SATELLITE RAINFALL ESTIMATES VALIDATION AND APPLICABILITY IN DISASTER MANAGEMENT

A Dissertation Submitted to the Institute of Science and Technology, Tribhuvan University in Partial Fulfillment of the Requirement for the Masters Degree in Environmental Science (Water Resource Development and Planning)

MADAN KRISHNA SUWAL

Symbol No 1284

T U Registration No.: 5-1-12-33-98

Khwopa College

Affiliated to Tribhuvan University

Dekwacha, Bhaktapur – 5

December, 2007

Acknowledgements

My supervisor Dr Binod Shakya is an integral part of the thesis. I would like to express my sincere gratitudes to him for his supervision, guidance and continuous encouragements.

I also would like to express my sincere thanks to Mr Sagar Ratna Bajracharya (ICIMOD), Mrs Mandira Shrestha (ICIMOD) and the Water Hazard and Environment Management Department (WHEM, ICIMOD) for providing me the SRFE data; Department of Hydrology & Meteorology (DHM/GoN) for providing me the rainfall data of different stations; Department of Water Induced Disaster Prevention (DWIDP/GoN) for providing me the disaster data.

Thanks are also due to Khwopa College giving me the permission to undertake this research. I also would like to thank my collegue Mr Sushil Dangol & Mr Resham Baniyan for supporting in GIS, NGO Forum for Urban Water and Sanitation for providing me stationery support, Mr Hari Sundar Suwal and Mr Shiva Bhakta Basukala for helping me to correct the draft copy. Red Panda Network-Nepal (RPN-N) is highly encouraged for providing me the essential softwares and stationery.

Last but not the least I would like to remember the continuous support of my family and relatives throught my study period.

Madan Krishna Suwal

M Sc Environmental Science

Khwopa College

December, 2007

Abstract

Rainfall is variable environmental component. Its measurement and management is vital for the social welfare. There have been different methods developed for the measurement of it, from ancient period. Still, there is lack of reliable and real time rainfall data. The satellite rainfall estimate (SRFE) is emerging as an alternative method for the real time rainfall data. Many researches have been carried out for the reliability test of satellite rainfall estimate and different tests have been preformed for the validation of the satellite rainfall. In this study, Depth Area Duration (DAD) equation was used for the interpolation of point rainfall into areal rainfall. Then, validation for monthly cumulative rainfall, seasonal rainall and daily rainfall was perfomed. The monthly SRFE had better estimations compare to daily rainfall and followed by the monsoon seasonal rainfall. The daily SRFE can not be used in flood warning mechanism as it has significant erorros and low correlation coefficient.

Key words: SRFE, rain gauge, validation, disaster, DAD, point rainfall

Acronyms and Abbreviations

AD	Anno Domini
ANN	Artificial Neural Network
BAR	Basin-wide Average Rainfall
BC	Before Christ
cm	Centi-meter
CPC_RFE	Climate Prediction Center Rainfall Estimation
CTTa	Cloud Top Temperature-a
DAD	Depth Area Duration
DHM	Department of Hydrology and Meteorology
DLTE	Dependence Line of Topographic Elevation
GIS	Geographic Information System
GPCP	Global Precipitation Climatology Project
GPI	GOES Precipitation Index
GTS	Global Telecommunication System
HMG	His Majesty's Government
ICIMOD	International Center for Integrated Mountain Development
IR	Infrared
K	Kelvin
MAE	Mean Absolute Error
mm	Millimeter
NGOs	Non Governmental Organizations
NOAA.	National Oceanic and Atmospheric Administration
NWP	Numerical Weather prediction
QPF	Quantitative Precipitation Forecast
RMS	Root Mean Square
RMSE	Root Mean Square Error
SD	Standard Deviation
SRFE	Satellite Rainfall Estimation
SSM/I	Special Sensor Microwave/Imager
TRMM	Tropical Rainfall Measurement Mission
US	United State
VDC	Village Development Commettee
VIS	Visible
WMO	World Meteorology Organization

Table of Content

List of Tables

List of Figures

Chapter I

Background

Water in the form of precipitation is a valuable commodity and therefore monitoring of it, and subsequent management of freshwater resources is economically important. Unfortunately, rainfall, unlike other meteorological parameters, is highly variable both spatially and temporally, with precipitation limited to a few percent of the earth's surface water at any one time.

