andes Mountains, which constitute only about 10% of the basin area. As such, Amazon River despite being very big and having large flow, it does not have a particularly high sediment yield per unit area. From the suspended sediment discharge, a large variation in the sediment yield is observed in various rivers around the world. Even though the Amazon River is very big, the sediment yield in this river is much less compared to some of the smaller rivers in southern Asia (Chakrapani, 2005). Table 2.2 shows the water and sediment discharge in some of the large rivers of the world.

Table 2.2: Water and Sediment discharge in some large rivers of the world (McLennan, 1993)

River	Water discharge (km^3/yr)	Drainage area (10^6 km^2)	Sediment discharge (10^6 t/yr)	Sediment yield (t/km^2/yr)
Amazon	6300	6.15	1200	195
Colorado	20	0.64	0.01	0.02
Columbia	251	0.67	10	15
Congo (Zaire)	1250	3.72	43	12
Danube	206	0.81	67	83
Ganges/Brahmaputra	**971**	**1.48**	**1060**	**716**
Huang He	49	0.75	1050	1400
Indus	**238**	**0.97**	**59**	**61**
Mackenzie	306	1.81	42	23
Mekong	470	0.79	160	202
Mississippi	580	3.27	210	64
Niger	192	1.21	40	33
Nile	30	3.03	0	0
Orinoco	1100	0.99	150	152
St. Lawerence	447	1.03	4	4

In Table 2.2, the rivers marked in bold letters are the rivers in the Himalayan region. The Nile River has no sediment discharge or sediment yield. This is because of the Aswan dam which was built to prevent the river's flooding, generate electricity and provide water for agriculture in 1970. Before the dam was built, the Nile River carried approximately 124 million tonnes of sediment to the sea every year, now 98% of that sediment remains behind the dam (Biggs, n.d).

In Bhutan, the rainfall decreases with increase in altitude as explained in section 1.3. The surface runoff in the summer due to rainfall flows very fast because of the topography and causes a lot of soil erosion. While in winter, there is less rainfall and more snow fall. Since snowfall is solid form of precipitation, it does not flow immediately. Hence the sediment load is less in the winter months and very large during the monsoon months.

The river flow rate is an important factor affecting the transport pattern in any river. The ability of the river to carry along sediment with it is determined by the velocity of the river while the availability of sediment for transport is another issue. Burbank.et al, (2003) shows that despite the huge variation of rainfall within the Himalayan region, there was no large difference in the erosion rate. The rate of erosion, though high did not show significant variation from the monsoon to arid conditions in the Himalayas. From this study, the author states that the erosion rates are not closely linked to dramatic change in the climate.

2.3 Topography

With the change in topography from the tributaries of the rivers to the downstream reach of the river, the river flow changes. The velocity of flow in the river is greatly influenced by the slope of the river bed. Sediment transport depends on the flow rate and hence topography influences the sediment transport. Because of the steep topography in Bhutan, soil erosion is a naturally happening process. Soil erosion has a significant influence on the sediment load in the rivers.

Sediment is contributed to the headwaters of the major rivers by melt water issuing from glaciers, by processes such as mass movement and mud flow, by debris torrents, and by channel erosion during catastrophic outburst floods from landslide-, moraine-, and glacier dammed lakes. Although storage in the river bed and flood plain interacts with sediment transport, upper parts of a basin greatly influence water quality downstream. (Collins and Hasnain, 1995)

The massive landslides occurring in Bhutan have not resulted from human activities but from weak geology and heavy monsoon, for example, the landslide prone area near Gedu, a small town in Bhutan. The national highway from the capital, Thimphu to Phuntsholing, a big town in the southern part of Bhutan passes through Gedu. A stretch of the highway lies in this landslide prone area. This area is not inhabited by human settlement. Mass wasting, unstable slopes and natural erosion are mainly the result of tectonic uplifting of major mountain ranges and consequent down cutting by the river systems.

Very little is known about the severity, cause, consequences and long term costs of soil erosion. Little research has been done on soil erosion in Bhutan (Gyaltshen, n.d). These researches show that the areas facing more soil erosion problems are caused by the difference in land formation, rainfall and land-use practices. Most soils in Bhutan are said to have low erodibility because of their high permeability and high infiltration rate. However, during very wet years, landslides, landslips and soil creep are more likely to occur as a result of high moisture content and the high groundwater level, particularly in some parts of eastern Bhutan. A particular type of red soil found in the open valleys of the north-west (especially Punakha, Wangdue Phodrang and

Thimphu districts), and the layered alluvial or colluvial soils found in some valley bottoms, have been found very susceptible to water and wind erosion. Erosion by rivers also affects significant areas of flat lands in major agricultural valleys. (Gyaltshen, n.d)

2.4 Land use

Natural vegetation has a regulating influence on runoff. Deforestation and urbanization not only increase the danger of flood inundation but also promote erosion. Increase in discharge of up to 100% is reported as an effect of land use change by Bosch and Hewlett (1981) when they did the review of 94 catchment experiments around the world. In the case of sediment yield values 310 times higher, compared to the original magnitude, were observed in small areas. Although these phenomena have long been known, no readily transferable quantitative relations do exist for predicting effects of land use change on discharge and sediment yield. (Bosch and Hewlett, 1981)

The relationship between erosion occurring on-site and sediment load at a point in a stream is expressed as sediment delivery ratio for the catchment. Sediment delivery ratio is the ratio of sediment yield of a drainage basin to the total amount of sediment moved by sheet erosion and channel erosion. While it may be 90 percent for a drainage area of one hectare area, it probably averages only 50 percent for an 80 ha area and is less than 30 percent for any drainage area over 500ha. Sediment delivery ratio may be close to 100 percent for a short stream with a very steep catchment, but it decreases significantly with decreasing steepness and increasing stream length. (Roehl, 1962) Most of the sediment loads in the lower reaches of the river are from materials being taken out of storages and from channel erosion. Hence, there would be little change in sediment in the lower reaches of the river for large river basins for decades even if land conservation activities could inhibit all human caused, accelerated erosion in the hills. For flood and sedimentation problems in the Himalaya, human activity has less impact on the sediment load than natural factors. (Lawrence, 1987) As seen from Figure 4.1, the land use in Punatsangchhu River basin is dominated by forest cover with very little human settlement along the river banks. Human influences in this river basin are minimal.

2.5 Geology

"The effect of lithology on mechanical erosion rate is probably high with respect to channel erosion, but less important with respect to hill slope erosion because the outcropping lithologies are normally covered by soils. River flowing over crystalline terrains erode with difficulty, whereas unconsolidated sedimentary rocks yield greater sediment loads to rivers. The Ganga-Brahmaputra Rivers carry huge sediment loads because they flow over easily erodible carbonates and through the Himalayan terrains." (Chakrapani, 2005).

The area of Punatsangchhu River Basin comprises the middle part of the country. The northern region of this river basin is covered with glacial lakes and is associated with glaciofluvial deposits. Downstream at the confluence of the two main tributaries; Mochhu and Phochhu Rivers, the valley widens past Punakha as one approaches the town of Wangdue Phodrang. Wangdue valley has gently sloping hills containing significant quaternary deposits. Travelling further downstream past Wangdue and into the Tsirang and Sarpang Dzongkhags (Districts) topography decreases toward the Indian border. In some of the higher areas the geomorphology resembles that of relict peneplains, areas that have been eroded to topography and then tectonic uplifted. Along the southern foothills near the towns of Sarpang and Gelephu extensive fluvial outwash planes containing significant quaternary deposits characterize the topography and geomorphology. The underlying geology can be characterized by the Tethyan succession of sedimentary rocks and tertiary intrusions of leuco-granites in the north followed by the crystalline sheets and lower Himalaya meta-sediments and sedimentary rocks in the south. (DoE, 2003)

3 Sediment transport in the Himalayas

3.1 Overview

Sediment transport influences many situations that are of importance to mankind. Silt deposition reduces the reservoir capacity and modifies the path of water courses. In rivers, sediment movements form a part of the long term pattern of geological processes. Sediment transport maybe understood as occurring in one of the two modes:

- By rolling or sliding along the floor/bed of the rivers; sediment thus transported constitutes the bed load.
- By suspension in the moving fluid (finer particles) which is the suspended load. (Chadwick and Morfett, 1993)

The sediment supply and transport in the Himalayas is quite significant and is considered to be highest in the world. Sediments transported globally to the oceans are estimated at about 15–20×10^9 tonnes per year (UNEP, 2003). Due to the high rate of sediment production in the Himalayan region, Southeast Asia contributes approximately half of the sediment discharge to the oceans (Singh et.al. 2006) and 20% of the global sediment input is contributed by the rivers originating from the Himalaya (Milliman and Meade, 1983). The Ganga River in India transports about 729×10^6 tonnes of sediments annually to the Bay of Bengal, 95% of which is transported during monsoon. After joining the Brahmaputra River, the total estimated combined sediment flow to the Bay of Bengal is 1620×10^6 tonnes annually. (Singh et.al. 2006). Table 3.1 gives the global suspended sediment discharge.

Table 3.1: Suspended sediment discharge and distribution per region (UNEP, 2003).

S. No	Region	Suspended sediment discharge (million tonnes/year)	Distribution of suspended sediment discharge (%)	Remarks
1	Asia	6 349	47.1	Global suspended sediment discharge is about 15 to $20x10^9$ tonnes/year
2	Oceanic Islands	3 000	22.2	
3	Central and South America	2 230	16.5	
4	North America	1 020	7.6	
5	Africa	500	3.7	
6	Europe	314	2.4	
7	Australia	62	0.5	

The Himalayas are characterized by a steep and rugged terrain in terms of topography which plays a significant role in the spatial distribution of rainfall. A heavy rain in the catchment area results in an unusual stream flow event creating widespread slope instabilities, sediment transport and flooding. Hydrologically, the Himalayas are characterized by four months of rainy season termed as ‘monsoon’ or the wet period. About 70-80% of the annual precipitation occurs over the four months monsoon season extending from June to September. The peak flow and maximum sediment transport in most rivers in the Himalayas occur during July and August which is the time for highest monsoon rain period. (Pradhan, 2004)

Having such characteristics, the Himalayan Rivers pose an immense challenge with regard to sediment management. Sediment transport in these Himalayan Rivers does not follow the basic sediment transport mechanics developed for sand bed and silt bed rivers. The sediment transport is much more random and difficult to quantify based on statistical records (Dorji, 2003). This could be due to the fact that most of the sediment is carried out along the slopes of the river banks and in the tributaries, where mass wasting plays an important role. Mass wasting is basically the down slope movement of a mass of sediment and/or rocks mainly due to force of gravity. Mass wasting is also referred to with the term "landslide". It is also difficult to correlate between rainfall intensity and the corresponding sediment production.

The sediment concentration varies largely with time and a major bulk of the annual sediment load may be transported within a few days and may go unmeasured at gauging site if the sampling frequency is poor. The sediment transport in Himalayan Rivers is normally much higher than the actual sediment transport in other rivers (Pradhan, 2004). Several studies have shown that the river flow is not a reliable key for monitoring the suspended sediment concentration in the river flow (Yadav, 2002).

A common problem with sediment handling in regard to hydropower plants in the Himalayan region is the reservoir sedimentation. Another problem is the effect of suspended sediments on the turbines which causes wear of the turbines and hence reduce electricity production. Studies are carried out in most of the region to optimize the plant efficiency by finding means to reduce the sediment exposure of the turbines through settling basins and improved plant operation strategies as well as measures to increase the resistance of the turbines to sediment induced wear.

3.2 Sediment transport studies in Bhutan

Despite a program to determine sediment data for Bhutan's rivers no information on sediment transport appears to have been published (DoE, 2003). An MSc Thesis work by Tashi Dorji in 2003 on 'Headworks Design and Sediment Handling at Punatsangchhu Hydropower Plant' is the only available report with regard to sediment handling in Punatsangchu River. In his report, he has reviewed and assessed the headworks design and sediment handling of the 870MW Punatsangchhu hydropower project and come up with some possible alternative headwork arrangements to achieve safe and reliable power production at a reasonable cost.

The sediment data from the sediment sampling stations are sometimes used for bridge design. There are two gauging stations along Punatsangchhu River which measure the sediment concentration. The data available from one gauging station has been used for analysis in this study. Sediment data could be obtained from Wangdi Rapids gauging station only.

The main objective of sediment study for a reservoir scheme is to collect data needed to determine the long-term average sediment transport rates in the river. This provides the basis for reservoir sedimentation studies and estimation of the life of the reservoir. Sedimentation rate is the total estimated total sediment load per year divided by the sediment density and catchment area. For Punatsangchu hydropower project (a project proposed along this river), reservoir sedimentation studies and also all the studies related to this proposed project was carried out and from their report (DoE, 2007), the average sedimentation rate for the proposed hydropower project dam was taken as 0.75mm/year although the observed sedimentation rate was 0.33mm/year. Higher value of sedimentation rate was taken because the sedimentation rates in the other tributaries of the Brahmaputra River were much higher than 0.33mm/year. Table 3.2 shows the sedimentation rate in the northern tributaries of Brahmaputra River. It is assumed that this rate would be adequate for the sedimentation control for a basically diversion scheme with little storage.

Table 3.2: Sedimentation rate (mm/y) [DoE, 2007]

S.No	Name of the River	Sedimentation Rate mm/year
1	Subansiri	1.13
2	Lohit	1.2
3	Dibang	1.26
4	Puthimari	1.4
5	Pagladiya	1.6
6	Wangchhu	0.2
7	Punatsangchhu	0.28

The sedimentation rate calculated based on data up to the year 2008 for this river is 0.28mm/year which is even less than the rate calculated in 2005. Hence, the sedimentation rate is taken as 0.75mm/year for studies in this river based on adjacent tributaries sedimentation rate. From Table 3.2 we can see that the sedimentation rate varies from 0.2 to 1.6, this could be because of the different location of these tributaries or size of each river.

3.3 Sediment transport studies in other parts of the Himalayan Region

Several studies on sediment transport have been carried out in different places within the Himalaya region. The Himalayan Rivers have a huge potential for hydroelectricity generation because of the topographic and hydrologic features. Because of the steep topography, fragile geology and intense rainfall, the sediment transport rates in these rivers are exceedingly high. The main problem with such a high rate of transport is sediment handling at the headworks of the hydroelectricity power plants. Severe sand erosion of the turbines has also caused loss in energy production (Pradhan, 2004).

