GLACIAL LAKE OUTBURST FLOOD FREQUENCY ANALYSIS IN THE SAPTA KOSHI RIVER BASIN OF NEPAL

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ABSTRACT

In recent years, Glacial Lake Outburst Floods (GLOF) has become a huge challenge for any infrastructural development in the Sapta Koshi basin, the most flood prone river of Nepal. This study presents the empirical and statistical analysis of GLOF discharges to estimate the event magnitude and frequency of its occurrence. The empirical approach requires comparison of discharge calculated using the four established methods for GLOF peak estimation with the measured peak at gauging stations. The statistical analysis involves estimation of design flood using Gumbel (EV1) distribution and the standard error associated with it. For the GLOF frequency analysis, instantaneous maximum and daily maximum discharges of the day of the event were obtained from literature and from the Department of Hydrology and Meteorology (DHM) of Nepal**.** The result based on empirical analysis shows that among the all four methods compared, the calculated discharge values using the Walder and Costa method are closest to the measured GLOF values. The probability plot shows that datasets follow the EV1 distribution quite well. Further, the flood frequency analysis shows that designed values obtained using the EV1 model and published design flood peaks of the Koshi basin lies within 95% confidence Interval. However, higher calculated design flood values in comparison to published values highlights the need of GLOF and Seasonal High Floods (SHF) to be analyzed individually. For more accurate estimation establishment of more gauging stations and regular study on GLOF is strongly recommended.

Keywords:

Glacial Lake Outburst Flood (GLOF), Sapta Koshi River basin, EV1 (Extreme Value Type I) distribution, Frequency analysis, empirical analysis, design flood, flood peak estimation

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GLOSSARY

Q	Discharge
T	Return Period
Q_T	the T year Flood
Q_{max}	Maximum Discharge
EV1	Extreme Value (Type I) Distribution
EVY1	Reduced Variate
F(x)	Cumulative Probability
F_i	Probability Plotting
R^2	Correlation Coefficient
u	EV1 Location Parameter
α	EV1 Scale Parameter
se	Standard error
RPF	Return Period Flood
cdf	Cumulative Distribution Function

1. INTRODUCTION:

1.1 Background:

Nepal is a Himalayan country and the entire country falls in the Hindu Kush Himalayan Region, which is home to 30% of the world's glaciers (ICIMOD, 2011). Due to rapid melting of glaciers in recent years, glacial hazards have become frequent in highly glaciated regions of Nepal. Since, glacial lake formation and outburst is a phenomenon closely related to glacial retreat, increasing global temperature is of great concern in climate sensitive areas, such as the Nepal Himalayas. Nepal consists of about 3,252 glaciers covering an area of 5,323 km^2 and consists of 2,323 glacial lakes with area coverage of 75.70 km^2 (Mool *et al.,* 2001).

About 25 Glacial Lake Outburst Flood (GLOF) events have been recorded in last 30 years in Nepal among which 10 GLOF events originated from Tibet causing trans-boundary impact (ICIMOD, 2011) (Refer :Table 1). Most of the outburst goes unnoticed due to the remote location of glacial lakes and inadequate stream gauging stations along the rivers of Nepal (Walder *et al.,* 1997). Though other flood and sediment disasters occur in the Koshi basin, GLOF has gained alarming attention due to huge loss of human lives, infrastructure, cultivable lands and vegetation in low lands caused by a single event. Also, GLOF causes significant impact downstream as the river profile gets shallower and wider, inundating larger areas (Sinha *et al*., 2008).

The incidence of GLOF has led to extensive study and awareness programs about GLOF in countries like Iceland, Norway, and Canada, but in the case of Nepal, only a few GLOF events have been studied in detail (ICIMOD, 2011). The major GLOF events in terms of peak discharge that took place in the Sapta Koshi River basin were outbursts of the Nagma and the Tam glacial lakes on 23 June 1980 and 3 September 1998 with peak discharge of 24,000 m^3/s and 9,800 m^3/s respectively (Refer: Table 2) (Shrestha *et al*., 2010). These peak discharges measured were several orders in magnitude greater than seasonal high floods (Refer Figure 3) and the average annual discharge of the Sapta Koshi River (Refer: Table 3) (WWF, 2005).

However, in terms of socio-economic effect, outburst of the Dig-Tsho Lake on 4 August 1985 and the Zhangzangbo Lake on 11 July 1981 was catastrophic (Refer: Table 1). Human casualties during the Dig-Tsho event were enormous, along with destruction of the Namche hydropowerplant, 14 bridges, and cultivable land. The economic loss during this event was estimated to be more than $500 million (Shrestha *et al.,* 2010). Similarly, the GLOF from the Zhangzangbo Lake in Tibet flooded the Sunkoshi basin and damaged the Arniko Highway, the Nepal-China Friendship Bridge, 10 suspension bridges, and houses with estimated rebuilt cost of $3 million (Shrestha *et al*., 2010). Though outburst of the Tam Lake had higher recorded discharge than the Dig-Tsho and the Zhangzangbo Lake outbursts, its impact on infrastructure and human lives are poorly documented (Osti *et al*., 2009).

GLOF is an extreme event and includes numerous source of uncertainty about physical processes that give rise to such event. Moreover, the rivers in Nepal are poorly gauzed and less documented, thus statistical approach for GLOF data analysis is often desirable. A frequency analysis involves determining relationship between the magnitude and frequency of extreme events by fitting the data sets to a probability distribution and extrapolating peak discharges (Chow *et al*., 1988). There are various empirical equations established using extensive data sets to estimate the GLOF peak discharge but GLOF in Nepal Himalayas cannot be accurate analyzed by this method due to lack of discharge data at site.

Table 1: Past Glacial Lake Outburst Flood (GLOF) Events in Nepal

S.N	Date	Name of lake	Location	River Basin
1	450 years ago	Machhapuchare	Nepal	Seti River
2	Aug, 1935	Taraco	Tibet	Bhote koshi
3	1956	Imja	Nepal	Dudh Koshi
4	Jan, 1964	Tiptala	Nepal	Tamur
5	21 Sep, 1964	Chubung	Nepal	Arun
6	21 Sep, 1964	Gelaipco	Tibet	Arun
7	1964	Zhangzangbo	Tibet	Sun koshi
8	1964	Longdo	Tibet	Trishuli
9	1968	Ayaco	Tibet	Arun
10	1969	Ayaco	Tibet	Arun
11	1970	Ayaco	Tibet	Arun
12	3 Sep, 1977	Nare	Tibet	Bhote koshi
13	23 Jun, 1980	Nagma Pokhari	Nepal	Tamur
14	11 July, 1981	Zhangzangbo	Tibet	Bhote koshi
15	27 Aug, 1982	Jinco	Tibet	Arun
16	4 August, 1985	Dig Tsho	Nepal	Dudh Koshi
17	12 July, 1991	Chubung	Nepal	Arun
18	3 Sep, 1998	Tam	Nepal	Dudh Koshi
19	15 Aug, 2003	Kawachi	Nepal	Madi
20	8 Aug, 2004	Kawachi	Nepal	Madi

(Adapted from: Mool *et.al,* 2001)

1.2 Objective

The purpose of this study is to estimate the peak discharge of GLOF events that took place in the Sapta Koshi River basin of Nepal using empirical and statistical methods.

Human settlement tends to increase downstream due to installation of infrastructure for flood control such as dams and embankments. But, during bigger GLOF events, such infrastructure is destroyed causing increased economic loss and human casualties. Additionally, studies show that the glacial lakes are increasing in size rapidly, increasing their potentiality of outburst and eventually increasing the frequency of GLOF events (Ghimire, 2005). Thus, determining probabilities of such events has become an integral part of designing any infrastructure or land use planning. Flood frequency analysis that has been conducted for the Koshi River basin includes discharge of both Seasonal High Flood (SHF) and GLOF (UNESCO, 2009). However, GLOF frequency analysis has not been carried out till date. Since, GLOFs are different set of data compared to SHF, analyzing it separately will improve the understanding of GLOF impact downstream.