Chyurlia (1984) found the average area-weighted annual precipitation for Nepal is about 1630 mm, with half of the country lying within the 1500 to 2000 mm precipitation zone. Both the temporal and spatial variations in precipitation are highly pronounced. Nearly 80% of all precipitation occurs during the monsoon (June – September), with 8% falling during the post-monsoon (October – January) and 12% during the pre-monsoon periods (Chalise & Khanal 1996; Chyurlia 1984). The intense rainfall in Nepal is mainly caused by two synoptic situations, one is 'break monsoon' in India and the other is the track of monsoon depression towards Nepal (Shakya 1998). Due to the high amount of rainfall in the short course of time, numerous flash floods and many landslides occur in this short span of time.

Most of the disasters caused by natural phenomena are either hydrological or weather related. It shows that the hydrological and meteorological services at national as well as at international level have been contributing towards disaster mitigating activities and have a very important role to play in future. Hydrological and meteorological information is essential in planning and design of any disaster mitigation scheme or in zoning disaster prone areas. On the other hand, real time precipitation data is must for early warning system during the flash flood. In case of Nepal, there is lack of real time data for early warning on flood due to technological lag.

Most of the landslides occur in late monsoon while the flash floods occur right after the rainfall or at the same time simultaneously with rainfall. Many lives and property losses occurs during the flash flood. The control of flash flood is quite difficult; in spite of this, the losses can be reduced simply by warning the local peoples about the flash flood by estimating the rainfall in upstream with real time data. The rainfall distribution is not even throughout the nation. The central part faces higher amount of rainfall followed by the eastern parts and less by the western part of Nepal.

There have been 34 times of natural disasters of importance in the world since 20th century, 19 of which occurred in Asia and flooding and Hurricane to produce widespread damage and death occurred 11 times. Most of the hazards occurred in China, Bangladesh and India. The losses from the floods were very large caused many deaths. There were 5 times in which the deaths were more than 100 thousands, and 2 times 50 thousands or more, no less than disaster of earthquake and volcanic eruption (Chen 1991).

There is no way to prevent the natural disaster with the available technology. The only action that can be taken is to minimize the adverse consequence of such hazards. It has been successfully done in many parts of the world with adequate hydrological and meteorological forecasts and warnings.

Introduction

Surface-based observation of precipitation is accomplished primarily by rain gauges and, where economically viable by radar. Over the world's oceans, these measurements are often non-existent, and even over the land areas the coverage from surface observations is not uniform. Nepal's hydro-meteorological network is still poor; the existing observational network is not capable of capturing the diversity of the mountain landscape, and there are difficulties in the generalization of weather and climate because there is little or no long-term data beside the topographic heterogeneity. Methodological problems in generating data and a poor understanding of flow-path dynamics, water balance, and highland-lowland interaction have created problems in accurately predicting the magnitude of natural hazards. Special efforts are therefore required to improve the understanding of hydro-meteorological processes and the thresholds for different types of natural catastrophe.

Estimates of rainfall from satellite data address this shortcoming in that they provide spatially uniform coverage over both land and ocean; however, comparisons between the available surface observations and satellite-based estimates are complicated by the nature of the measurements from rain gauge data. Rainfall is conventionally measured as an integral of time at a point in space, whereas satellites measure an integral of space at a point in time. Radars can provide measurements similar to satellite-based systems, but suffer from reflectivity to rain-rate conversion errors and limited spatial coverage (Kidd *et al.* 2003). The timely data can be used in weather forecasting as well as in the prediction of precipitation induced upcoming disaster such as flash flood, dam operation, debris flow, and landslide.