A study (Pradhan, 2004) concluded that the thermodynamic efficiency measurements carried out for a turbine in Jhimruk Hydropower Plant, Nepal showed decrease in efficiency substantially due to sand erosion. It was recommended to collect and analyze data from several hydropower projects with respect to sediment measurements and erosion on turbines so that it can provide guidelines to understand the sediment problems in Himalayan Rivers in a much more informed manner, this will facilitate handling the sediment problem optimally in run-of-the-river power plants.

Ali and Boer, 2006 state that the suspended sediment transport characteristics in the upper Indus basin show considerable variation due to differences in physiographic, climate, hydrologic regime, and drainage area.

Bedload transport rate is one of the less studied fields in the Himalayan region. Bedload is generally considered hard to measure and in most of the cases, it is taken as a certain percentage of the suspended load. This percentage varies largely from 15% to 50% depending on the river or the type of study done. Sitaula, B, P. et al., (2007) suggest that a likely bedload to suspended load ratio for steep mountain rivers as ~ 1:2; this is based on the assumption that the lake sediments accurately represent the suspended load in the mid-Holocene Marsyandi River and that the delta deposit represent its bedload. Sometimes the bedload is underestimated and which may lead to reservoir sedimentation.

There are many other studies done related to sediment transport in the different regions within the Himalaya, some of the studies of interest are as stated below:

- *Drainage sediment transport and denudation rate of Nanga Prabat Himalaya, Pakistan.* In this study, field measurements were carried out and computer programs were used to compute the discharge, sediment load, and sediment yield and denudation rate. (Cornwell. K., et.al, 2003)
- *Regional sediment yield pattern for the west flowing rivers of Kerala state, India.* This study is done to understand the spatial and seasonal distribution of suspended sediment load carried by major west flowing rivers of Kerala State, India, which lies in the humid climatic zone. Daily discharge and sediment load data are used to understand the sediment yield pattern and the influencing factors were analyzed. The sediment yield characteristics are explained mainly with respect to the two major rainfall seasons of the State and their spatial and temporal coverage over the state.(Chandramohan, T., Balchand, A, N., 2007)
- *Relation between Precipitation in Dabie Mountain Watershed and Sediment Transport in Dasha River Valley.* In this study, the characteristics of precipitation (based on observational records from 1954 to 1999) changing over Dasha River Watershed and its connection to sediment yield were studied using tendency analysis and correlation analysis. Results showed that the precipitation had a high variability and the sediment discharge correlates most closely with the frequency of rainstorm with a daily precipitation of 100mm, 50-100mm and number of rainy days with correlation grades of 0.98, 0.9 and 0.85 respectively. Major countermeasures and methods for controlling soil and water losses in this area are also suggested. (Zhang, J., Shi, Z., 2004)
- *Runoff and sediment transport from giacierized basins at the Himalayan scale* (Collins.D.N., Hasnain.S.I., 1995).
- *Sediment Management for Sustainability of Storage Projects in Himalayas - A case study of the Kulekhani Reservoir in Nepal* (Sangroula, D, P., 2007).

- *Sediment characteristics and transportation dynamics of the Ganga River* (Singh, M., et.al, 2006)
- *Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India and Bangladesh* (Mukherjee, A., et.at. 2008).
- *Abnormal monsoon effects on erosion and sediment flux in the northern Himalaya*.(Bookhagen.et.al, 2005)

4 Punatsangchu River Basin

4.1 Overview

Punatsangchhu consists of the major rivers Mochhu and Phochhu at its upper basin, having their sources in the north-eastern part of the Himalayas and merging with each other at Punakha. The catchment above 4200 m is covered by glaciers. The Punatsangchhu River has a total length of about 320 km from its source in Bhutan to its confluence point with Brahmaputra in India. Its course in Bhutan has a length of about 250 km (Pradhan, 2008). The Mo Chu River has a glacier covered area of 169.55 km^2, the glacier covered area in Pho Chu is 333.56 km^2 (IRI, 2007). The two catchments have an area of 5640 km^2 and reaches from around 1200 m.a.s.l. up to over 7000 m.a.s.l. (Pradhan, 2008). The catchment area up to the principal gauging station at Wangdi rapids is 6271km^2.

The Punatsangchu River Basin has a total land area of 13 263 km^2 with a population of 162 071 people living within the basin area (DoE, 2003). Table 4.1 gives an overall impression of this river basin. Figure 4.1 shows the map of the basin; the map is a land use map of the basin which was obtained from Department of Energy, Bhutan. Seventeen projects (total capacity of 8035 MW) have been identified in the Punatsanchhu river basin as per the Power System Master Plan (2003) Bhutan. Most of the plants are run-of the river type. Table 4.2 gives a brief understanding of some of the hydropower projects along this river.

Table 4.1: Key facts about Punatsangchhu River (DoE, 2003)

Name of the River	Punatsangchhu
Main tributries	Mo Chhu and Pho Chhu
Length of the river in Bhutan	250 km
Area covered by glaciers	506.11km^2
Basin Area	13 263 km^2
Population	162 071
Catchment Area	6271 km^2

Table 4.2: Some of the hydropower projects along Punatsangchu River (DoE,2003)

Name of Project	**Capacity (MW)**	**Location**	**Remarks**
Punatsangchhu Stage –I	1095	Dam site 8 kms downstream of Wangdue Phodrong (A district in Bhutan through which Punatsangchhu river flows)	Construction started in 2007
Punatsanchhu Stage- II	1000	Dam site 20 kms downstream of Wangdue Phodrong	Feasibility study
Basochhu	64	Located on Right Flank of Punatsanchhu project area	Completed
Dagachhu	100	Downstream of Puantsangchhu in Dagachhu tributary.	Feasibility study completed

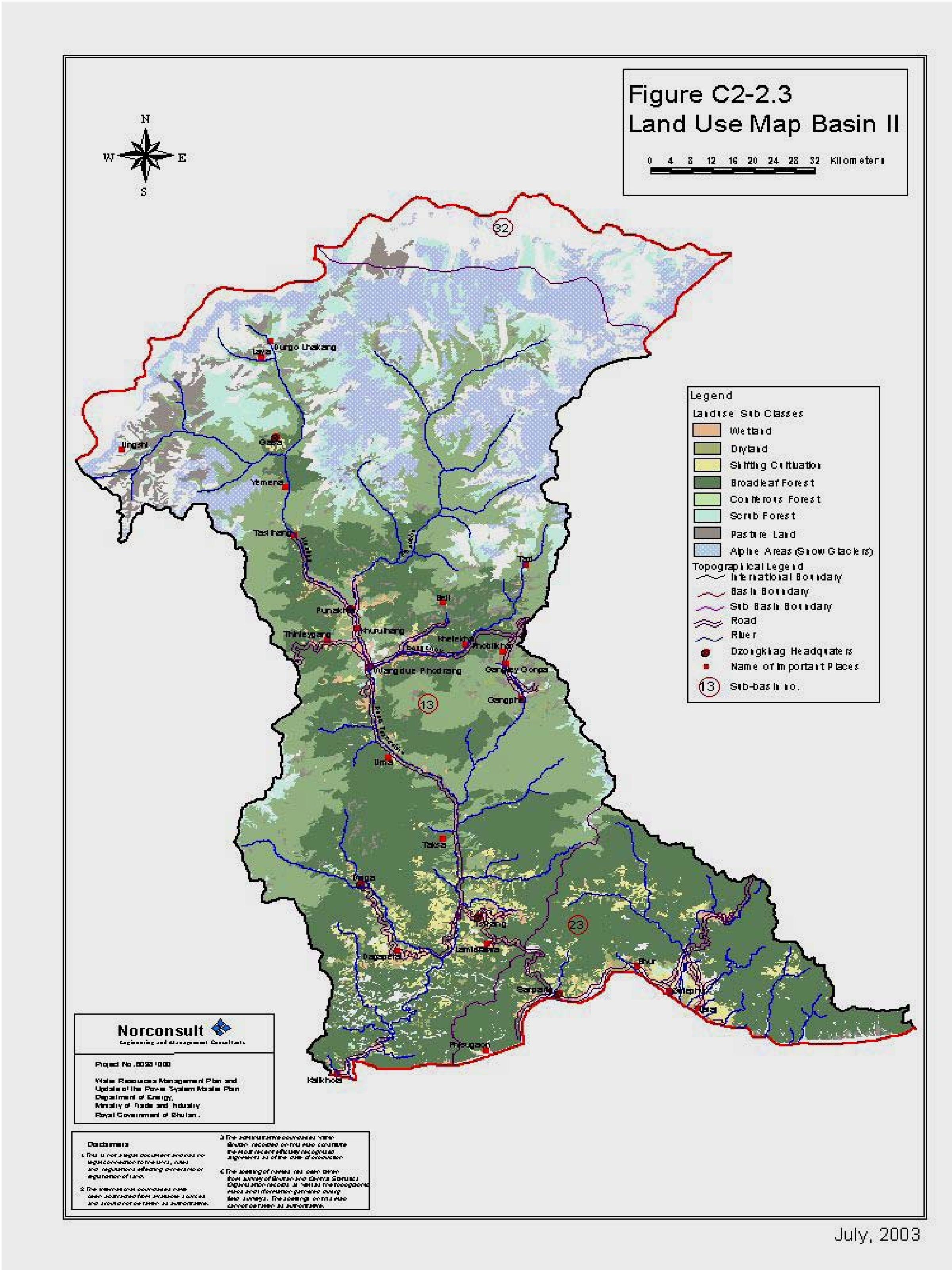

Figure 4.1: Punatsangchhu River Basin. (Department of Energy, Bhutan, 2003)

4.2 Climate of Punatsangchhu River Basin

The climate in the midstream region of the river is categorized as monsoon climate, which consist of wet season during June to September and dry season during October to May in general. Annual precipitation varies from 400 to 600 mm in the upstream region, 700 to 900 mm for midstream region where the data is collected and exceptionally more than 2000 mm for steeply inclined topography in mid to downstream areas of the basin. Climate in the downstream region near the border with India is also categorized to be subtropical with annual precipitation of 3000 to 5000 mm. (Dorji, 2003)

4.3 Geology of Punatsangchhu River Basin

The area of this River Basin comprises the middle part of the country. The northern region of the river basin is covered with glacial lakes and is associated with glaciofluvial deposits. Downstream at the confluence of the two main tributaries; Mochhu and Phochhu Rivers, the valley widens past Punakha (one of the districts in Bhutan through which Punatsangchhu River flows) as one approaches the town of Wangdue District. Wangdue valley has gently sloping hills containing significant quaternary deposits.

In the southern part of Bhutan, the foothill region, the river flows through two towns and finally leaves Bhutan to join the rivers in India. In these two towns, the geological formation is significantly dominated by quaternary deposits. As per the Water Resource Management Plan, 2003, the underlying geology has been characterized as Tethyan succession of sedimentary rocks and tertiary intrusion of leuco-granite in the north followed by the crystalline sheets and lower Himalaya meta-sediments and sedimentary rocks in the south (DoE, 2003).

4.4 Hydrology

The highest rainfall and river flow occurs in the monsoon months. Meteorological observations were carried out in the Lunana region (the northern part of the river basin), Bhutan Himalayas, from September 2002 to October 2004. The precipitation increases in summer monsoon season and decreases in winter. Over 70% of the total precipitation was observed from June to September in 2003. An annual precipitation of 900mm was measured in the year 2003. The amount of winter precipitation is uncertain due to undetected snowfall and freezing of the precipitation gauge. However, these data imply spatial variability of precipitation. (Suzuki.et.al. 2006)

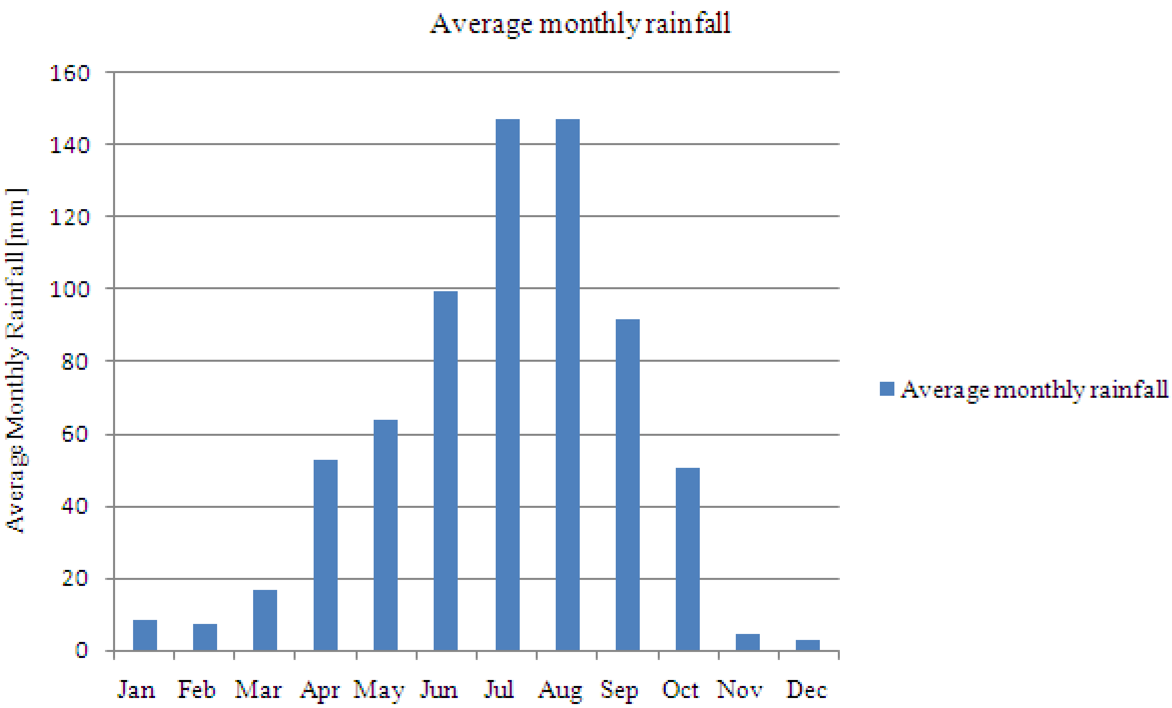

Figure 4.2: Monthly average rainfall (1993 to 2006) at the Wangdi Rapids gauging station

Figure 4.2 shows the monthly average rainfall at the Wangdi Rapids gauging station along the Punatsangchhu River for a record period from 1993 to 2006. The rainfall in the middle reach of the river at Wangdi rapids gauging station shows the highest rainfall of 900.5mm in 2001 of which 75.7% is contributed by the monsoon which is from June to September. Average annual rainfall in this region is 619mm and 76.6% is contributed by the monsoon. No information on evaporation is available, but a thesis work done by Pradhan in 2008 on 'Hydrological Studies of Punatsangchhu River' shows that the evapotranspiration at a height of 4250m which could be representative for the whole catchment area was 421 mm per year. The monthly potential evapotranspiration was calculated using the Thornthwaite formula (Pradhan, 2008).