2. LITERATURE REVIEW

GLOFs in Nepal are studied extensively by International Center for Integrated Mountain Development (ICIMOD) and World Wildlife Fund (WWF) Nepal. Accurate estimation of peak discharge of GLOF events in Nepal is a challenging task, given the lack of gauging stations and the measured discharges at site. Peak discharge of different GLOF events in Nepal has been estimated using the geomorphological method, numerical methods, and different hydrological models such as the DAM-BREAK Model and the Step-Backwater Model (Cenderelli *et al*., 2002; Cenderelli *et al.*, 2001). For instance, peak discharge of GLOF in the Everest Region in 1977 was estimated to be 1900 m^3/s and that of the year 1985 was estimated to be 2350 m^3/s by using the Step-backwater flow model (Cenderelli *et al.,* 2002).

Till date, flood analysis in the Sapta Koshi River Basin of Nepal is mainly focused on risk and vulnerability assessment, which is mostly Geographical Information System (GIS) and field study based hazard mapping (Sinha *et al.*, 2008). A study conducted by UNESCO on hazard and flood risk assessment in the Koshi Basin is the only literature available that uses the flood frequency analysis technique to assess a flood that occurred on 18 August 2008 in the Koshi River and had a huge impact in Bihar, India. The flood on18 August of 2008 was analyzed using 30 days of hydrological data from the 12 to 25th of August 2008 and compared it with flood peaks in the Koshi River during previous years (UNESCO, 2009). According to the flood frequency analysis of discharge at Chatara of Sapta Koshi, the peak discharge of flood with five year return period was estimated to be 11, 578 m^3/s using Log-Pearson III and 13,703 m^3/s using Gumbel distribution (UNESCO, 2009). The design return period for flooding in 1980 with discharge of 24,000 m^3/s was estimated to be 40-50 years (UNESCO, 2009). The paper concludes that the flood peak on 18 August, 2008 with the discharge of 4250m^3/s was not significantly high in comparison to critical flood discharge of the river and less than the magnitude of the five year return period flood of the Koshi River (UNESCO, 2009). The description of GLOF events that affected Nepal as described in different literature is given below.

2.1 Description of the GLOF events in Nepal:

a. Taraco Lake

The outburst of Taraco Lake in Tibet took place in August of 1935 causing a flood in the Sun Koshi River in Nepal (Yamada and Sharma, 1993). The outburst was caused by the collapse of an ice-cored moraine dam due to seepage, resulting in damage of livestock and cultivation land (Yamada and Sharma, 1993).

b. Imja Lake

The outburst of Imja glacial lake took place in 1956, flooding and leaving 40,000 people homeless in the Indrawati valley (Yamada and Sharma, 1993).

c. Tiptala Lake

The Tiptala glacial lake is situated in the Kanchanjungha Conservation Area (KCA) of Taplejung district (WWF, 2012). The lake is very close to the Nepal-China border and situated at an altitude of 4982 m above the sea level (WWF, 2012). The flood due to the Tiptala moraine dammed lake outburst in January of 1964 had high discharge and gradient. This event disrupted trekking trails and swept away houses (WWF, 2012).

d. Gelhaipuco Lake

The outburst of Gelhaipuco glacial lake in 1964 was triggered by glacier surge that resulted in flooding of the Arun River in Nepal and damaged the highway (ICMOD, 2011).

e. Glacial lake on Longda Glacier

The glacial lake situated at the base of the Longda glacier in Tibet caused a flood in the Gyirongzangbo river basin in Tibet and the Trisuli river in Nepal in 1964 (ICIMOD, 2011).

f. Nare Lake

The GLOF occurred on 3 September, 1988 in the Nare Lake situated below the peak of Mt. Ama Dablam due to the rapid inflow of water into Nare Lake from the small glacial lake at higher elevation, causing ice core end-moraine to overtop and discharge into the Dudh Koshi valley (ICIMOD, 2011). The GLOF caused destruction of bridges downstream and the loss of lives, property and mini hydropower plant (ICIMOD, 2011).

g. Nagma Lake

A GLOF event in the Tamor basin occurred due to the collapse of the moraine of Nagma Pokhari on 23 of June, 1980 (ICIMOD, 2011).This event destroyed villages downstream. It is listed in the potentially dangerous lake category due to its increasing size and weak moraine material with high probability of outburst (ICIMOD, 2011).

h. Ayico lake

GLOF occurred three times in the years 1968, 1969 and 1970 in the Ayico glacial lake situated in Tibet, causing flooding in the Arun River in Nepal and damage to roads and bridges (Yamada and Sharma, 1993).

i. Jinco lake

Flooding in the Arun river of Nepal occurred due to glacial lake outburst of Jinco Lake of Tibet on 27 August, 1982(Yamada and Sharma, 1993). The glacier sliding into the Jinco Lake caused moraine to collapse, eventually leading to outburst of the lake, damaging eight villages, livestock, cultivation fields, roads and bridges (Yamada and Sharma, 1993).

j. Chubung Lake

An outburst of the Chubung glacial lake in the Rowling valley took place in July 1991 (Kattelmann, 2002). The outburst of the Chubung Lake that lies at the end of Ripimo Shar Glacier happened due to end moraine dam collapse, releasing about 0.5-1 million m^3 of water, eroding the Arun River in Nepal and a few houses (ICIMOD, 2011; Kattelmann, 2003).

k. Zhangzangbo Lake

The Zhangzangbo glacial Lake that lies north of the international border in Tibet AR (China) outburst two times in 1964 and 1981, causing flood in the Sun Koshi river basin in Nepal (ICIMOD, 2011). The triggering mechanism for the outburst of the lake in 1964 was moraine collapse which caused a rise of water level to 8 m (Yamada and Sharma, 1993).The triggering mechanism for the outburst in 1981 was an ice avalanche which produced large wave to overtop end moraine, resulting in drainage with initial discharge of 16,000m^3/s and damage to the Arniko Highway and the Sun Koshi Hydropower plant of Nepal (ICIMOD, 2011; Yamada et al., 1993).

l. Tam Lake

The GLOF event in Tam Pokhari or Sabai Tsho on 3 Septemper 1998 was triggered by an ice avalanche that induced a large wave, overtopping the end moraine dam (ICIMOD, 2011). The event also resulted in the loss of lives and damages of approximately 2 million US$ (ICIMOD, 2011).The flood in Koshi barrage after the event was not recognized as GLOF until after subsequent investigation (Kattellmann, 2002).

m. Dig Tsho Lake

The outburst of Dig Tsho glacial lake at the end of the Langmoche glacier in the Khumbu Himal occurred on 4 August 1985, flooding the Bhote Koshi and Dudh Koshi valleys (Kattellmann, 2002). The outburst was triggered by a large ice avalanche of 150,000 m^3 plumbing into the lake, generating a wave of approximately 5 m high that over topped the moraine dam (Vuichard et al., 1987; Kattellmann, 2002). The lake drained for 4-6 hours with estimated peak discharge of 2,000 m^3/s (Vuichard and Zimmermann, 1987). The GLOF caused destruction of the Namche hydroelectric power plant, 14 bridges, about 30 houses, agricultural land and a loss of four to five people (Vuichard and Zimmermann, 1987).

n. Kawache lake

Two GLOF events occurred in the Kawache Lake of Nepal in 2003 and 2004 due to moraine collapse, flooding the Madi River (ICIMOD, 2011).