Statement of the Problem

Nepal lies in monsoon zone, most rain falls over short time period of 3 to 4 months (Chalise & Khanal 1996; Chyurlia 1984). To measure the rainfall throughout the nation, Nepal has 422 rain gauge stations (Department of Hydrology and Meteorology). Shakya (2004) says, these rain gauges measure 24 hourly cumulative point rainfalls. They are ground-based stations. These stations cannot share the rainfall data rapidly to the center in Kathmandu i.e. real time data is not available from those rain gauges. The extensive rainfall within short duration causes flood in low land, water logging in agricultural fields, landslides in slope lands. The delay in sending these data makes difficult in predicting the flood in the downstream of the basin. On the other hand, the 24 hourly data is not useful on estimating the flash flood on the basin. To overcome these situations and for the pre-hand preparedness the reliable and immediate real time rainfall data is must. Due to the technological lag, Nepal is facing many lives and property loss during the flash flood that might be prevented at the presence to the rapid data processing. There is an increasing demand for improved rainfall estimates from satellite systems throughout the range of scales in space and time, from global–climate down to local–instantaneous resolutions. Applications requiring rainfall products cover a range of hydro-meteorological sciences, including water resources, flood forecasting, numerical weather prediction, and moisture budgets.

Satellite rainfall estimation is new branch of precipitation study in the world. Nepal does not have its own satellite and must rely on the satellite rainfall estimated from international weather satellites. There is very less studies on this aspect in Nepal. Hence, this thesis focuses on the application of satellite rainfall in disaster management.

Research Questions

1. How to compute the rainfall at a place where rain gauge is not installed?
2. What role the satellite rainfall can play in disaster management?

Scope of the study

This study comprised the validation of monthly cumulative rainfall of satellite estimates of year 2006 and 2007, daily rainfall estimates validation of year 2007 till September and seasonal rainfall validation of the monsoon season of year 2006 and 2007. There are different interpolation methods for conversion of point rainfall to areal rainfall such as IDW, Kriging, etc. In the present study, for the validation of the SRFE the point rainfall of raingauge was converted to areal rainfall by using Deapth Area Duration equation for the first time. There are 422 raingauge station under DHM throughout Nepal. Out of those only 20 raingauge stations that share the daily rainfall with the center DHM were used in validation of the SRFE. The drought analysis or climate change analysis from the SRFE is out of scope of this study.

Chapter II

Literature Review

This chapter deals with the available literatures on rainfall, rainfall measurement methods and application of the rainfall in disaster management yet. This chapter is divided into three parts namely; rainfall measurement methods in ancient era, rainfall measurements in modern era and disaster management.

Rainfall Estimation in Ancient Time

The Vedic Aryans had not hit upon any technique for measurement of rainfall over their region by carefully recording the number of rainy days during the rainy season. Balkindi (1996) found that the 'figure 49' is repeated in almost all the *mandals* of the Rigveda. It is a figure arrived at by a product of 7 days of week multiplied by 7 weeks of rainy season. He concluded that in the western parts of Punjab (now a part of Pakistan), even today, the normal dates of onset (15 July) and withdrawal of monsoon (1 September), as compiled by the Indian Meteorological Department, clearly indicate a period of 49 days (both dates included) during which the seasonal quantum of rainfall is received. This act testifies to a remarkable continuity of a weather phenomenon such as rainfall, from 7000 BC to present day, i.e. a period of approximately 9000 years.

The book Kautiliya's Artha-Sastra was compiled by Vishnugupta Chanakya who lived around 327 – 326 BC {(Bhave 1991); (cited in Balkundi 1998)}. *Artha* means the sources of livelihood of man which in that age was land inhabited by him. Gains from this land and the ways for maintaining the fertility of land are the main subjects of the Artha-sastra (Chapter 15.1; 1-2). In *Adhyaya* 24 and *Prakaran* (Subject) 41 of Artha-sastra, the technique for measuring rainfall during the 4th century BC is described in detail {(Datar 1991) cited in (Balkundi 1998)}. In this technique, a circular vessel, having a diameter equal to the length of a human arm (that is equal to the distance measured by the widths of twenty fingers of a human hand), and a depth equal to the distance measured by the widths of eight fingers (in modern units the width would be approximately 38cm and the depth 13cm), was used to measure rainfall. When the vessel was filled with rainwater collected in open space, rainfall was 50 *palas* or one *adhaka.* Four such *adhakas* made one *drona* of rainfall. The distribution of rainfall in different parts of India during the period is also recoded in Artha-sastra (table below) (Balkundi 1998).