4.5 Measurement Stations

There are four principal river gauging stations along this river as shown in Figure 4.3. Three additional secondary stations are located on the tributary streams flowing into the main north-south Punatsangchhu River. The Punatsangchhu River basin was selected as the pilot basin for sediment sampling by Department of Power (present day called Bhutan Power Corporation) in Bhutan, and four sediment-sampling stations were located at: Yebesa on Mochhu, and Wangdi Rapids, Dubani and Kerabari on Punatsangchhu. As of 2003, only two of the sediment sampling stations is functional i.e. Wangdi Rapids and Yebesa. (DoE, 2003).

The sediment data consisting of fines and sand concentration in the river is measured in ppm and processed in an excel program called SEDAT. The depth integrating samplers are used and hand held sampling will be introduced in the future. In the depth integrating samplers, the samples are accumulated as the samplers are lowered to the stream bed and raised to the surface at a uniform rate. For the discharge measurement, staff gauge, cableway and pressure transducer (water logger) is used. The gauging stations are installed with bank operated cableway system.

For this study, the data from Wangdi rapids gauging station for both sediment concentration and discharge is used. The data from the other principal and secondary gauging stations could not be obtained. The sediment and flow data is available from 1992 July to 2008 December. However, the 1992 data is not complete since measurement is available only from July. 1994 data is also only 31% complete; this is because of the Glacier Lake Outburst Flood in 1994 which has made the river change it course and during the flooding a huge amount of sediment was deposited on the high levels of the river channel. These sediments were eroded by the river with passing of time and hence the 1995 data shows a huge sediment concentration. For this study, the data of 1992, 1994 and 1995 is not included.

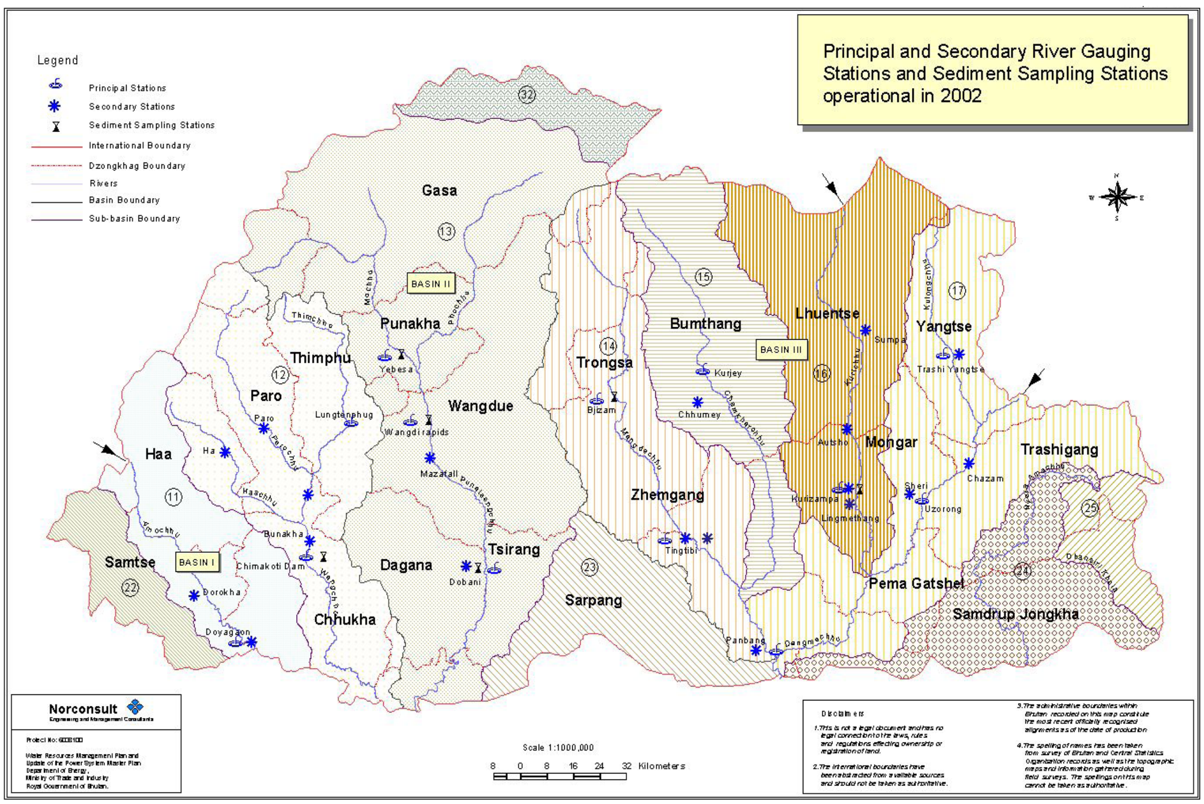

Figure 4.3: Map of Bhutan showing the principal (in main rivers) and secondary (in the tributaries) river gauging stations and sediment sampling stations operational in 2002 (DoE, 2003)

5 Results: Sediment transport pattern in Punatsangchhu

5.1 Measurements

For the discharge measurement, staff gauge, cableway and pressure transducer (water logger) is used. The gauging stations are installed with bank operated cableway system. The length of track cable is 111 m. Winch shed is located on the right bank of the river; sinker weights of 50 kgs are used. Velocity-area is measured with a propeller type current meter. Daily water level is monitored by the observer two times a day (9:00 & 15:00). Cableway discharge measurement is done twice a month. (DoE, 2003) Figure 5.1 shows the picture of the cableway system installed at Punatsangchhu River.

Figure 5.1: Cableway system installed at Punatsangchhu River. (Department of Energy, 2009)

Daily sediment concentrations of sand and fines in ppm and river discharges are measured at the gauging stations and the SEDAT program is used to process these data. The SEDAT program is an excel program used to process and present the sediment and discharge data of a river. The program was developed by Dr. Haakon Støle (Dorji, 2003). The daily observed data for a station is recorded in a prescribed format and this information is used to estimate the total average annual sediment (bed + suspended) load carried by the river and also the sediment yield of the catchment. The program can process and maintain a yearly record. The measurement of sediment concentration at the gauging station is done using the depth integrating sediment sampler with additional sinker weight for cableway. The sinker weight prevents sampling close to the bottom. The sampler is of Swedish type (Lysne.et.al, 2003).

Daily measurements for both sediment concentration and discharge are done at the gauging stations and when the measurements are not done for some reasons, the recorded values for the month is taken into account and a data recovery is applied which gives the total monthly values as sum of observed concentrations divided by the number of days for which concentrations are observed. An abstract from the SEDAT program data is presented in Table 5.1 giving us a better understanding of the data.

Table 5.1: Sample of summary of sediment data from SEDAT (the years marked with * is not used in the present study)

	Years→	1992*	1993	1994*	1995*	1996	1997	Continued till		2008
1	Average data recovery rate for the whole year (%):	47	84	31	68	75	65	------	-----	84
2	Observed suspended sediment load (tonnes):	527 839	498879	60784	5788052	1129080	1431421	------	-----	1818379
3	Estimated suspended sediment load for record period (tonnes):	595 096	513645	109 272	744 4860	1490241	1509989	------	-----	1818379
4	Estimated unmeasured load, including bed load (%):	30	30	30	30	30	30	------	-----	30
5	Estimated unmeasured load, including bed load (tonnes):	178 529	154093	32782	2233458	447072	452997	------	-----	545360
6	Estimated total sediment load for record period (tonnes):	773 625	667738	142 054	9678318	1937313	1962985	------	-----	2363226
7	Estimated specific sediment yield for record period (tonnes/km2):	123	106	23	1543	309	313	------	-----	377
8	Estimated total runoff for record period (M m3):	5727	8362	7732	9365	9925	8811	------	-----	9660
9	Estimated specific runoff for record period (mm):	913	1333	1233	1493	1583	1405	------	-----	1540
10	Average total sediment content for record period (ppm):	135	80	18	1033	195	223	------	-----	245
11	Average flow(m^3/s)	180	263	244	295	313	278	------	-----	304

In Table 5.1, the different variables are explained as below:

1. Average data recovery rate for the whole year: This is the ratio of sum of observations made in the year to the number of days in that year multiplied by 100 to get it in %.
2. Observed Suspended Sediment Load: This is the total observed suspended load for the whole year. The load is computed by multiplying the sediment concentration with the river discharge.
3. Estimated Suspended Sediment Load (tonnes): This is the total suspended load for the whole year taking data recovery into consideration.
4. Estimated Unmeasured load, including bedload (%): This is shown in Figure 5.2. The bed load here is assumed as 30% and this assumption is not based on measurements done in Bhutan. (Information on what the 30% assumption is based on could not be found)

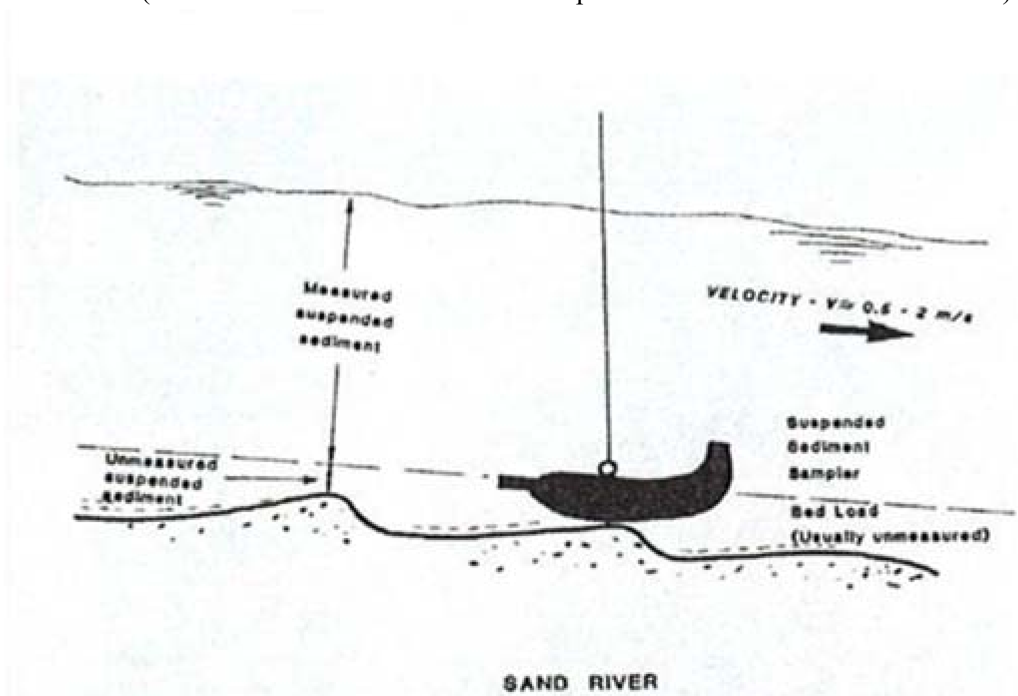

Figure 5.2: Sediment sampling in Sand bed Rivers showing the unmeasured load (Bishwakarma, M, B., 2008)

5. Estimated Unmeasured load, including bedload (tonnes): This is just the 30% of the estimated suspended load in tonnes.
6. Estimated total sediment load for record period (tonnes): This is the sum of estimated suspended load and estimated unmeasured load including bedload for the whole year.
7. The estimated specific sediment yield for record period (tonnes/km^2): is obtained by dividing the estimated total sediment load by the catchment area.
8. Estimated total runoff for record period (M m^3): is computed from the discharge and number of days in the month giving the units of mil.m^3.
9. Estimated specific runoff for record period (mm): is computed by dividing the total runoff by the catchment area.

10. Average total sediment content for record period (ppm): this is the average concentration in one year.
11. Average Flow (m3/s): this is the average flow for the year.

From the above variables, serial number 3, 5, 6, 7, 10 and 11 are used to compare with the results obtained from calculations. There are always some uncertainties in the measurement of any data. Sediment sampling in the Mountain Rivers is difficult and the available data are often questionable with respect to quality. Sediment concentrations are measured once in a day, but it could be possible that a major bulk of the annual sediment load may be transported within a few days; a large quantity of the sediment load may easily pass a sediment gauging station unmeasured if the sampling frequency is poor.

The data available (from Wangdi Rapids station) is used to understand the spatial and temporal variation of sediment transport characteristics of the Punatsangchhu River and the factors affecting this variability.