3. DATA AND METHODOLOGY

3.1 Data

For the study, peak discharge of seven GLOF events that took place in the Sapta Koshi Basin and measured at different hydrological stations downstream were considered (Refer Table2, Figure 1).The peak discharge of the Nagma, Tam and Dig Tsho Lake outburst are the maximum instantaneous data obtained from both literature and DHM Nepal. While for the other events, average daily discharge data was obtained from DHM Nepal. Average daily data were considered, since in the normal days, discharge is measured only once a day at the gauging stations of Nepal. Measured peak discharge values were standardized by using glacial lake area and catchment area.

Table 2: Measured GLOF Discharges at Different Gauging Stations of the Sapta Koshi Basin

Glacial lake	**Year**	**Gauging Station**	**Discharge (m^3/s)**	**Basin**
Nare	1977	Source: GAPHAZ Database	1,200	Dudhkoshi
Nagma	1980	Chatara Kothu (695)	24,000	Tamur
Zhangzangbo	1981	Pachuwarghat (630)	2,316	Bhote Koshi
Jinco	1982	Chatara Kothu (695)	4,160	Arun
Dig Tsho	1985	Rabuwa (670)	4,800	Dudh koshi
Tam pokhari	1998	Rabuwa (670)	9,800	Dudh koshi
Chubung	1991	Turkighat (604.5)	1,810	Arun

(Adapted from Shrestha *et al.,* 2010; DHM Nepal and GAPHAZ Database)

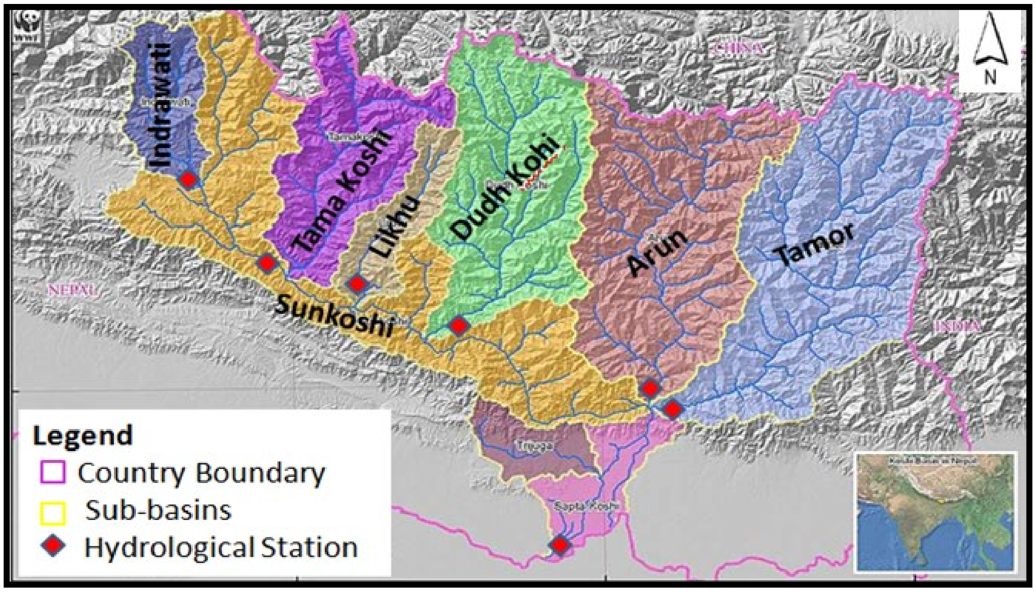


Figure 1: Hydrological Stations at the Sapta Koshi River Basin of Nepal (Modified from WWF, 2012)

3.2 Methodology

Two approaches are considered to estimate the peak discharge of the GLOF.

3.2.1 Empirical Approach

The peak discharges were calculated using four empirical equations established for GLOF peak estimation that show the volume and peak discharge relationship (Mool *et al.* 2001).

a. Clark method (For subglacial tunnel drainage)

$Q\max = 46 * V^{0.66}$ ($r^2 = 0.70$)

Where, Qmax= Peak flood discharge (m^3s^{-1})

V= Volume of the lake (m^3)

b. Walder and Costa (For Breach drainage)

$Q\max = 1100 * V^{0.44}$ ($r^2 = 0.58$)

Where, Qmax= peak flood discharge (m^3s^{-1})

V= Volume of the lake (m^3)

c. Clague and Mathew (for ice dammed lake)

$$Q\max = 113\left(V_0 * 10^{-6}\right)^{0.64}$$ (Modified equation, 1988)

Where, Qmax= peak flood discharge (m^3s^{-1})

V_0 = Total volume of water drained out from lake (m^3)

d. Desloges et.al (1989)

$$Q\max = 179\left(V_0 * 10^{-6}\right)^{0.64}$$

Where, Qmax= Peak flood discharge (m^3s^{-1})

V_0 = Total volume of water drained out from lake (m^3)

To estimate the peak discharges, values calculated using the empirical equations were compared with the measured GLOF discharge at the four hydrological stations at Rabuwa Bazar, Pachuwarghat, Turkighat and Chatara. The equations that gave the calculated discharge values closest to the observed GLOF discharges were identified for further analysis.

3.2.2 Statistical Approach

Generally, flood frequency analysis of ungauzed or poorly gauzed stations is conducted using regression analysis or using available empirical equations (Senaratne and Cunnane, 2001). Since discharges in the rivers of Nepal are poorly gauzed, estimates of magnitude and frequency for future floods can be made using available empirical equations. Thus, Gumbel or EV1 (Extreme Value Type I) distribution was used for analysis of observed GLOF discharges and estimate the flood peak discharge in the Sapta Koshi Region.

a. Gumbel Distribution or EV1 distribution:

Gumbel extreme value distribution is used to describe the distribution of peak discharges of GLOF and to model the probability of flood magnitude and frequency in the Sapta Koshi catchment. The cumulative probability function of extreme value as described by Hosking can be written as:

$$F(x) = \exp\left[-\exp\left(-\frac{x-u}{\alpha}\right)\right]$$

Where, x= discharge values

u and α are parameters of the Gumbel distribution and can be calculated by:

$$\alpha = \frac{\sqrt{6}}{\pi} * \sigma$$

$$u = \mu - 0.5772 * \alpha$$

By using these EV1 parameters, estimated peak discharges for floods of particular return period can be calculated using the equation:

$$X_T = u + \alpha\left[-\ln\left(-\ln\left(1-\frac{1}{T}\right)\right)\right]$$

Where, X_T = estimated peak discharge, T = Return Period

b. Probability plot:

Floods are random events and cannot be predicted with certainty thus need to be analyzed using probability concepts. The probability plots are particularly used to check the consistency of data sets with a distribution (Weibull, 2001). If the sample datasets plots close to straight line, it indicates that data can be fitted with the Gumbel distribution

(Flood Manager 2010). The plotting probability (F_i) for Gumbel as described in Cunnane, 1989 can be calculated by:

$$Fi = \frac{i - 0.44}{N + 0.12}$$

Where, i = rank or indicates the smallest sample member, N= sample size

And, reduced variate (EVY1) which is inverse of cumulative distribution function (cdf) is calculated by:

$$EVY1 = -\ln[-\ln(Fi)]$$

In the probability plot, data points are expected to be close to a straight line (Das, 2010). Strong deviation from the straight line indicates that the data set does not fit the particular distribution (Das, 2010).

c. Determination of best fitting empirical relationship between discharge (Q) and catchment area(A):

The best fitting empirical relation between discharge and catchment area is determined by using the equation relating Q and A as described by Griffiths and Mckerchar (2008)

$$Q = A^b$$

Where, A = (lake area/ catchment area) and b= factor (0.70 to 1)

The distribution with highest R2 value was selected to validate the relationship.

d. Estimation of standard error of Q_T:

The standard error associated with the estimate of the T year flood (Q_T) needs to be calculated as it indicates the reliability of the estimates. Standard error (se) can be calculated using scale parameter (α) determined form the observed data. The theoretical expression of se for estimates of QT, in EV1 case, is given by Das (2010) as follows.

$$se(Q_T) = \frac{\alpha}{\sqrt{n}}\sqrt{\left[1.1128 + 0.4574y + 0.8046y^2\right]}$$

And, $y = -\ln\left(-\ln\left(1 - \frac{1}{T}\right)\right)$

Where, α = the EV1 scale parameter

n = the number of observations in the sample

y= reduced variate

4. STUDY AREA

4.1 Koshi River Basin

The Koshi river basin lies in the eastern part of Nepal between the longitudes of 85° 30' and 88° 12'.The river system of eastern Nepal consists of network of seven major rivers forming the Sapta Koshi River Basin. The seven rivers are: Tamor, Arun, Dudh Koshi, Likhu, Tama Koshi, Sun Koshi and Indrawati (Refer: Figure 2) (Mool *et al*., 2001). Among the tributaries, Sun koshi, Bhote Koshi, Tama koshi and Arun Rivers originates in Tibet (Mool *et al*., 2001). There are 799 glaciers in koshi basin covering an area of about 1,410 km^2 and 1,062 lakes covering an area of 25 km^2 (Mool *et al*., 2001). Figure 2 shows the Sapta Koshi Basin of Nepal and GLOF events that has impacted this basin.

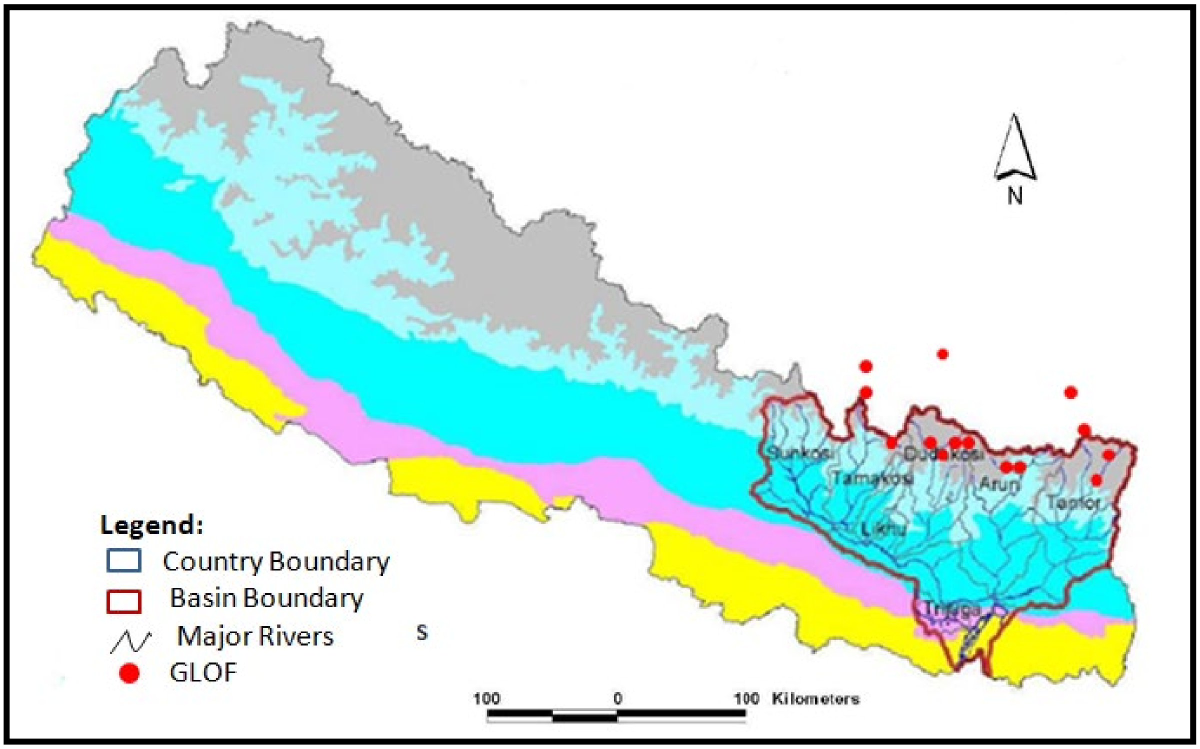


Figure 2: GLOF Events in the Sapta Koshi River Basin of Nepal (Modified from UNESCO, 2009)

4.2 Topography:

The elevation of the Koshi basin ranges from 8848m towards the north with higher channel gradient to 65 m towards the south. Due to steep slope towards the north, erosion and transportation by this river system is higher. The river channel becomes braided near Chatara and flows towards India (UNESCO, 2009).

4.3 Hydrology:

Discharges in the major rivers in the Koshi basin is characterized by low flow from October to June and high flow from July to August due to monsoonal precipitation, glacial and snow melt with average annual mean discharge of about 1400 m^3/s (Refer: Figure 3 and Table 3) (Mool *et al*., 2001). Due to high annual sediment load of 120 million m^3 carried by the Koshi

River, river channel is very dynamic and has resulted in shift of about 115 km from east to west in last 220 years (UNESCO, 2009). The high sediment load from landslide, avalanches, GLOF, and erosion is transported downstream by heavy monsoon rain (Andermann *et al.,* 2012). The annual precipitation at the Sapta koshi basin is 920 mm (Andermann *et al.,* 2012). The studies show that the lower reaches of the Koshi River basin is flattening at faster rates (UNESCO, 2009).

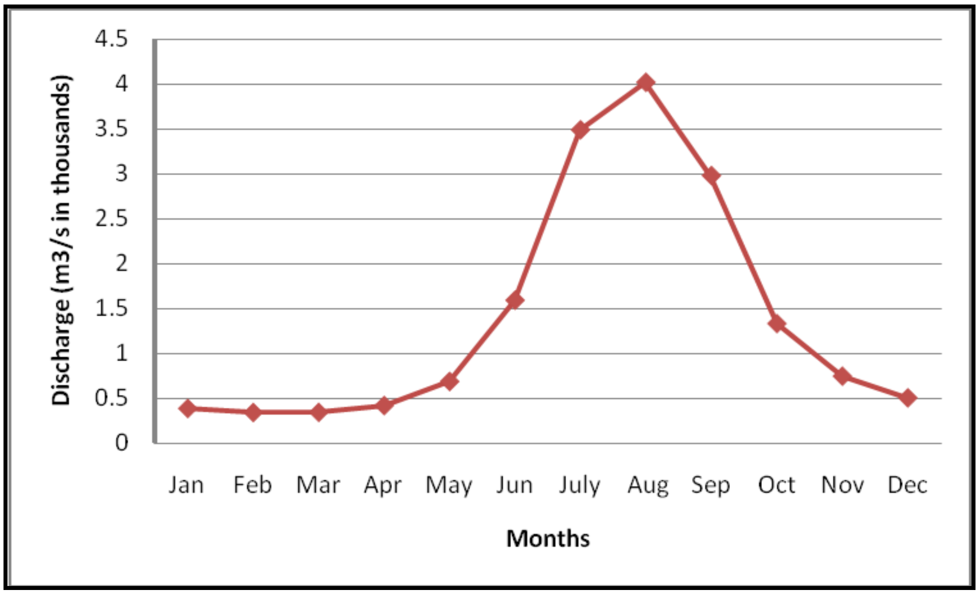


Figure 3: Monthly Discharge at the Sapta Koshi River Basin of Nepal

Table 3: Sapta Koshi Drainage Basin Characteristics

Sapta Koshi Drainage Basin	**Data**	**Source**
Drainage area (km^2)	54,100	DHM Nepal
Annual Rainfall (mm)	920	Andermann *et al.,* 2012
Annual Discharge (m^3/s)	1400	Mool *et al.,* 2001

4.4 Channel Characteristics:

The lower reaches of the Koshi River comprises of alluvial fans with prominent deposition of sediments (UNESCO, 2009). Avulsions or shifting of river channel is a common phenomenon at low flat lands (UNESCO, 2009).The slope of the upper reach is about 0.95 km and 0.03 km towards the mouth of the river (UNESCO, 2009). The sharp decrease in slope causes reduction of sediment transport and increase in deposition.