Table 1: Distribution of rainfall during rainy season in the 4th century BC in India

Ancient name or region	Modern name of region	Amount of rainfall	
		In ancient units	In modern units
Ashmaka	Northern inland Maharashtra	13 *dronas*[1]	83.2 cm
Aratta	Southern inland Maharashtra	13.5 *dronas*	86.4 cm
Avantika	Ujjain city in Madhya Pradesh	23 *dronas*	147.2 cm
Malwa	Konkan (coastal Maharashtra)	23 *dronas*	147.2 cm
Aparanta	Himachal Pradesh	Unlimited[2]	
Hilly areas in the North[3]		Unlimited	
1. *1 drona = 6.4 cm*			
2. Beyond measurement			
3. Receive snowfall in winter			

Varahamihira around 505 AD described method for measurement of rainfall in “Varahamihira“ in Chapter 23 entitled "Pravarshan Adhyaya" (Chapter on rainfall) on his book (cited in Balkundi 1998; Bhat 1993). A circular vessel with a diameter equal to one (human) arm or the distance measured by the width of 20 (human) fingers and with a depth equal to the distance measured by the width of eight fingers should be accepted for measurement of rainfall. When this vessel is completely filled with rainwater, the rainfall should be equal to 50 *palas* or one *adhaka.* This method has been explained by Seer Parasher (see the box below). Using this method of conversion, we can relate the data given in Kautilya's Artha-sastra to modern units. Thus, the amount of rainfall received by inland Maharastra and Malwa in the fourth century BC or even earlier is estimated in modern units (table above).

According to Parashar (cited in (Balkundi 1998) the basic units of rainfall is *adhaka.*

1 *adhaka* = 17600 ÷ 7 = 2514 cubic fingers = ¼ *drona*---------------------- (eq.1)

Volume of the vessel = $Лr^2d = 3.14 \times 10^2 \times 8 = 2512$ cubic finger------------ (eq.2)

Three units were used to measure rainfall in ancient India, *pala, adhaka* and *drona* (50 *pala* = 1 *adhaka* = ¼ *drona*).

These ancient units can be related to the modern ones using the relation 2514 cubic fingers of rainwater or 1 *adhaka* is equal in weight to 11 oz or 311.85 g . As 1 cc of water weighs 1 g, so

1 adhaka = 2514 cubic fingers = 311.85 cc----------------------- (eq. 3)

In a modern rain gauge with a 200 cm^2 container, volume of 1 cm of rainwater collected is: 200 $cm^2 \times 1$ cm = 200 cm^3 = 200 cc------------------------- (eq. 4)

Based on equation 3, rainfall measured using the ancient method could be related to modern units as:

1 *adhaka* = 311.85 ÷ 200 = 1.6 cm

[i.e., volume of rainwater ÷ area of container = amount of rainwater collected (see eq. 4]

Form equation 1 and 5:

1 *drona* = 4 *adhakas* = 6.4 cm

Similarity in the technique for measurement of rainfall by both Chanakya and Varahamihira confirms our opinion that this technique, invented during the period earlier than the fourth century BC, remained unchanged even in the sixth century AD, more than one thousand years later.

Rainfall Measurements in Modern Era

In general, rain gauge observations yield relatively accurate point measurements of precipitation but also suffer from sampling error in representing area means and they are not available over most oceanic areas and undeveloped land regions. For these reasons studies are going to be largely developed over the central area of the island where data seem to be more consistent and more numerous (Michaelides *et al.*).