5.2 Annual Variations

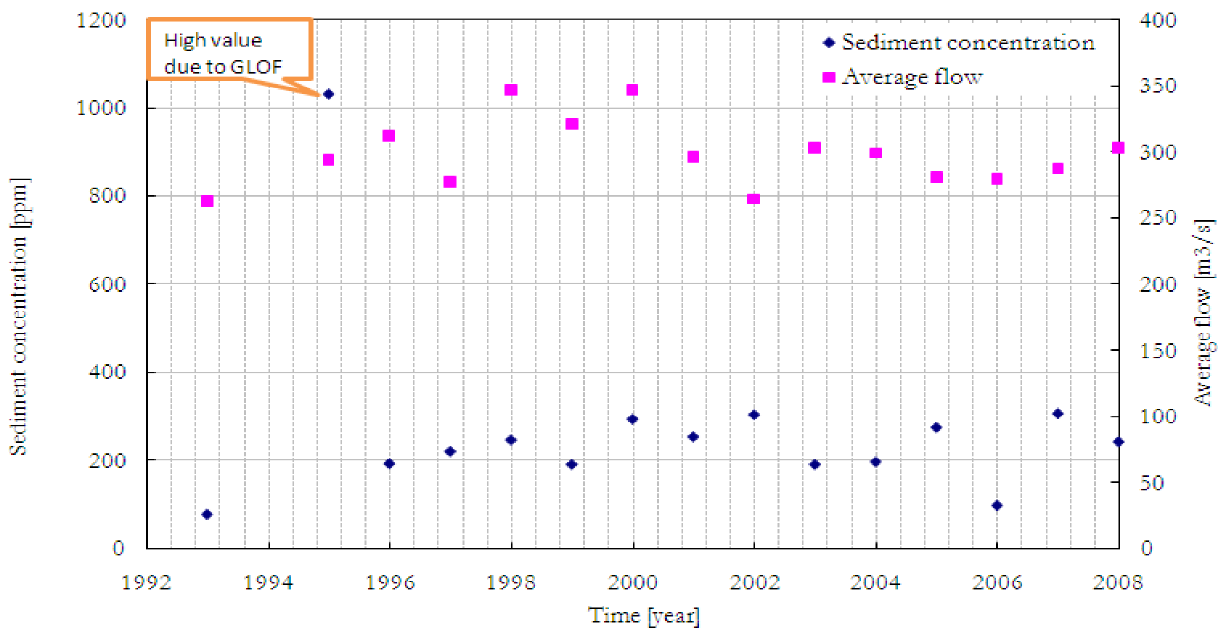

Figure 5.3: Average annual variation of sediment concentration and flow for Punatsangchhu River

The high value of sediment concentration as reflected in Figure 5.3 is because of the GLOF that occurred in 1994; the effect of which is seen in 1995. Both the river flow and sediment concentration varies largely over the years. The fluctuation in the annual sediment load is much higher than the variations in water runoff. The highest sediment concentration was observed in 1995 with an average sediment content of 1033 ppm corresponding to a total load of 9 678 318 tonnes in that year. This is unusually high compared to the loads in other years. The minimum concentration was observed in 2006 with an average total concentration of 100 ppm corresponding to 889 888 tonnes. Excluding the 1995 load, the highest load of the record period was found to be 2 825 875 tonnes in 2007. The average yearly river discharge varies from 263m^3/s in the year 1993 to 348 m^3/s in 2000.

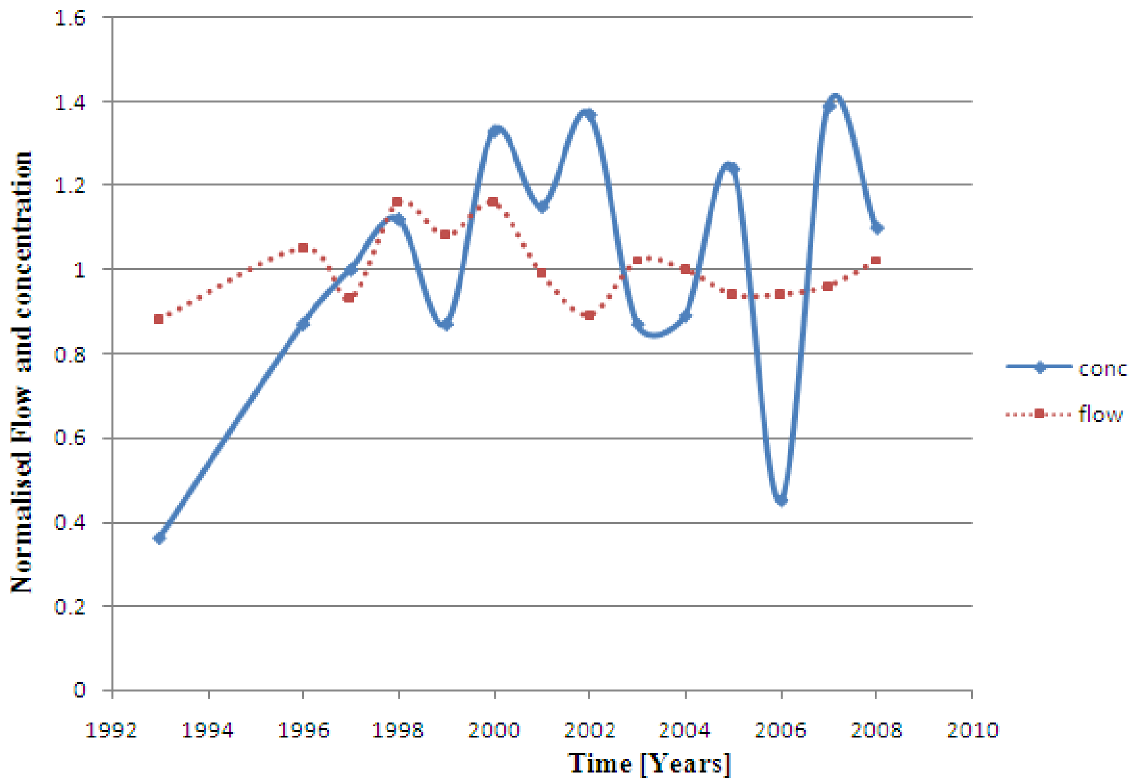

Figure 5.4: Average annual non-dimensional river flow and sediment concentration variation in time for Punatsangchu River. (Non-dimensional values are obtained by dividing with the average)

The sediment concentration over the years varies, but there is no clear trend in the variation. It is not linear and no clear relation between flow and sediment concentration can be drawn from the plot above. However, we can see that the sediment concentration and average flow do not vary with the same magnitude. We can get a better understanding of this variation when both the flow and concentration is divided by their average value and plotted as shown in Figure 5.4. River flow of one year earlier (Q_{T-1}) and sediment concentration were plotted for the yearly values and this shows a little similarity in the trend. When the Q_{T-2} and sediment concentration for the year T was plotted, the trend in river flow and sediment seems to follow similar trend at least for the first few years. This is shown in Figure 5.5. The reason for this similar trend could be because the sediments gets trapped on the way in some small storage along the river banks and is later brought into the river when there is heavy rainfall. Since the data series is for a very short time series, it is difficult to say that the same trend will be followed in the future.

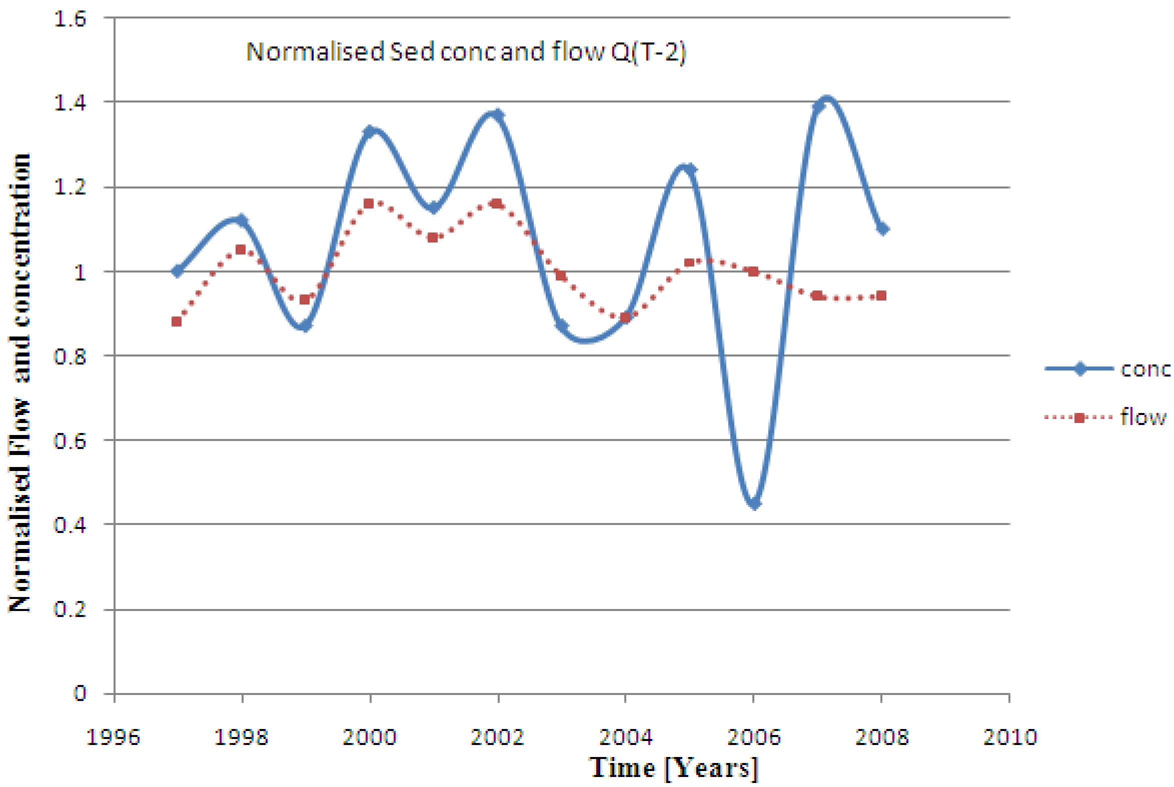

Figure 5.5: Normalized flow (Q_{T-2}) and concentration for Punatsangchhu River

The sediment yield also showed a variation over the time; it seems to increase for the first 6 years of the record period after which the trend seems to decrease and then again increase over the remaining record period. The river flow does not follow the same trend as the sediment yield. The highest sediment yield observed was in 1995 as 1543 tonnes/km^2. The lowest sediment yield was observed in 1993 with a value of 10^{6}tonnes/km^2. Excluding the 1995 value, the highest yield was observed in 2000; 520 tonnes/km^2.

5.3 Monthly Variations

The seasonal variation is very large. The maximum flow occurs in the monsoon months; i.e. June, July, August and September. This is very obvious for the Himalayan region. The sediment concentration is also highest in these months. This trend is followed in all the years of the record period. From the data, it is observed that 87% of the sediment load is transported during the monsoon month of June to September. In the months from December to April only 3% of the total yearly load was transported. The rest (10%) is transported during the months May, October and November. The river discharge follows a similar trend. Flow in the monsoon months contribute to 70% of the total flow while 12% is contributed by the months of December to April and the remaining 18% from May, October and November.

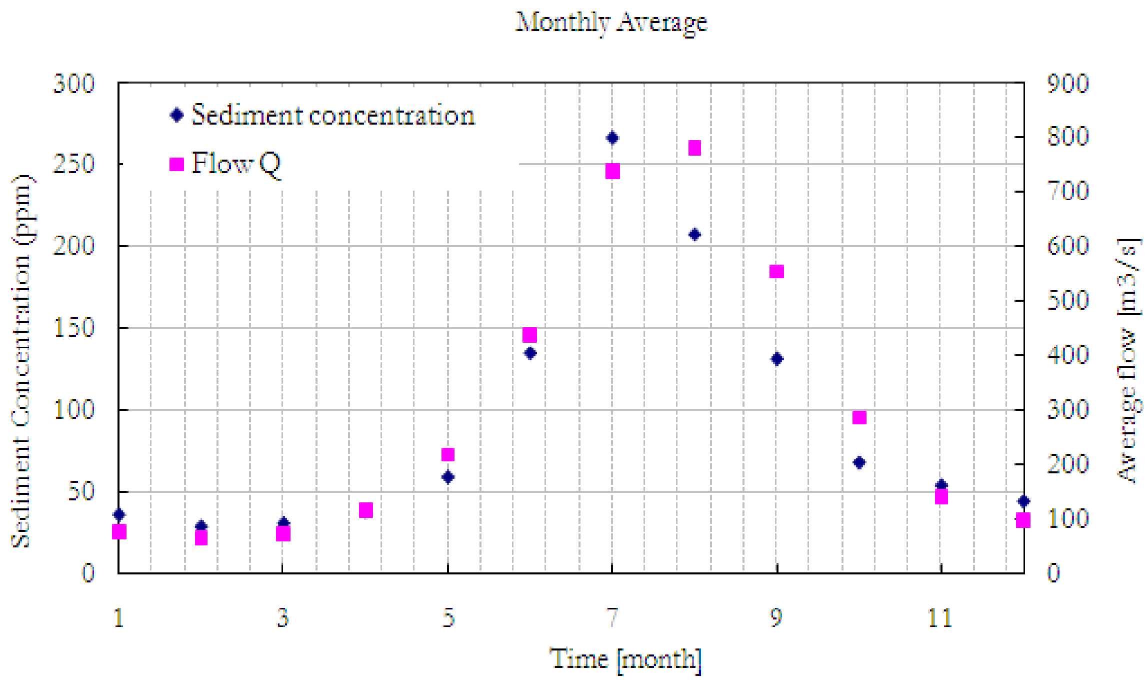

Figure 5.6: Monthly variations of sediment concentration and discharge of Punatsangchhu River for 1993 and 1996 to 2008

Figure 5.6 shows the monthly variations of sediment concentration and river discharge of Punatsangchhu River. The sediment concentration does not necessarily follow the same trend as the flow. For instance, in the month of August the sediment concentration decreases while the flow increases. However, both the flow and sediment concentration follows the same trend. From this we can say that the river flow is not the only factor affecting the sediment concentration. The sediment rating curve is plotted as shown in Figure 5.7. A simple linear regression analysis is done in excel and from this plot we can see that the R^2 value is 0.538.