The sub-basins of the Sapta-Koshi River with higher number of GLOF events experienced are described in detail below:

4.4.1 Sapta Koshi Sub-basins:

Dudh Koshi Sub-basin:

Dudh-koshi is the major tributary of the Sapta Koshi which originates in the Khumbu and Nojumpa Glaciers of Nepal flowing north to south (UNESCO, 2009). This sub-basin has total drainage area of 4,140 km^2 and average slope of 1:30 upstream and 1:250 downstream (UNESCO, 2009).

The Dudh koshi Sub- basin has 278 glaciers covering an area of 482.2 km^2 and consists of highest number of glacial lakes among koshi sub basins with 473 glacial lakes. The glacial lakes in the Dudh koshi sub-basin are comparatively larger in size and average area than other sub-basins. About25% of the total lake area is occupied by moraine dammed lakes which has much higher peak discharges than ice dammed lakes (Mool *et al.,* 2001). The Dudh Koshi sub basin has experienced the highest number of GLOF events. The eight glacial lakes (Lumding Tsho, Dig Tsho, Chokarma Cho, Imja Tsho, Dudh Pokhari, Hungu, Tam Pokhari and Chamjang) in the Dudh koshi basin has outburst in the past but only few events are well recorded and studied.

Arun river basin:

The Arun River originates from a glacier on the northern slope of Mt.Xixabangma Feng of Tibet. The river is called Pengqu within Tibet that flows east and then south to join the Sapta Koshi at Tribeni of Nepal. The total drainage area of the river is about 36,000 km^2 of which 25,310 km^2 lies in Tibet. In Tibet, the river has a gradient of 1:130 upstream and 1:630 downstream. In Nepal, the slope gets steeper with upstream slope of range 1:30-1:50 and downstream slope of range 1:300-1:400. The Arun sub-basin consists of 91 glaciers with drainage area of 482.2 km^2 (Mool *et al.,* 2001).

The Aurn River sub-basin has experienced outburst of four glacial lakes namely Gelaipco, Jinco, Ayaco and Chubung Lake. This basin consists of glacial lakes that outburst frequently. For instance, Ayaco lake outburst three times (Refer:Table 2).

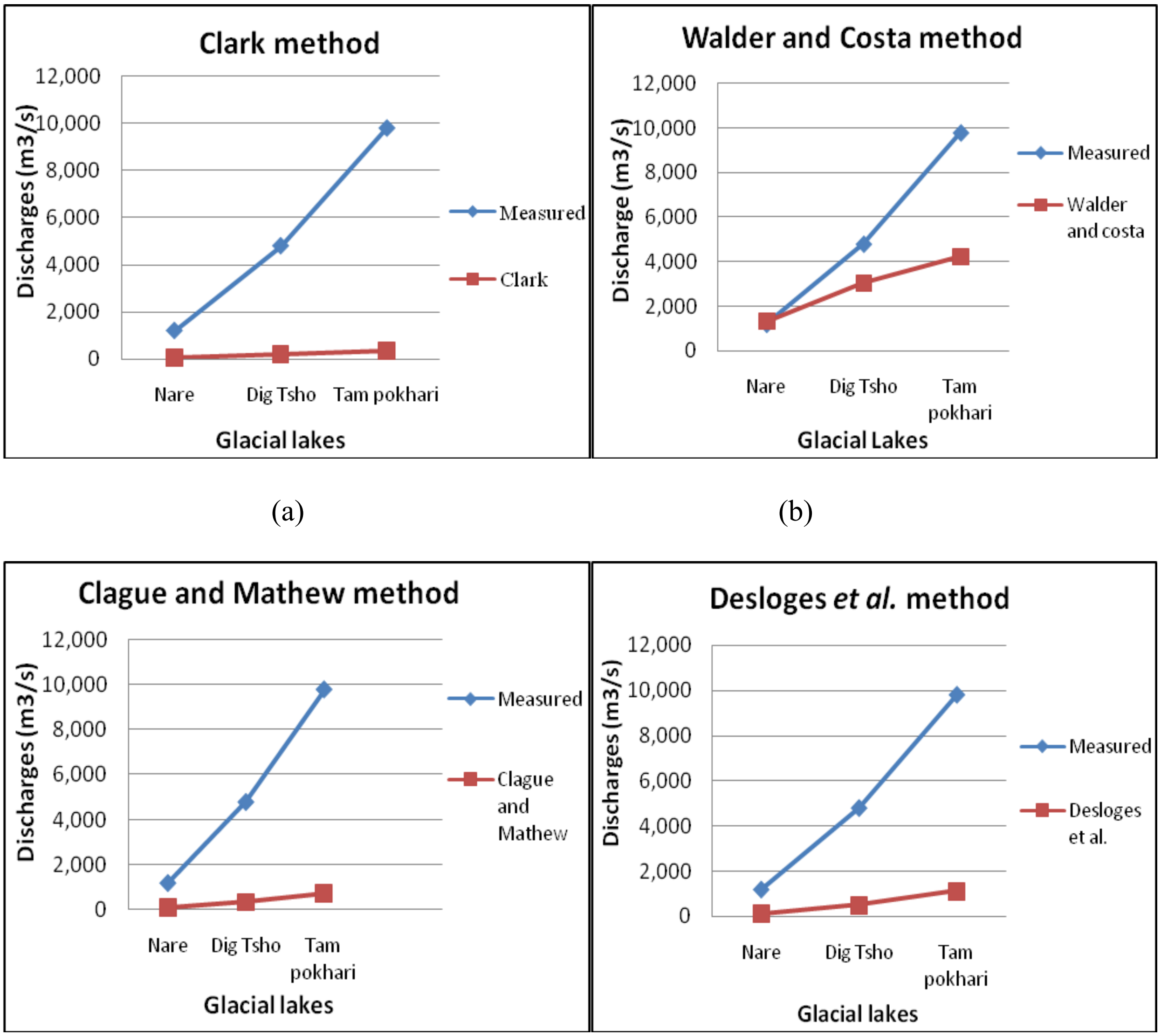
Tamur river basin:

The Tamur River originates from the high Himalayas of Nepal. The northern boundary of the catchment borders Nepal form Tibet and the eastern boundary borders Nepal from India (UNESCO, 2009). The Tamur sub-basin consists of 261 glaciers with total drainage area of 474.15 km^2 (Mool *et al.,* 2001). In this sub-basin, two events of GLOF have been recorded. Outburst of the Nagma Lake had highest peak discharge among all the GLOF events (Shrestha *et al*., 2010).

5. RESULT AND DISCUSSION

5.1 Estimation of Peak Discharge of GLOFs in Dudh Koshi Basin by Empirical Approach:

Empirical equations have been derived by Clark, Walder and Costa, Clague and Mathew and Desloges *et al.* for GLOF peak discharge estimation (Mool *et al.,* 2001). Figure 4 shows the comparison of measured peak discharge of three GLOFs that took place in Dudh Koshi Basin, with calculated peak discharges using the four established empirical equations. The measured values of GLOF discharges were compared to calculated discharges to determine the most suitable equation for GLOF peak estimation for the GLOFs in the Himalayas of Nepal.