Shih (1989) indicated that there is a non-linear relationship between the increase in number of gauges and the improvements in accuracy. A dense network is costly to maintain and operate. While the rain gauge network continues to be the principal method at present, Remote Sensing technique could provide a more rapid and comprehensive overview of a given area. Thus, the feasibility of using a remote sensing technique to estimate the rainfall is in urgent need of investigation.

Tsonis and Georgakakos (2005) assumed that rainfall amount, radiation in the visible (VIS), and radiation in the infrared (IR) are three of the variables of the climate system, which is high dimensional. By trying to estimate rainfall from only visible and infrared images, in effect we are trying to estimate a response from information from just a few other observed variables of the climate system. Truly enough, the amount of rainfall is related to how thick the clouds are (visible count) and how tall the clouds are (infrared count). However, precipitation depends on many other factors. As such, estimating precipitation from information in the visible and infrared frequency domain only represents estimation in a much lower state space.

Liu et al (2000) found that the accurate retrieval of rainfall intensity from satellite data must involve the scattering and emission signals, respectively, which makes the retrieval process complex. There has always been problem that the sensors mounted on satellites measure a vertical column, but that raindrops or ice particles aloft do not fall to the ground instantly. It is thus only meaningful to compare the rain gauge–measured rainfall intensity with those retrieved from satellite data for a certain period. However, what is the optimal period? It is difficult to answer this question for satellite data because of the poor time resolution.

The use of conventional rain gauge measurements in flash flood watches and warnings systems applications is limited because their distribution is sparse and not available in mountain and scarcely populated areas. Meteorological radar data have their own limitations; the extensive network in the US is effected by ground clutter (both urban and mountain), attenuation problems, beam overshoot, and varying Z-R relationship associated with different precipitation regimes. However, satellite derived rainfall rate estimates are available every 15 minutes at a 4 km spatial resolution and thus can assist in the detection of flash flood and heavy precipitation areas in real time (Vicente *et al.* 2001).

Satellite rainfall estimate is a significant method for rainfall measurements. Compared with conventional gauges data, it can provide real-time information. Moreover, the satellite divided rainfall amounts are the only data we can get over oceans and deserts. Its results revealed that its error is 30% for daily maximum rainfall estimate, and their correlation coefficient is 0.69 in orographic regions. It is reasonable to guess that this technique will perform better when applied in plains where the weather systems are relatively uniform (Zongyi *et al.* 2004). However, there are some problems still existing in satellite rainfall estimates:

1) Low spatial resolution: In middle latitudes, the area of one pixel covers tens of square kilometers in which the convective rainfall activities as well as the rain rates can be quite different.

2) The terrain effects have to be considered in the rainfall estimates.

3) Convective cloud top temperatures do not express rain rates physically. Compare to radar and microwave methods that can detect the droplets in clouds, the satellite rainfall estimates are more difficult.

A great number of investigations on rainfall-elevation relationships have been conducted from the beginning of the 20th century (e.g., Lee 1911; Alter 1919; Henry 1919). According to them, it is already evident worldwide that climatological rainfall typically increases with topographic elevation {(Alter 1919; Donley and Mitchell 1939; Lull and

Ellison 1950; Burns 1953; Peck and Brown 1962; Houghton 1979; Osborn 1984; Daly et al. 1994; Brunsdon et al., 2001) cited in (Zongyi *et al.* 2004)}.

The Artificial Neural Network (ANN) algorithm is compared with a more conventional satellite estimation algorithm and with a multiple linear regression one having the same inputs as the ANN algorithm. As a second step the ANN based algorithm has been experimented in mid-latitude regions for instantaneously rainfall estimation using both infrared and microwave satellites measurements. The ANN based algorithms experiments show a good capability in reproducing the precipitation observations and this is confirmed as well by the satisfactory performances of the hydrological model simulation in case of flood alert when the estimated rain is assimilated into it (Coppola *et al.* 2005).