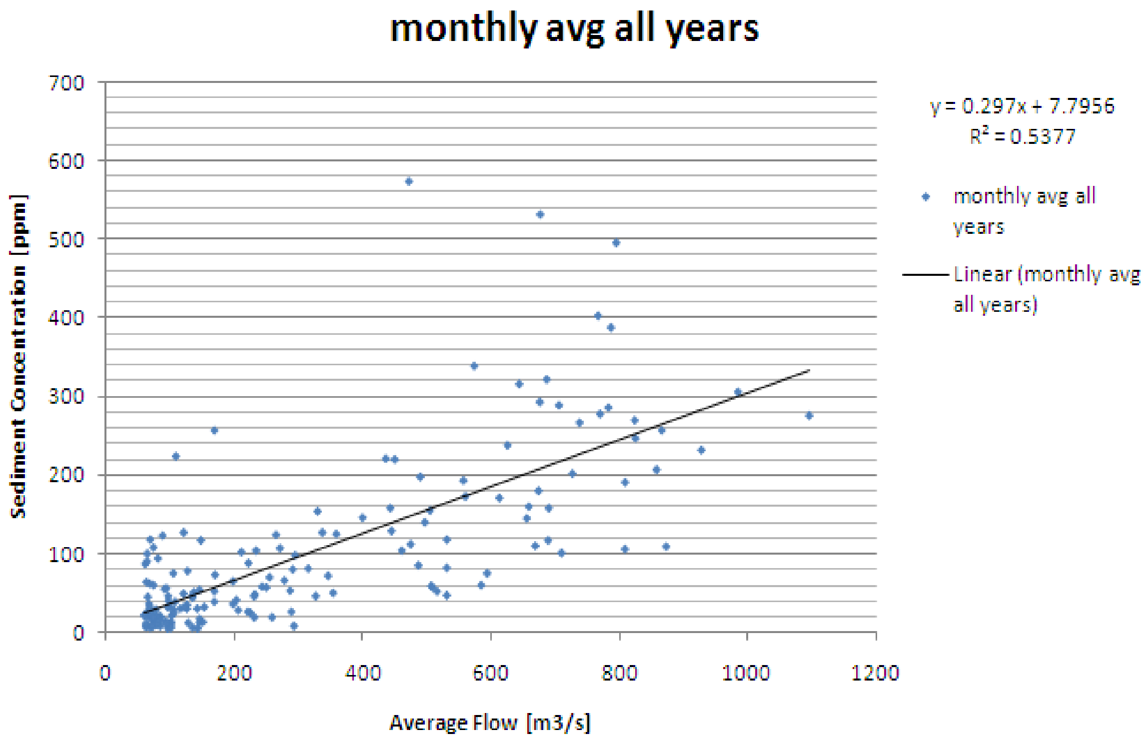

Figure 5.7: Plot of sediment concentration and flow with regression analysis fit and R^2 value for Punatsangchhu River; Average monthly values 1996-2008 and 1993

The normalized monthly flow and sediment concentration was plotted for all the years separately and from these plots, it was noticed that the river flow and sediment concentration did not correlate very well. In fact, in some of the years, there was no similarity at all. But when the average values over the year are taken, the trend looks similar. This is shown in Figure 5.8 which shows the average value plot and Figure 5.9 shows some years for which the plot shows no similarity in the trend.

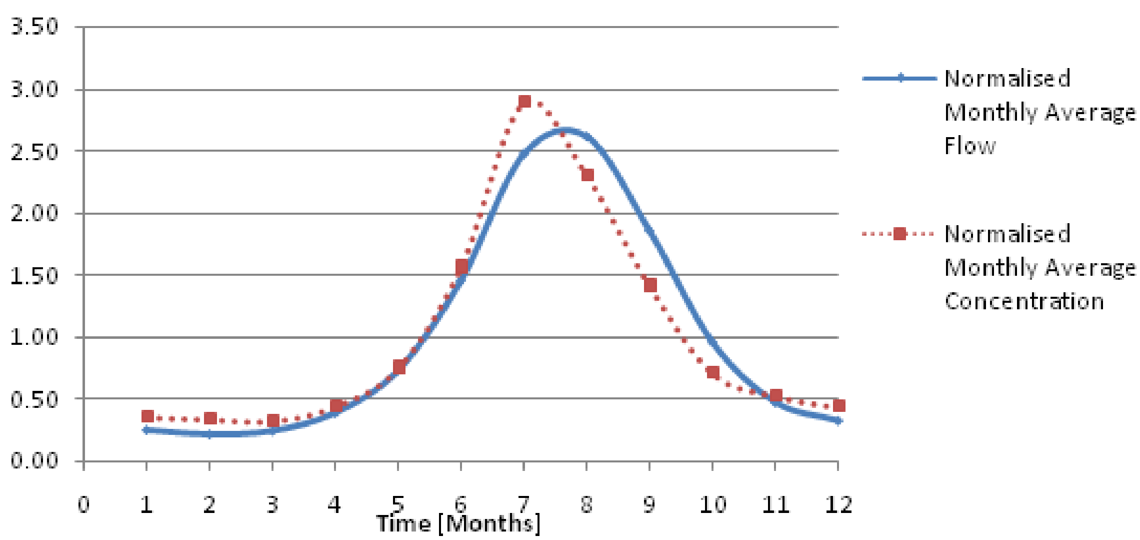

Figure 5.8: Normalized monthly flow and concentration of Punatsangchhu River

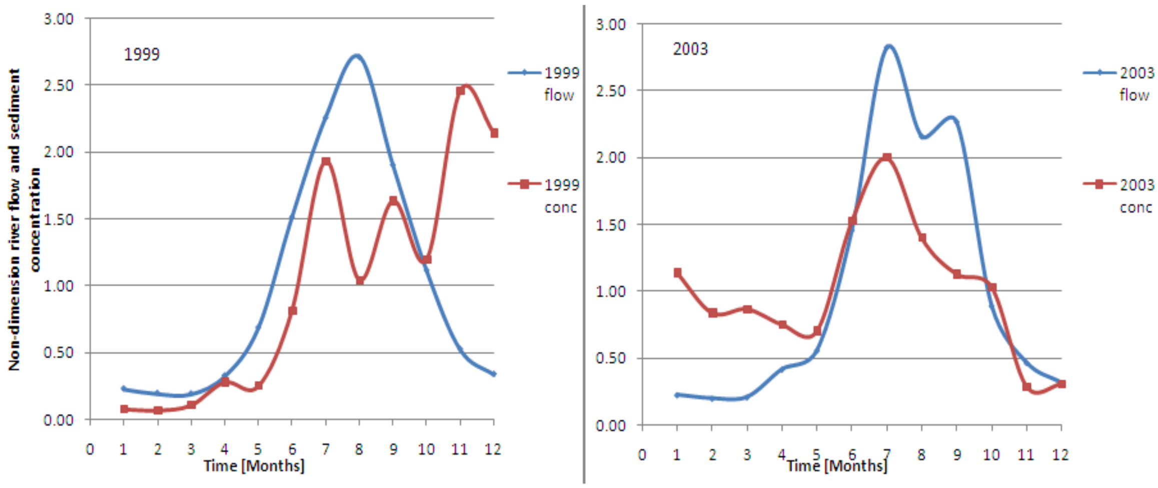

Figure 5.9: Normalized flow and concentration for 1999 and 2003 of Punatsangchhu River

The monthly average sediment concentration for the record period is highest during the monsoon months with 358, 708, 550 and 349mg/l for June, July, August and September respectively. (The unit conversion to mg/l is done assuming a density of sediment as 2650kg/m^3 as information on sediment density in this region could not be found). This is comparable to the concentration in Garhwal Himalayas, see (Singh.et.al, 2003), the mean daily suspended sediment concentration from a 4 years data for June, July, August and September was found to be 452, 933, 965 and 275 mg/l respectively. Figure 5.10 shows the comparison of sediment concentration in Garhwal Himalayas and Punatsangchu River.

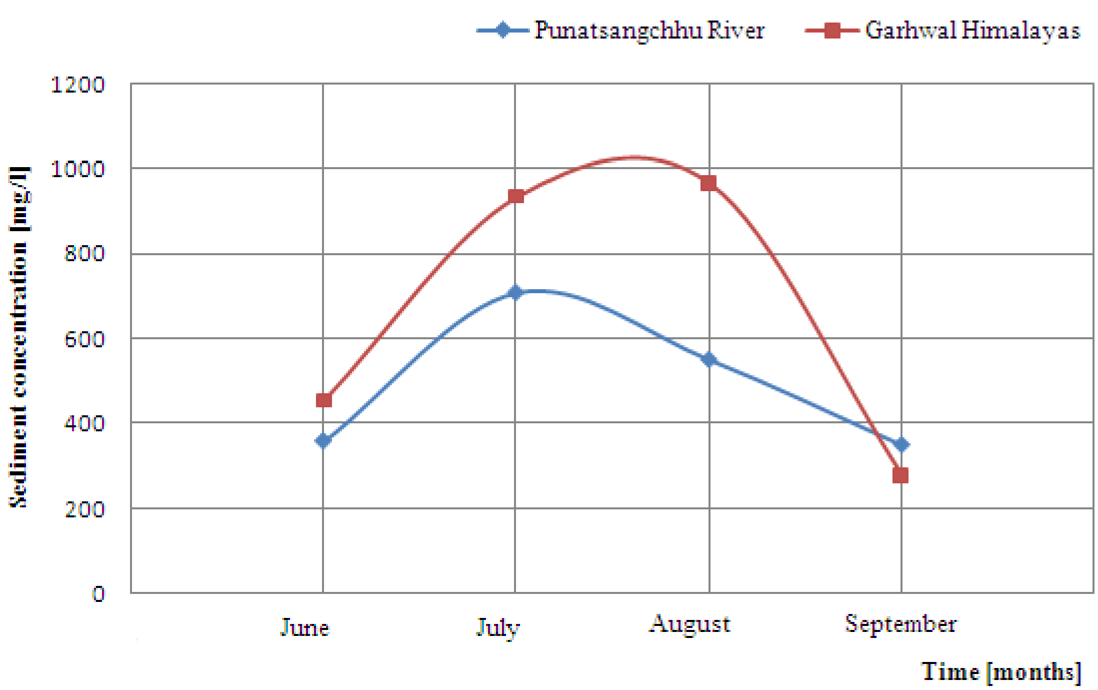

Figure 5.10: Sediment concentration at Garhwal Himalayas and Punatsangchhu River in the monsoon period

This study area had 60% of total drainage area covered by glacier. This study also showed a poor correlation between suspended sediment concentration and river flow. Punatsangchhu river basin has a glacier covered area of 8.6 % of the catchment area and the correlation between suspended sediment concentration and river flow is also poor, hence the values are comparable. Another study (Ali and Boer, 2007) also states that river basin influenced by glaciers and snowmelt are characterized by high temporal variability of suspended sediment fluxes.

5.4 Daily Variations

The daily discharge and sediment concentration was plotted for the record period and this plot shows a very large scatter. Considerable scatter indicates that there are other variables besides river flow influencing the sediment concentration. Another reason for this scatter could be because of the irregular sampling at the gauging stations. From the 12 years of data only one year data is 100% complete. The daily sediment concentrations were plotted against the day before flow and 2 days before flow. The scatter was almost the same also with the lag time discharge. Figure 5.11 shows the daily sediment concentration and river discharge plot for two random months showing a poor correlation.

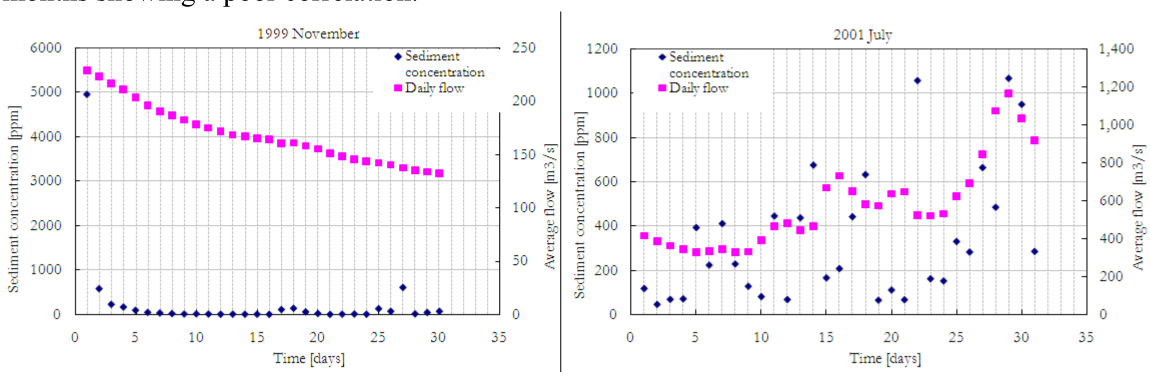

Figure 5.11: Sediment concentration and river discharge in November 1999 and July 2001 at Punatsangchhu River

The daily rainfall data could not be used to correlate with sediment concentration because the rainfall data was available only for one gauging station i.e. the station where the sediment data is obtained from. The river flow and sediment concentration at that station is not only contributed by the rainfall at that station. There are many tributaries in the upstream reach of the river which contribute to the river flow and sediment concentration to this point where the measurement for the sediment concentration is done. The highest rainfall in this region is 900.5mm in the year 2001 out of which, 75.7% is contributed by the monsoon which is from June to September. Average annual rainfall in this region is 619mm and 76.6% is contributed by the monsoon. A plot of rainfall versus the river flow and sediment concentration was done and the correlation was poor. Figure 5.12 shows the daily sediment concentration and daily river flow plot showing a poor correlation between the two.

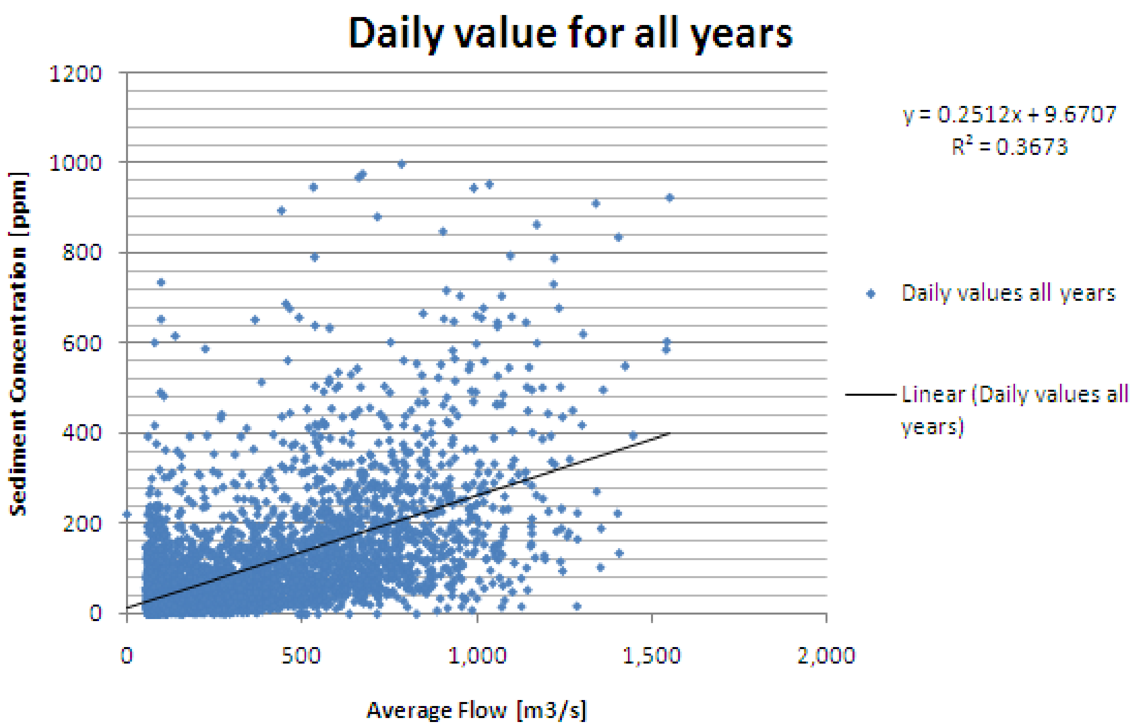

Figure 5.12: Daily values of sediment concentration and flow for the record period for Punatsangchhu River

Different trend lines were fitted to the monthly average discharge and sediment concentration plot and the best fit was a linear and exponential trend. Figure 5.13 shows the different trend lines and corresponding R^2 values. The average monthly discharge plotted over the years of the record period is shown in Figure 5.14. The discharge from year to year varies but the trend is similar. The maximum flow is during the monsoon month.