(a) (b)

(c) (d)

Figure 4 Comparison of Observed Peak Discharges of GLOF and Calculated Discharge Using Empirical Equations: (a) Clark Method, (b)Walder and Costa Method, (c) Clague and Mathew, and (d) Desloges *et al.*

Among all the four established equations for estimation of peak discharge, the calculated discharge using Walder and Costa method was found to be closest to the measured GLOF peak (Refer: Figure 4). However, the results cannot be accurately analyzed through this approach due to lack of measured peak at site of the event. The measured peak at the hydrological station is much lower as compared to the site of the event, as in most cases, the flood peak attenuates while flowing downstream. Since conclusion cannot be made through this analysis, next approach namely frequency analysis was considered.

5.2 Estimating the Flood Peak Downstream by Statistical Approach

Probability plot is used for graphical analysis of flood data usually to determine the consistency of particular datasets with the distribution (Weibull, 2001). Figure 5 shows the probability plot of the observed discharges (Q) versus reduced variate (EVY1). The discharge values in Figure 5 are the standardized values using catchment area of the lake and the basin. To determine the best fitting relationship between discharge and catchment area, the seven factor values were considered between 1- 0.7. The factor that gave the highest correlation coefficient (R^2) value was considered for further analysis of Q and EVY1 relationship (Refer: Figure 5 and Figure 1-A).

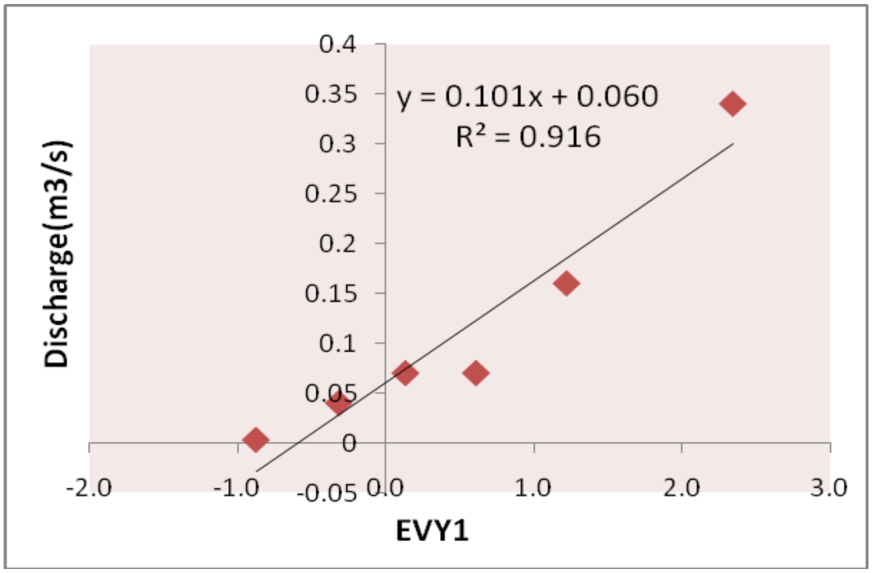


Figure 5 Probability Plot of Observed GLOF Discharge Plotted Against Reduced Variate

The graph shows that the discharge data points lies close to the straight line which indicates that the measured data of GLOF peak discharge follows EV1 distribution very well with R^2 value of 0.916 (Refer: Figure 5). The analysis of the best fitting discharge and catchment area relationship using the equation ($Q = A^b$) showed that the factor value of 1 (b=1) gave the highest R^2 value of 0.916 (Refer: Figure 5 and Figure 1-A), thus was considered for Q and EVY1 relationship analysis. The EV1 parameters α and u values were calculated to be 11684.3 and 1042.13 respectively. The Table 4 shows the design flood values calculated using the EV1 model.

Table 4 Designed Values of Return Period Flood

T (Years)	EVY1	Q_T (m^3/s)
2	0.3665129	5325
5	1.49994	18568
10	2.2503673	27336
15	2.6737521	32283
25	3.1985343	38415
100	4.6001492	54792

The Return Period Flood (RPF) values obtained using EV1 model shows that 100 years return period flood was estimated to be 54,729 m^3/s (Refer : Table 4). Based on the flood frequency analysis at Chatara of the Sapta Koshi River conducted by UNESCO, the discharge of 100 year return flood using EV1 model was estimated to be 27,415 m^3/s (UNESCO, 2009). The published RPF values is based on both GLOF and Seasonal High Flood discharges, while the RPF values obtained in this study was based entirely on GLOF discharges. The result shows that the100 year RPF values considering only GLOF discharges is almost twice the published 100 years RPF.

5.3 Evaluation of the Error Associated with Estimates of Flood Magnitude:

The standard error (se) of the estimate of the T year flood (Q_T) was calculated to test the reliability of the model. The calculated se of Q_T (Return Period Flood) is of order 36% of Q_T. The standard error values were further used to calculate the upper and lower confidence interval values. Figure 6 is a line graph showing design flood values, published design flood value, and 95% confidence interval of design flood.

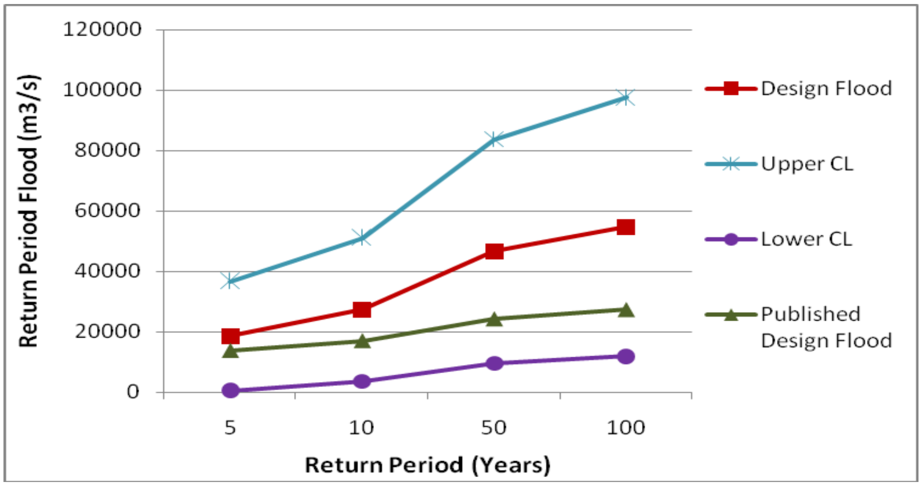


Figure 6 Line Graph of Confidence Intervals of Q_T, Designed Values of GLOF and Published Return Period Flood Values.

The graph above indicates that all the calculated and published design values falls within 95% confidence interval. However, the calculated design values are much higher than published values which points out the necessity of GLOFs to be analyzed separately for accurate estimates of future floods.

6. CONCLUSION AND RECOMMENDATION

This study was carried out to estimate the peak discharge of GLOFs in Sapta Koshi River basin of Nepal using empirical and statistical method. The empirical analysis of GLOF peak flow based on four different established methods for estimation of GLOF peak conclusively demonstrates that the calculated discharge using the equation derived by Walder and Costa gives the values closest to the observed GLOF discharge. The 100 year RPF for GLOF using the EV1 model was obtained to be 54, 729 m^3/s which is much higher than the published 100 year RPF for Sapta Koshi River Basin with a discharge of 27, 415m^3/s. However, both the values lie in 95% confidence interval. Conclusively, the result illustrates the need of GLOF events to be analyzed separately so as to get more accurate estimate of GLOF frequency and reduce its impact downstream. The following suggestions are recommended for future studies on GLOF:

- Establishing of more gauging station along the river of Nepal especially upstream
- Further detailed and regular study should be done to eliminate the data gap
- Incorporate temperature and precipitation models in analysis of floods to identify the cause of flood and evaluate them individually.