The linear relation of 'Dependence Line on Topographic Elevation' (DLTE) can be formed in partitioned mountain slopes, which are limited in the spatial scale. The DLTE represents rainfall-elevation relationships clearly by partitioning mountains. The spatial scale of partitioned mountain slope does not have much effect on whether the linear relation of DLTE is formed or not on a partitioned mountain slope around an object grid. Accumulated rainfall, however, does on the contrary. The optimum spatial scale was found to be the scale represented by the influence radius of 40 km approximately. The values of RMSE and SD around DLTE had a tendency to differ noticeably between the eastern and western side of mountains; relatively small on the western side. Thus, the linear relation of DLTE can be formed clearly on the western side of mountains but not so well in the eastern side (Suzuki *et al.* 2004).

Wei & Cheng (2005) found Cloud Top Temperature-a (CTTa) from satellite imagery and ground hourly rainfall records were medium correlated. The regression coefficient ranges from 0.5 to 0.7 and the value decreases as the altitude of the gauge site increases. The regression coefficient of CTT and next 2 to 6 hour accumulated Basin-wide Average Rainfall (BAR) decrease as the time scale increases. The rainfall forecasting for BAR were analyzed by Kalman Filtering Technique. The correlation coefficient and average hourly deviates between estimated and observed value of BAR for two typhoon events were 0.619, 0.478 and 6.488 mm, 8.722mm respectively. The result shows that scheme proposed in this study can be used in mountains for operational rainfall forecasting. The suggested time interval for rainfall forecasting should be one hour due to high variation in spatial and temporal scale.

Mishra & Sharma (2001) results indicated that nearly all clouds with their tops colder than 275K contribute to precipitation. On combining the results of precipitation intensity with cloud type, it has been found that during the monsoon season the contribution of different clouds to rainfall over an area decreases: the maximum being from cumulonimbus (1.75 — 1.49 mm h^{-1}), followed by nimbostratus (0.97 — 0.86 mm h^{-1}) and altocumulus / altostratus (0.97 — 0.86 mm h^{-1}). The contribution from other cloud types, such as status, cumulus or stratocumulus, is insignificant. The study result clearly illustrates the relationship between the cloud top temperature and precipitation intensities that may be utilized in actual practice.

Islam & Uyeda (2006) Tropical Rainfall Measurement Mission (TRMM) is useful for estimating the average values of rainfall in Bangladesh. The prominent difference between rainfall estimated by rain gauge and V5 3B42 was found to be period- and location-dependent. The V5 3B42 overestimated the rainfall during the pre-monsoon period and in dry regions but underestimated it during the monsoon period and in wet regions. The reason for the differences according to season and locations is considered the vertical cross section of convection obtained by TRMM-PR 2A25 data. The rainfall overestimation in pre-monsoon and underestimation in monsoon period measured by V5 3B42 is reduced to reasonable amount by V6 3B42 and V6 3B43.

Laurent et al (1998) found interesting result, that is the satellite-based methods and the ground based method lead to similar scores in rainfall estimation. The satellite-gauge combined method leads to slightly better scores. For this method, the estimation error for the 10-day cumulated rainfall and a 0.5°x0.5° spatial resolution is of about 35% of the mean rainfall amount. Other results concern the general methodology of method inter-comparison.

A set of well-controlled data collected by the ground based dual-frequency microwave radiometers at the National Central University of Taiwan (24.98^{0}N, 121.18^{0}E) from January of 1996 to December of 1997 was used to find the optimal time period for the comparisons between rain gauge rainfall intensity and those retrieved from radiometer data. The results show that a 1-h period will provide a better accuracy (Liu *et al.* 2000) than the other options, and the appropriate choice in optimal time period is very important in reducing root mean square error.

The closing seminar of SRFE validation was carried out in ICIMOD 2007, October 1st to 5th. Following validation papers were presented by different South Asian Country representatives.

Nepal: Rajbhandari (2007) finds, rainfall failed to capture in annual basis, SRFE is far below the observed value along the pockets of high rainfall area, the SRFE is not capturing the orographic rainfalls in this region. And still there is hope that, SRFE has tremendous potential in monitoring the drought condition in this region during dry season.