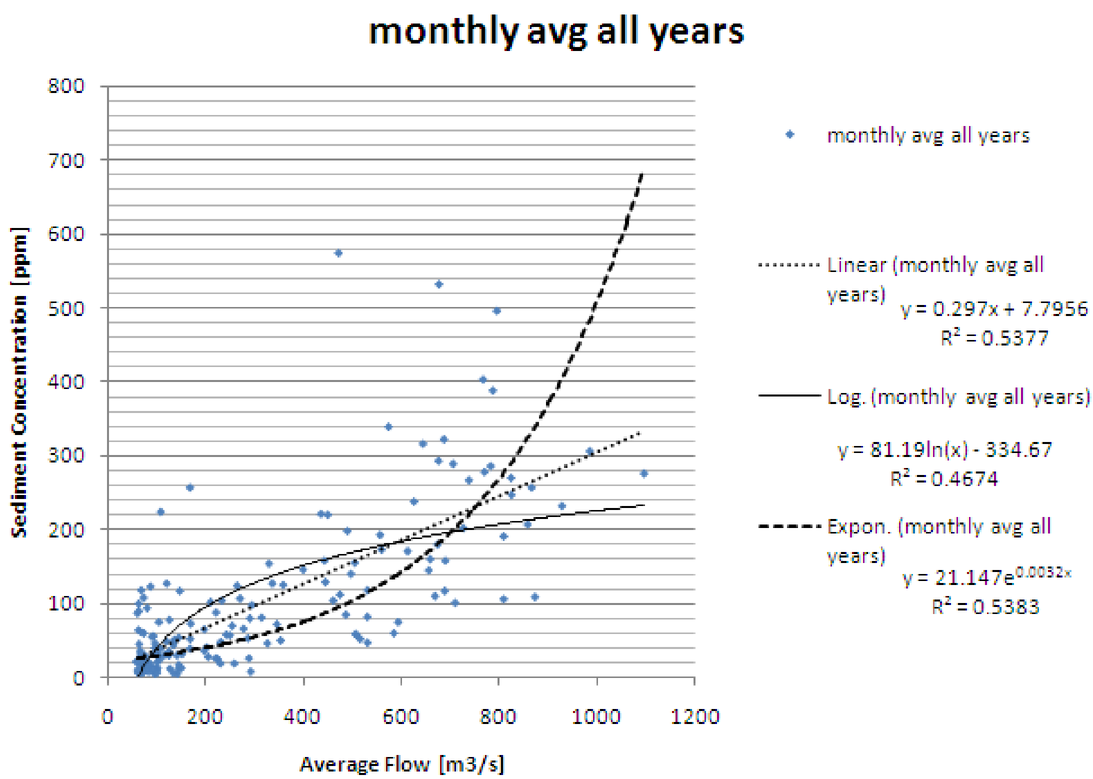

Figure 5.13: Average monthly sediment concentration and discharge of Punatsangchhu River showing different trend line.

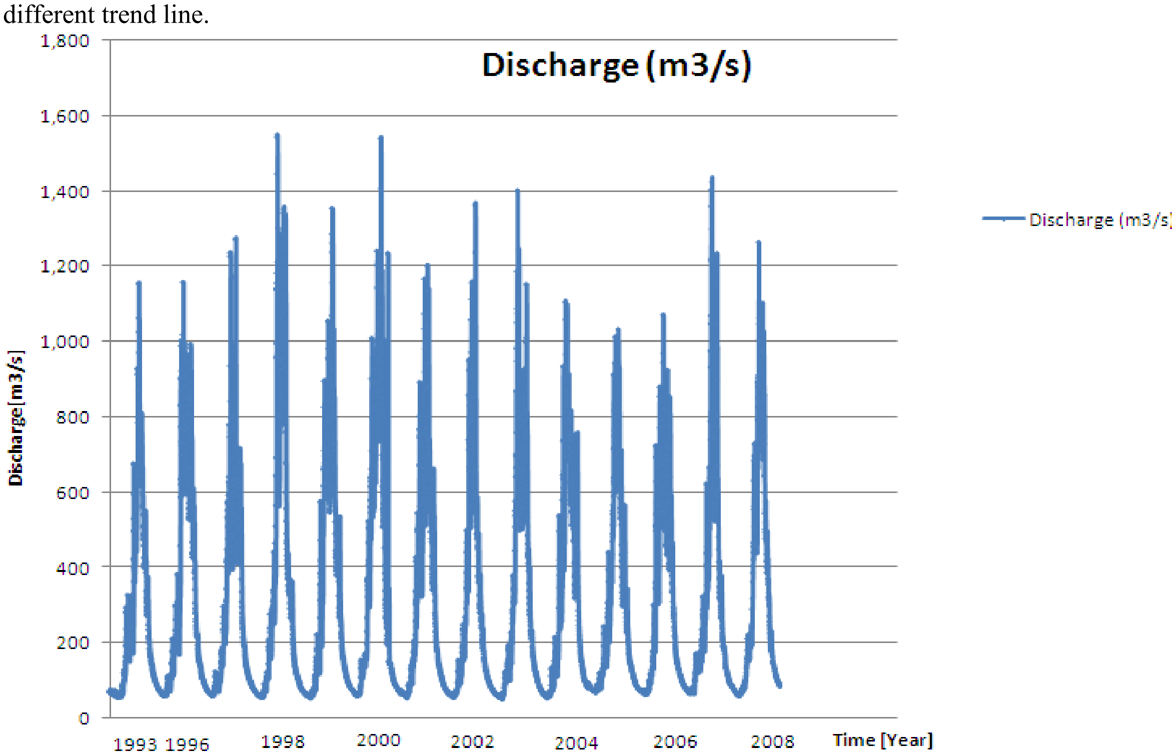

Figure 5.14: Daily discharge for the record period for Punatsangchhu River

5.5 Sediment load calculation

When the bedload was calculated using the bedload transport formula developed for non-cohesive sand bed rivers, the results were similar to the 30% assumed load. However, the calculations were based on some assumptions because of lack of data. Firstly, the particle size distribution was not available and an assumed distribution which was used in the past for studies in this river basin was used in this calculation also. Secondly, the river cross-section used here is the cross-section taken after the monsoon month. The cross section will vary throughout the year and this is taken as an average since the load is calculated on a yearly basis and the river flow is also taken as the average flow for the year. The velocity of the river flow is calculated based on river discharge and the cross section of the river. Since the discharge is taken as an average over the record period, the results obtained may differ if the calculations are done based on daily discharge. Bedload transport rate is expressed as volume of grains moving per unit time per unit width of the bed. Some of the more commonly used or recent bedload formulae for steady flows, developed for use in rivers are (Soulsby, 1997):

Meyer-Peter and Muller
$\Phi = 8(\theta-\theta_{cr})^{3/2}$……………………………………………………………..(I)

Nielsen
$\Phi = 12\,\theta^{1/2}(\theta-\theta_{cr})$……………………………………………..……… (II)

Camenen and Larson
$\Phi = 12\,\theta^{3/2}\exp(-4.5(\theta_{cr}/\theta))$ ……………………………………………… (III)

$\Phi = \frac{q_b}{\sqrt{[g(s-1)d^3]}}$ ……………………………………………………… (IV)
$\theta = \frac{\tau_0}{g\rho(s-1)d}$ ………………………………………………………..… (V)

$\tau_0 = \rho C_D \bar{U}^2$ ……………………………………………………………….. (VI)

$C_D = \left[\frac{k}{1+\ln\left(\frac{z_0}{h}\right)}\right]^2$ .... (VII)

k= Von Karman's constant =0.4
$k_s = 2.5*d_{50}$
$z_0 = k_s/30$

Where:

- θ = Shield's parameter
- θ_{cr} = Critical Shield's parameter
- Φ = Dimensionless transport number
- q_b = Volumetric bedload transport rate per unit width

- g = acceleration due to gravity
- ρ = density of water
- s = ratio of densities of sediment and water
- d = grain diameter
- C_D= total drag coefficient
- τ_0= Bed shear stress
- $\bar{U}$ = Depth averaged velocity

The above transport formulae were developed for rivers and are commonly used (Soulsby, 1997). The Meyer-Peter and Muller formula was developed to fit data from steep flumes and is therefore useful in many hydropower cases with steep rivers (Lysne et.al, 2003). These formulae (equation (I), (II) and (III)) were used for comparison with the assumed bedload percentage and the results are shown in Figure 5.15.

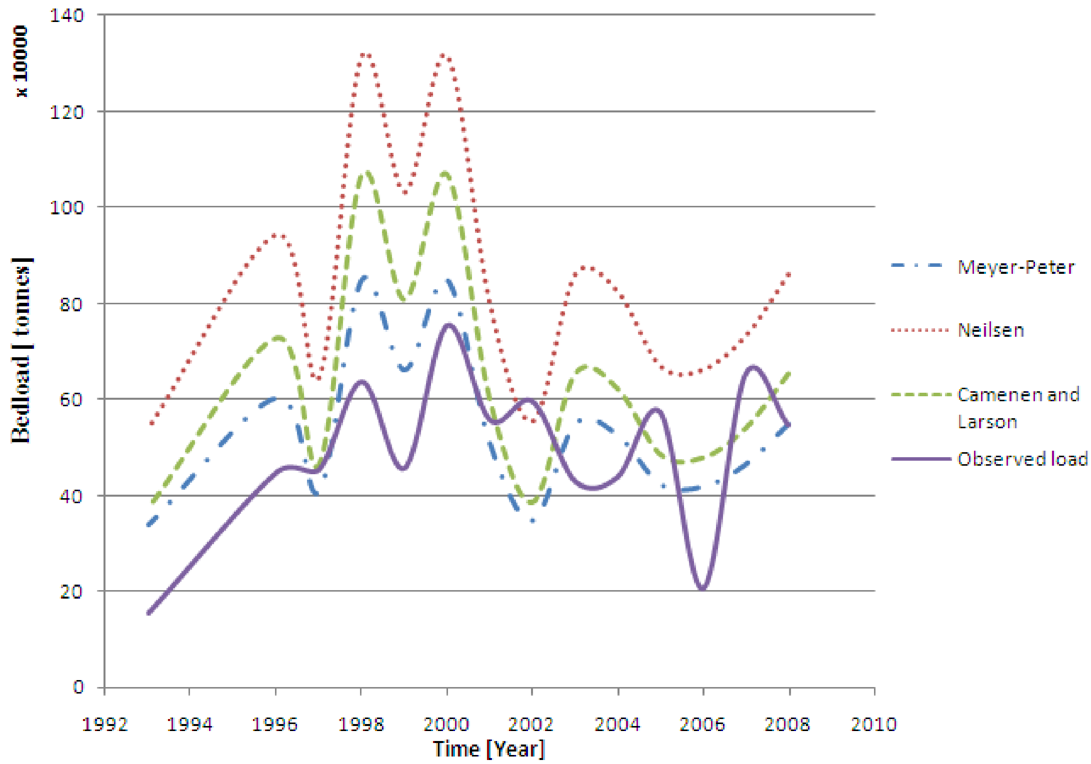

Figure 5.15: Calculated bedload using different formula and bedload (30% of measured suspended load) for Punatsangchhu River.