REFERENCES

Andermann, C.; Bonnet, S.; Crave, A.; Davy, P.;Longuevergne, L.; and Gloaguen, R. 2012. Sediment transfer and the hydrological cycle of Himalayan Rivers in Nepal. *Geoscience.* 344, 627-635

Cenderelli, D.A., and Wohl, E.E. 2002. Flow Hydraulics and Geomorphic Effects of Glacial-Lake Outburst Floods in the Mount Everest Region, Nepal. *Earth Surface and Landforms*. 28: 385-407. DOI: 10.1001/esp.448.

Cenderelli, D., Wohl, E. E. 2001. Peak discharge estimates of glacial-lake outburst floods and "normal" climatic floods in the Mount Everest region, Nepal. *ELSEVIER*. 40 (1-2): 57-90.

Chow, V. T., Maidment, D. R., and Mays, L. W. 1988. Applied hydrology, McGraw-Hill, New York.

C. Cunnane. 1989. Statistical distributions for flood frequency analysis. Operational hydrology report no. 33. *World Meteorological Organization*: Geneva, Switzerland.

Das, S.2010. Examination of Flood Estimation Techniques in the Irish Context. *Phd Thesis.* Retrieved on 10 April, 2013, from http://hdl.handle.net/10379/1688

Flood Manager. 2010. Flood Frequency Analysis of Annual Maximum Series. *Flood Manager*. Retrieved on 14 March, 2013, from http://daad.wb.tu-harburg.de/?id=328

GAPHAZ. Glacier and permafrost disasters in mountain regions. *GAPHAZ Database.* Retrieved on Feb 28, 2013, from http://maps.google.com.bd/maps?hl=en&rlz=1C2CHJW_enBD479BD479&bav=on.2,or.r_gc.r_pw.r_qf.&bvm=bv.41642243,d.aGc&biw=1280&bih=639&q=http://www.mn.uio.no/geo/english/research/groups/remotesensing/projects/gaphaz/database/gaphaz_new.kmz&um=1&ie=UTF-8&source=websearch

Ghimire, M. 2005. Review of Studies on Glacier Lake Outburst Floods and Associate Vulnerability in the Himalayas. *The Himalayan Review*. 35(36):49-64.

Griffths, G. A., and Mckerchar, A.I. 2008. Dependence of flood peak magnitude on catchment area. *Journal of Hydrology*. 47(2): 123-131.

Higuchi, K.; Watanabe, O.; Fushimi, H.; Takenaka, S.; and Nagoshi, A. 2010. Glaciers of Nepal-Glacier Distribution in the Nepal Himalaya with Comparisons to the Karakoram Range. *U.S.Geological Survey Professional Paper.* 1386-F-6.

Hosking, J.R.M, and Wallis, J.R. 2005. Regional Frequency Analysis: an approach Based on L-Moments. Cambridge: Cambridge University Press.

Huggel, C.; Haeberli, W.; kaab, A.; Bieri, D.; and Richardson, S. 2004. An assessment procedure for glacial hazard in the Swiss Apls. *NRC Research Press.* Retrieved on 14 March, 2013 from, http://folk.uio.no/kaeaeb/publications/huggel_cgt04.pdf

ICIMOD. 2011. Glacial Lakes and Glacial Lake Outburst Floods in Nepal. *ICIMOD*. Retrieved December 10, 2012, from http://www.icimod.org/dvds/201104_GLOF/reports/final_report.pdf

ICIMOD. 2011. New Reports Identify Impacts of Climate Change on World's Highest Mountains. *Science Daily*. Retrieved March 12, 2013, from http://www.sciencedaily.com/releases/2011/12/111204144656.htm

Kattelmann, R. 2003. Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard? *Natural. Hazards,* **28**(1),145–154.

Mool,P.K., Bajracharya, S. and Joshim S. 2001. Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods: Monitoring and Early Warning Systems in the Hindu Kush Himalaya. Kathmandu: International Center for Integrated Mountain Development.

Osti, R. and Egashira, S. 2009. Hydrodynamic characteristics of the Tam Pokhari Glacial Lake outburst flood in the Mt. Everest region, Nepal. *Wiley*. 23: 2943-2955. DOI: 10.1002/hyp.7405

Senaratne, S., and Cunnane, C.2001. Assessment of model error in regression estimates of floods at an ungauged site. *IAHS*. 272:355-361.

Shrestha, A.B., Eriksson, M., Mool, P., Ghimire, P., Mishra, B., and Khanal, N.R. 2010. Geomatics. *Natural Hazards and Risk*. 1(2): 157-169. DOI: 10.1080/19475701003668968

Shrestha, B.B., Nakagawa, H., kawaike, K., Baba, Y. and Zhang, H. 2010. Glacial Lake Outburst due to Moraine Dam Failure by Seepage and Overtopping with Impact of Climate Change. *Annuals of Disaster Kyoto University*. Retrieved February 2, 2013, from http://www.dpri.kyotou.ac.jp/nenpo/no53/ronbunB/a53b0p61.pdf

Sinha, R., Bapalu, G.V., Singh, L.K. and Rath, B. 2008. Flood Risk Analysis in the Koshi River Basin, North Bihar using Multi-Parametric Approach of Analytical Hierarchy Process(AHP). *Springer.* 36: 335-349.

UNESCO. 2009. Rapid Hazard and Risk Assessment Post-Flood Return Analysis. *UNESCO*. Retrieved Feb 3 2013, from http://un.org.np/node/10595

Vuichard, D. and M. Zimmermann. 1987. The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal:cause and consequences. *Mt. Res. Dev.,* **7**(2), 91–110.

Walder, J., Fountain, A. 1997. Glacier Generated Flood*.* *IAHS*. 239:107-113.

Wang, X.; Liu, S.; Ding, Y.; Guo, W.; Jiang, Z., Lin, J.; and Han, Y. 2012. An approach for estimating the breach probabilities of moraine- dammed lakes in the Chinese Himalayas using remote- sensing data. *Nat. Hazards Earth System. Science.* 12, 3109-3122, Doi: 10.5194

Weibull, W. 2001. Relaibility Basics. *Relaibility Engineering Resources.* Retrieved on Mar 2, 2013, from http://weibull.com/hotwire/issue8/relbasics8.htm

WWF. 2005. An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India and China. *World Wildlife Fund*. Retrieved January 21, 2013, from http://www.wwf.or.jp/activities/lib/pdf_climate/environment/Overview_of_Glaciers.pdf

Yamada, T. and C.K. Sharma. 1993. Glacier lakes and outburst floods in the Nepal Himalaya. *IAHS Publ.* 218 (Symposium at Kathmandu 1992 – *Snow and Glacier Hydrology*), 319–330.

APPENDIX

Table 1-A: Lake and Discharge volume of GLOF in Dudh Koshi Basin along with measured peak

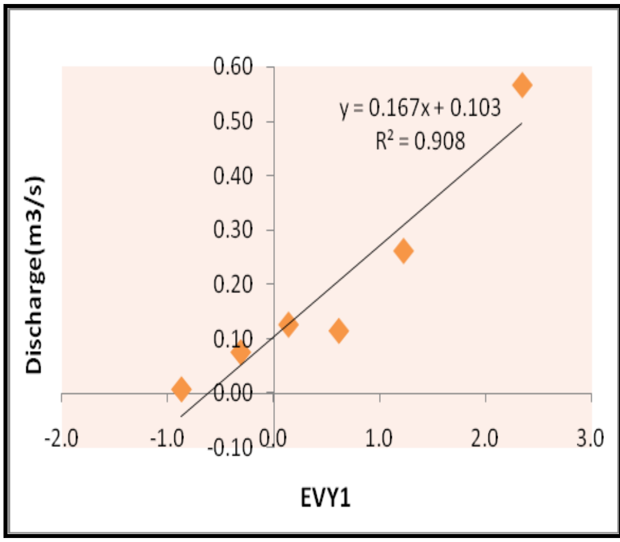
Lake	Measured Peak discharge (m3/s)	Lake Volume (million m3)	Volume discharged (million m3)
Nare	1,200	1.5	0.5
Dig Tsho	4,800	10	5
Tam pokhari	9,800	21.25	17.66

(Adapted from GAPHAZ database; Higuchi *et al.*, 2010; Shrestha *et al.*, 2010; Huggel *et al.*, 2004; and Wang *et al.*, 2012)

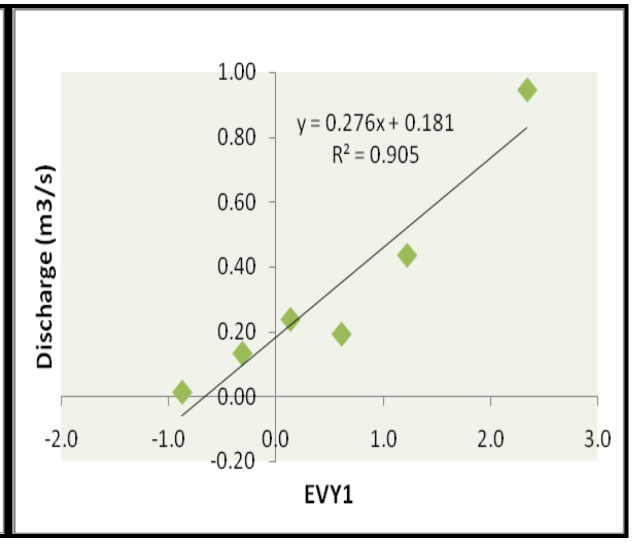
Table 2-A: Catchment area of basins and glacial lakes

Lake	Year	Discharge (m3/s)	Basin Area(km2)	Lake area (km2)
Chubung	1991	1810	28200	0.053
Jinco	1982	4160	54100	0.546
Nagma	1980	24000	54100	0.149
Zhangzangbo	1981	2,326	4920	0.143
Dig Tsho	1985	4480	4100	0.143
Tam	1998	9980	4100	0.139

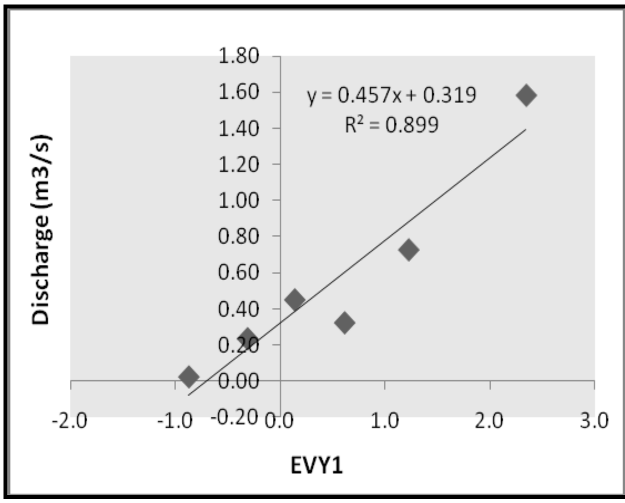
(Adapted from Shrestha *et al.*, 2010; DHM Nepal; Mool *et al.,* 2001)


y = 0.167x + 0.103
R^2 = 0.908
Discharge(m3/s)
EVY1

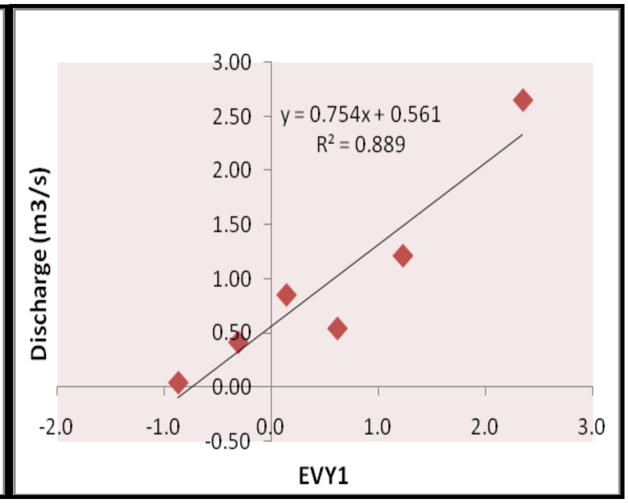
(i)


y = 0.276x + 0.181
R^2 = 0.905
Discharge (m3/s)
EVY1

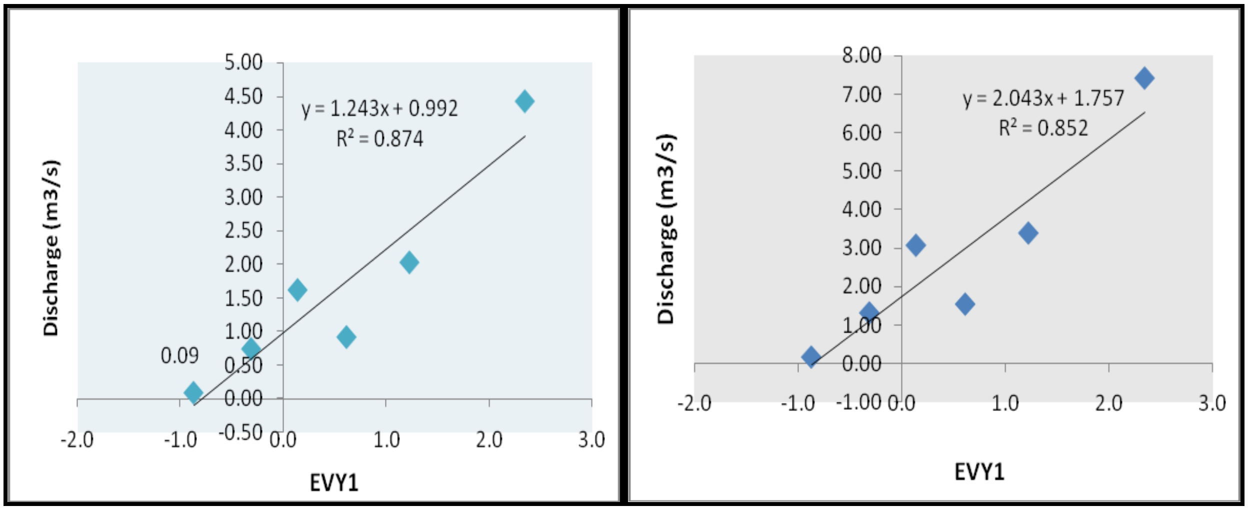
(ii)


y = 0.457x + 0.319
R^2 = 0.899
Discharge (m3/s)
EVY1

(iii)


y = 0.754x + 0.561
R^2 = 0.889
Discharge (m3/s)
EVY1

(iv)



(v) (vi)

Figure 1-A: Discharge and Catchment Area Relationship with different factor values: (i) b=0.95, (ii) b=0.90, (iii) b= 0.85, (iv) b= 0.80, (v) b=0.75, and (vi) b= 0.7

Table 3-A: Standard error and confidence interval of Q_T

T (Years)	EV1y	Q_T (m^3/s)	Standard Error	UCL	LCL
2	0.3665129	5325	5597.51	16520	-5870
5	1.49994	18568	9446.19	37460	-324
10	2.2503673	27336	12765.12	52866	1806
15	2.6737521	32283	14730.17	61743	2823
25	3.1985343	38415	17216.32	72848	3982
100	4.6001492	54792	24002.32	102796	6787