Relation between bedload and total load can be given by Figure 5.16. This figure was originally developed by E.M. Laursen in 1958. This figure shows the relative proportion of bedload to total load based on the shear velocity and fall velocity. From the figure it can be seen that the bedload is dominating transport mode as long as the fall velocity of particles is greater than the shear velocity. (Lysne et.al, 2003)

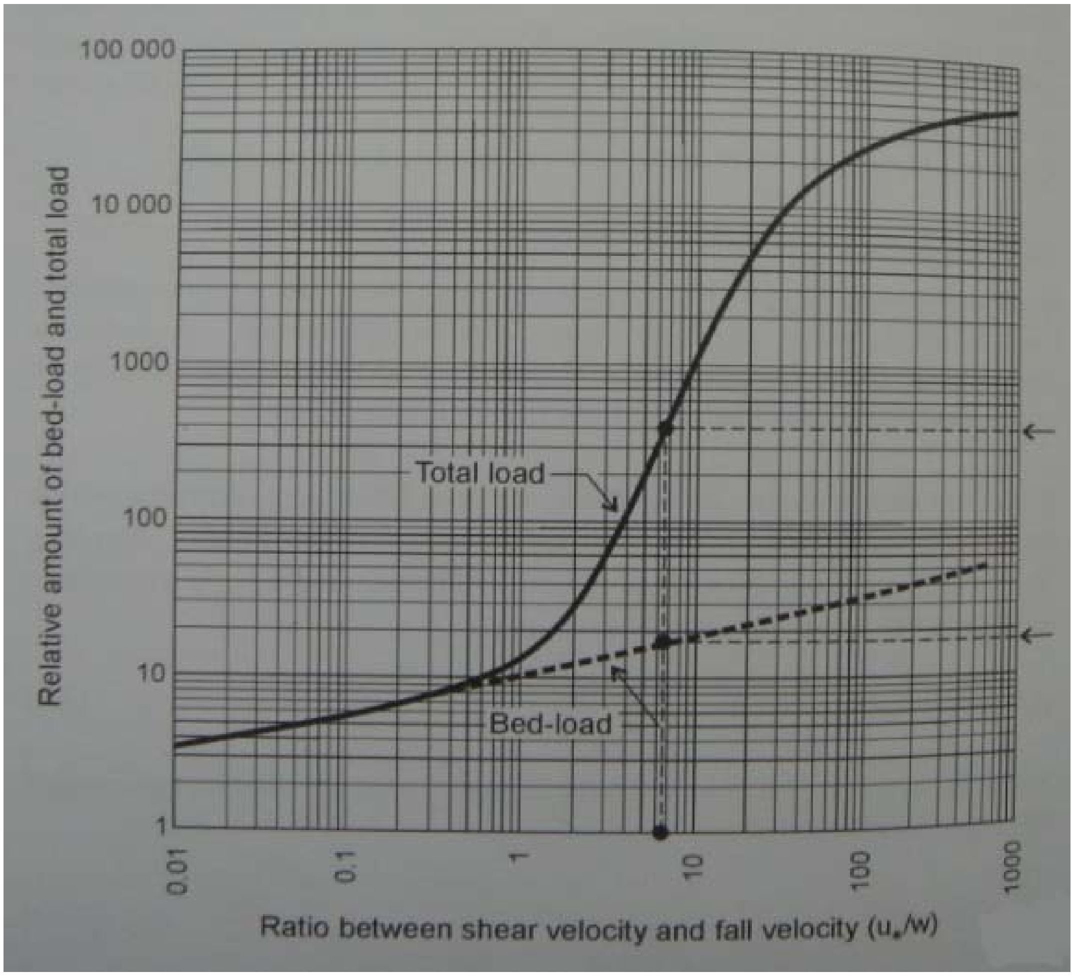

Figure 5.16: Relation between bedload and total load. (Laursen, 1958)

The shear velocity and fall velocity for Punatsangchu River was calculated. The shear velocity was calculated using the formula:

$\tau_0 = u_*^2 \cdot \rho_w$ …………………………………………………………….. (VIII)

The shear velocity based on average flow of 300 m3/s for Punatsangchu River is 0.05877m/s and the settling velocity was calculated using the formula:

$w_s = \frac{\upsilon}{d}\left(\sqrt{10.36^2 + 1.049\, D_*^3} - 10.36\right)$………………………………….. (IX)

$D_* = \left[\frac{g(s-1)}{\upsilon^2}\right]^{1/3} d_{50}$…….. (X)

Where:

- w_s= settling velocity
- u_* = Shear velocity
- υ = kinematic viscosity of water
- D_* = Dimensionless grain size for characterization of settling velocity

The fall velocity is calculated as 0.0506 m/s. Figure 5.17 shows the river cross section at the gauging station taken after monsoon period. And the assumed particle size distribution is shown in Figure 5.18.

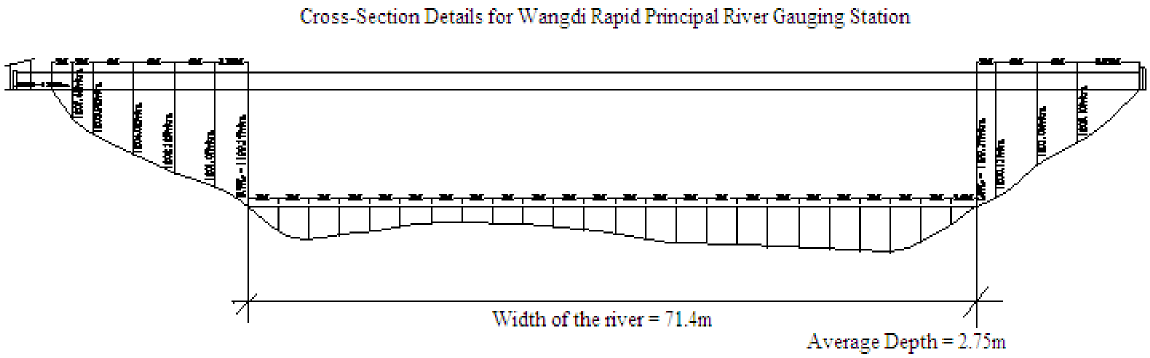

Figure 5.17: Punatsangchhu River cross section at Wangdi Rapids Gauging station. (DoE, 2009)

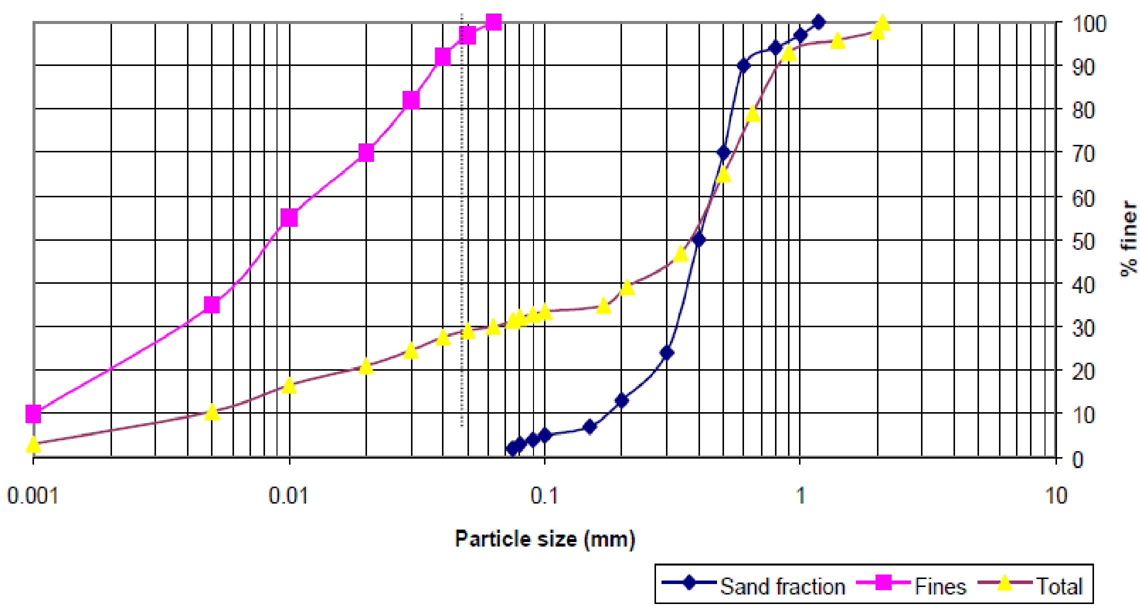

Figure 5.18: Assumed particle size distribution used for Punatsangchu River (Dorji, 2003)

Using these data the ratio between shear velocity and fall velocity is found to be 1.2. From Figure 5.16, the bedload is 59% of the total load. Here also the average river flow is used to calculate the velocity and the results obtained may differ if the calculations are done based on daily discharge.

When calculating the suspended load, the particle size was taken as d_{50} of the total fraction. The results obtained by using this size i.e. d_{50}=0.000375m, the suspended load was much less than the observed load. The formulae developed for sediment load are empirical and the particle size distribution for this river covers a wide range of particle size. Hence, the fraction d_{30} was used to calculate the suspended load and the results obtained were comparable to the observed suspended load from the data.

$$q_{ss} = U_C . c_R . \frac{K_0}{w_s} [1 - \exp\left(- \frac{w_s h}{K_0}\right)] \quad \text{(XI)}$$

The reference concentration as given by Camenen and Larson, 2007 are:

$$c_R = A_{CR}\ \theta \exp(-4.5\ \theta_{cr}/\ \theta) \quad \text{(XII)}$$
$$A_{CR} = 3.5.10^{-3} \exp(-0.3D_*) \quad \text{(XIII)}$$

Also see equation (V), (VIII), (IX) and (X).

Where:

- U_c= Critical velocity
- w_s= settling velocity
- D_* = Dimensionless grain size for characterization of settling velocity
- θ = Shield's parameter
- θ_{cr} = Critical Shield's parameter
- q_{ss} = Volumetric suspended transport rate per unit width

The suspended load was calculated based on equation (XI) and the results are compared to the observed load as shown in Figure 5.19.

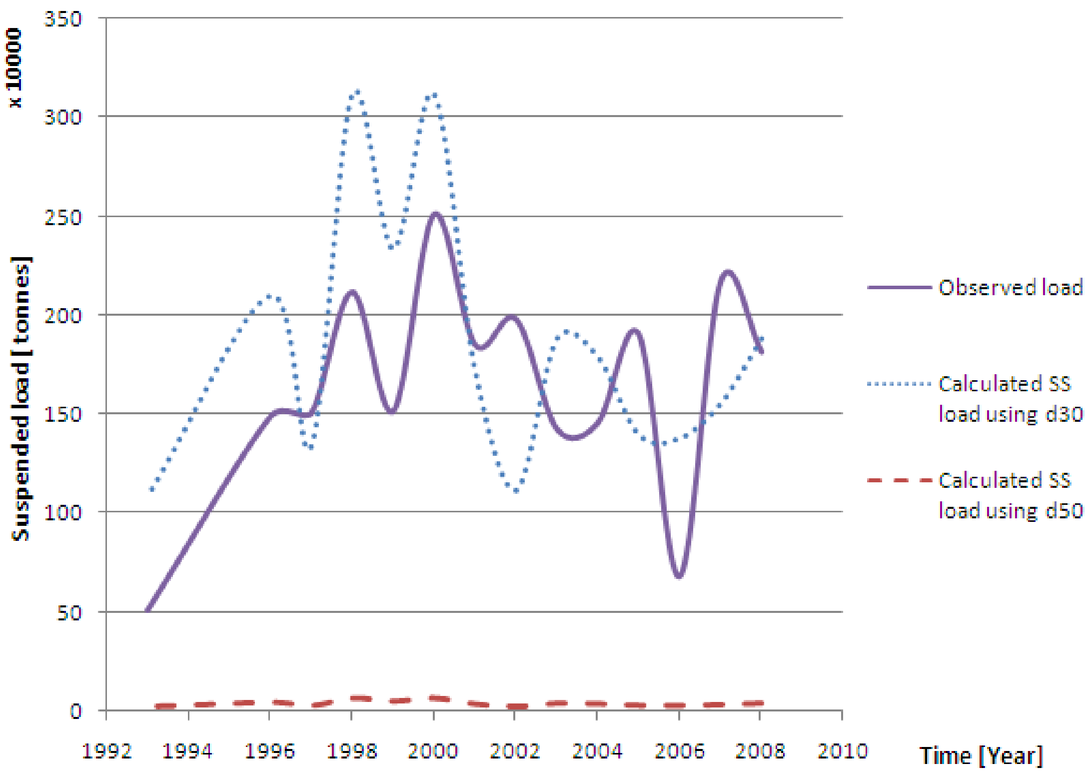

Figure 5.19: Calculated suspended sediment load and estimated suspended sediment load from measurements

6 Analysis and Discussion

The maximum sediment concentration and the maximum river discharge occurs during the monsoon months but the correlation between the sediment concentration and river discharge is not very good and reliable conclusions cannot be drawn from the regression analysis result. But for the sediment concentration, it is not only the rainfall and river flow that is contributing to the amount of sediments in the river, hence the correlation with sediment concentration is poor. From this kind of analysis, it can be concluded that the river flow and rainfall are not the only factors affecting the sediment concentration in the rivers. From Figure 5.7, we can see R^2 value is 0.537 which shows that the correlation is not very good. Similar plot for river flow and rainfall gives us an R^2 value of 0.59 which is better than the river flow-sediment concentration regression analysis but still not good enough. When the rainfall is correlated with the sediment concentration, the relationship is not very good. The R^2 value for this is 0.36.

Linear regression analysis was done for daily values of individual years and the results are presented in Table 6.1.

Table 6.1: Linear Regression Analysis Result (daily values) for Punatsangchhu River

Year	R2	Y=mx+c
1993	$R^2 = 0.4934$	$y = 0.1271x + 0.9949$
1996	$R^2 = 0.3453$	$y = 0.2232x + 3.3309$
1997	$R^2 = 0.5124$	$y = 0.2906x - 18.887$
1998	$R^2 = 0.4553$	$y = 0.2166x - 14.937$
1999	$R^2 = 0.128$	$y = 0.1749x + 28.924$
2000	$R^2 = 0.3479$	$y = 0.243x + 25.916$
2001	$R^2 = 0.2653$	$y = 0.2407x + 41.769$
2002	$R^2 = 0.324$	$y = 0.2248x + 50.717$
2003	$R^2 = 0.2687$	$y = 0.1622x + 53.094$
2004	$R^2 = 0.5477$	$y = 0.2867x - 6.5987$
2005	$R^2 = 0.5799$	$y = 0.4622x - 30.914$
2006	$R^2 = 0.3236$	$y = 0.15x + 2.8638$
2007	$R^2 = 0.7934$	$y = 0.4627x - 34.066$
2008	$R^2 = 0.6751$	$y = 0.3322x - 4.5638$
Average for all years	$R^2 = 0.5377$	$y = 0.297x + 7.7956$

From the results, we can see that the R^2 values are not very high and the correlation between river flow and sediment concentration is poor. It is interesting to see that the R^2 values are good for some years; for instance, the R^2 value for the year 2007 is about 0.8 and for 2008 it is about 0.68 which shows a good correlation between the flow and concentration. The discharge and sediment concentration were plotted for the year 2007 and the plot shows same trend in the sediment concentration and the discharge as shown in Figure 6.1. For this year, the correlation is very good.

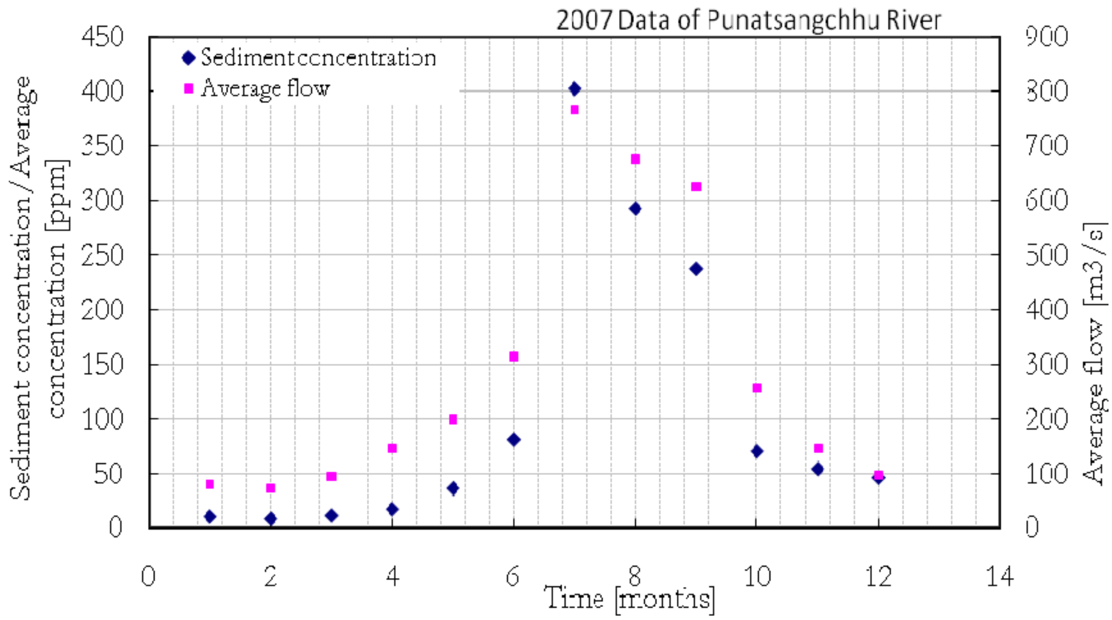

Figure 6.1: Monthly Sediment concentration and discharge for the year 2007 for Punatsangchhu River.

But there are other years where the correlation is very poor; the correlation for the year 1999 is very poor with an R2 value of 0.128, the plot of average monthly sediment concentration and discharge for the year 1999 is shown in Figure 6.2. We can see a huge variation in the sediment concentration for this year. The reason for this variation in the R^2 value over the years is not known. From this we can say that the river flow is not a reliable key for monitoring the suspended sediment concentration in the river. And also the sediment concentration varies largely with time and a major bulk of the annual sediment load may be transported within a few days and may go unmeasured at gauging site if the sampling frequency is poor. Seeing that some of the years of record have missing data for several days for the sediment concentration, this could be one reason why the sediment concentration correlates poorly with river flow. Moreover, the data is available only for a short time period of 15 years. If the data series was available for a longer duration, maybe the understanding of the sediment transport pattern in Punatsangchhu River will be more accurate.

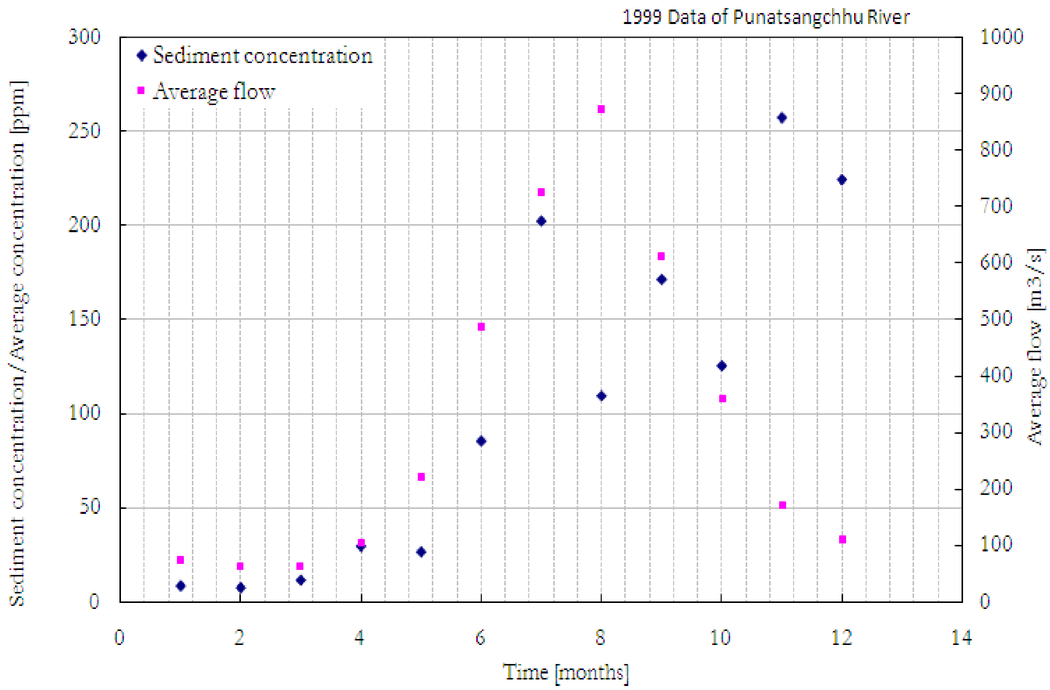

Figure 6.2: Sediment concentration and discharge for the year 1999 for Punatsangchhu River.

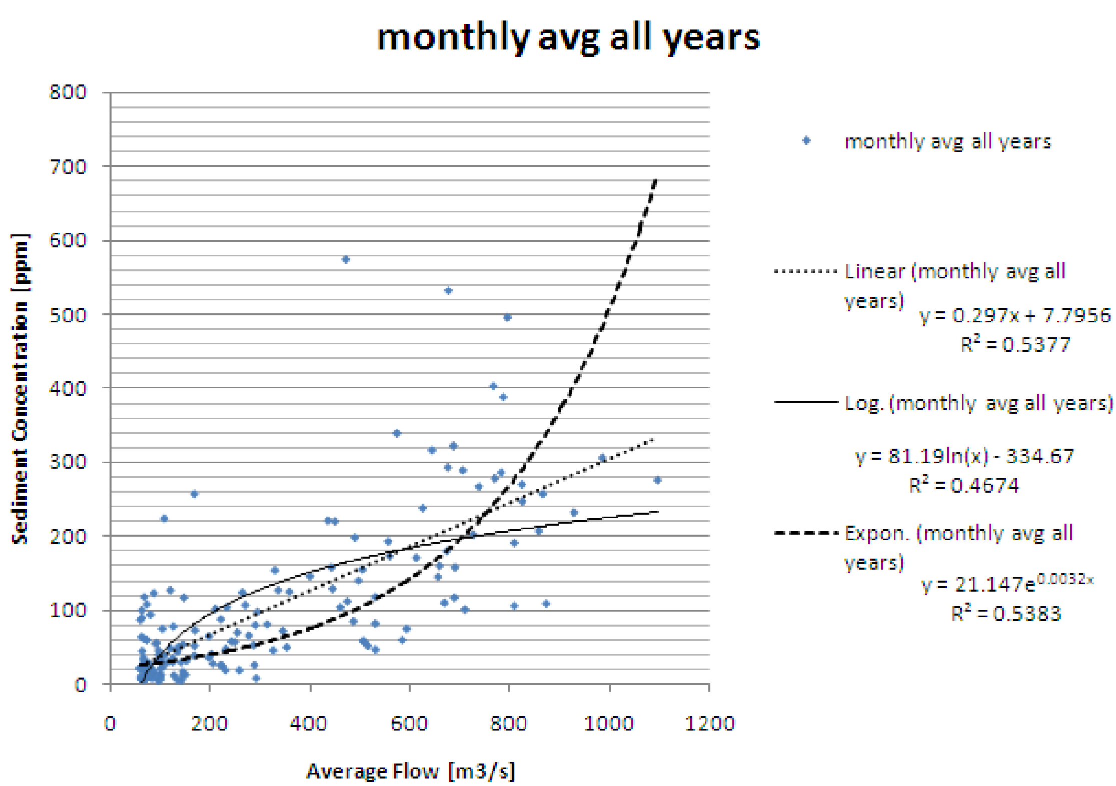

Figure 6.3: Monthly average of all years with possible trends of Punatsangchhu River.

Since the linear correlation was poor, other trends were plotted and the result is shown in Figure 6.3. From the plot, we can see that that exponential and linear trend gives a better correlation than the logarithmic trend. In the Himalayan Rivers upstream of the plains, from Pakisthan via India and Nepal to Bhutan, there are no gauging stations where a reliable and consistent sediment rating equation has been observed when reasonable sampling frequency has been applied. (Lysne et.al. 2003).

The factors affecting sediment transport in this river are topography, hydrology, climate, geology and landuse. Because of the steep topography of this area, the flow rate is quite high; this is one big reason for the erosions in this river. The rainfall which is heaviest in the monsoon months of June to September contributes significantly to the amount of sediments in the river. Erosion usually increases the sediment discharge from streams coming from the catchment; but it should be noted that not all erosion immediately shows up as sediments. Much of it moves into various temporary storages in the watershed. This is evident from the sediment data for the Punatsangchhu River also; the Glacier Lake Outburst Flood in 1994 brought in a huge load of sediment which was noticed at the gauging station a year after. The sediment transport pattern in Punatsangchu River is not known in details, but expectedly it is guided by the general characteristics of sediment processes in Himalayan Rivers i.e. having high flow and carrying huge sediment loads which vary a lot.

The altitudes within this very small country vary largely from 97 m above sea level (m.a.s.l.) in the southern sub-tropical region to 7553 m.a.s.l. in the Northern alpine region. (Central Intelligence Agency) Hence, the river flow regime can be divided into three stages. The rivers in Bhutan in their initial stages flow through narrow valleys from great height and are very energetic and fast flowing. In this stage of the river, a lot of erosion work is carried out by the river; vertical erosion dominates as the river bed is deepened. It also erodes the banks of the river through the process of lateral erosion creating deep narrow valleys.

As the rivers leave the mountains and hills, the speed of the river is reduced and the volume of water is increased. It deposits the heaviest part of its load such as small boulders and rocks. It continues to carry along small pieces of gravel, silt and mud and causes more lateral erosion than vertical erosion making the river course wider. This causes the rivers to meander and the outside edge of the bends is the place where erosion takes place mostly. During the monsoon seasons, the rain and melting snow increases the volume of water in the rivers and sometimes the neck of the meanders are cut through. This causes erosion again. (CAPSD, 1994) The point from where the data is collected lies in the inner Himalaya zone. Here the river changes gradient suddenly. Figure 6.4 shows the river near the gauging station. Higher concentration of sediments in the Punatsangchu River during the monsoon months can be explained by the above reasoning.

Figure 6.4: Punatsangchhu River near Wangdi Rapids gauging station. (Photo from Sonam Wangdi)

The annual rainfall in this area ranges from 500 to 900 mm, about 70% of which can be accounted by the rainfall in monsoon period, i.e. from June to September. Most of the meteorological stations along this river are located in the valleys which receive less rainfall compared to the rainfall on the mountains because of orographic effect. Since the rainfall data for this river basin from all the gauging stations couldn't be obtained, it was difficult to correlate rainfall with sediment load. The rainfall data available for the gauging station from which the sediment data was available could not be used to correlate with sediment load because much of the river flow is contributed from the upstream tributaries and also rainfall and snow melt in the upstream region of this river basin.

The land-use in Bhutan is dominated by forest cover of 72.5% while agricultural land consists of only 7.7% (National Statistics Bureau, 2007). About 55 % of the catchment area of this river lies in the altitude above 4000m (Pradhan, 2007) where there is very little human settlement. Most of the area above 3500m altitude lies in the alpine or sub-alpine region where the area is either covered with snow throughout the year or some vegetation cover consisting mainly of shrubs. As the river flows down into the valleys the land use is dominated by forest cover with little cultivated land. The amount of sediments contributed by erosion couldn't be quantified because of many missing data for this region.

The unmeasured load including bed load is estimated at 30% and it is not based on measurements in Bhutan. According to the WRMP, 2003; it is assumed that the Punatstangchhu River, like all rivers that originate from the Himalayas – an area of active geological uplift - will carry both a very high bed load and suspended sediment load. Studies in different regions within the Himalaya show different percentage of bed load considered ranging from 15% to as high as 50% (Sitaula, B, P. et al., 2007). The bedload calculated as in chapter 5.5 was comparable to the assumed 30% load. The difference in the results could be because of many reasons:

- The 30% assumed is not only the bedload but also the load which cannot be measured by the sampler just above the river bed.
- The calculation was based on some assumptions. The particle size distribution was an assumed distribution. The river cross section is taken to be constant throughout the year. The yearly load is calculated based on average flow.

The bedload assumed is 23% of the total load while the bedload based on shear velocity and settling velocity is 59% of the total load. Based on calculations using the Meyer-Peter formula, the bedload ranges between 14 to 51% of the total load. The suspended load calculated based on the formula mentioned in section 4.5 gave similar results to the observed suspended load from the SEDAT program. This could mean that in absence of measurements on sediment concentration, the sediment load calculation formulae can be used to obtain sediment load.

7 Conclusions

Sediment transport in the Himalayan Rivers is complex and these rivers contribute the highest sediment load to the oceans globally. Sediment sampling in the Mountain Rivers is difficult and the data available is questionable with respect to quality.

Sediment concentration varies largely with time and a major bulk of the annual sediment load may be transported within a few days and may go unmeasured at gauging site if the sampling frequency is poor. The correlation between sediment concentration and river discharge for Punatsangchu River for the year 2007 was found to be very good with an R^2 value of 0.8. The correlation of average discharge and concentration over the record period of 1993 and 1996 to 2008 was found to be 0.53. For some years the correlation was very poor with an R^2 value of 0.13. On a daily basis, the correlation is poor but for average monthly values, the correlation is very good. There are rapid and unpredictable changes in the water flow and suspended sediment concentration. Hence, river flow is not a reliable key for monitoring the suspended sediment concentration in the river. The monsoon months have both high sediment concentration and flow. About 90% of the sediment load is transported within the monsoon month of June to September.

The bed load in this sediment data is assumed as 30% which is not based on any measurements done in Bhutan. If this sediment data is to be used for predicting high sediment concentration for certain design flow, it might be better to calculate both the suspended sediment and bed load based on some measurements preferably done in this river.

The factors affecting the sediment transport in this river are the river flow, precipitation, topography, geology, climate and land use. Although it is difficult to quantify the individual effects on the sediment concentration in the river, it can be taken as a step towards better understanding of the sediment transport in this basin.

The SEDAT program used as of 2009 in Bhutan computes the suspended load based on the concentration and river discharge. In absence of measurements on sediment concentration, the sediment load calculation discussed in chapter 5.5 can be used to obtain sediment load. To get a better understanding of the sediment transport pattern in the Punatsangchhu River, it is recommended to study the factors affecting sediment transport in detail.

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