Nepal: Sharma (2007) finds, the grid wise daily correlation between CPC grids and observed rainfall is rather low in most of the rain regimes, CPC under estimates (negative bias), the rain for most of the rain regimes in monsoon period except Trans-Himalayan region (positive bias). CPC also over estimates the rain during pre-monsoon period, some CPC grids has shown extremely high rainfall (on the order of 400 mm / day), but neighbouring grids do not show such extreme rain and the decadal sum of CPC and observed rain has higher correlation as compared to daily data and bias trend is similar to that of daily data.

Nepal: Bajracharya et al (2007) finds, SRFE underestimates the average rainfall by an amount of -11mm, 2mm & -2mm in the case of intense, medium and less rainfall respectively. The averaged RMSE is 26.78, 11.21 & 0.34 mm in heavy, medium & low rainfall respectively. The average correlation coefficient is 0.45, 0.2 & 0.6 in heavy, medium & low rainfall respectively. The POD remains always above 0.7, 0.6 & 0.1 in heavy, medium & low rainfall respectively. The False alarm ratio is always near zero and average skill is above 0.7. He also concludes that, rainfall occurrence is underestimated by about half and more than half in monsoon during heavy and moderate rainfall. The algorithm fails to capture monsoon depression, monsoon break, monsoon trough and orographic condition. The limitation of SRFE is that it cannot produce more than certain amount of rainfall in 24 hour, which is not true in the case of monsoon depression and monsoon trough.

India: Das (2007) observed that the NOAA estimates over the northeast Indian region was significantly underestimated the error ranging from 40% to 60%.

Pakistan: Hussain (2007) found that, in winter SRFE under-estimates the average rainfall by an amount of -30mm while in summer SRFE under-estimates by an amount of -2mm, the averaged correlation coefficient is 0.701 in winter rainfall, 0.73 in summer rainfall and zero in low rainfall. The Probabilities of Detection (POD) are 0.631, 0.937 and 0.0 for winter, summer and low rainfall respectively. In addition, False Alarm Ratio (FAR) is always near zero and average skill is above 0.6. He also concludes that, accuracy of rainfall intensity in heavy rainfall is significant and rainfall occurrence is under-estimated by about half and more than half in monsoon.

Application of Rainfall Measurement

Balkundi (1996) explains that Vedic Aryans had discovered no means or techniques for measuring the actual rainfall received during the day or during the week. No information on measurement of rainfall during 5500 BC (when the composition of Rigvedic Hymns ended) to fourth century BC is available. They make count of the number of days of rainy season. This practice was intended for the crop production or agriculture management.

Vishnugupta Chanakya (around 327 – 326 BC) complied *Kautiliya's Artha-Sastra* {(Bhave 1991); (cited in Balkundi 1998)}. In which *Artha* means the sources of livelihood of man which in that age was land inhabited by him. Gains from this land and the ways for maintaining the fertility of land are the main subjects of the *Artha-sastra* (Chapter 15.1; 1-2). As the agricultural productivity of land depends on the quantity of rainfall received by it in rainy season, Chanakya compiled relevant information in this book from earlier works.

Bagchi (1982) explained that to generate stream flow from precipitation one should know the distribution of precipitation in the basin. However, in an average Himalayan basin there are very few rain/snow gauges and those are likely to be at the lowest point. If one attempts to predict stream flow from such data one must consider *(a)* change in the form of precipitation with altitude, and *(b)* orographic variation of precipitation.

Real time rainfall estimation using geosynchronous satellite data are indirect, the high frequency and high spatial resolution of the measurements, as well as the broad area that they cover, make them uniquely complementary to rain gauge and radar measurements. They provide valuable guidance to meteorologists and hydrologists issuing flash flood watches and warnings, especially when several storm systems need to be analyzed simultaneously (Vicente *et al.* 2001).

Shakya (2007) used the SRFE in flood estimation without validation in Lothar Kola in Churiya region of Nepal for Department of Road, Government of Nepal.

Rainfall Disaster

According to J B Miller (1997), in recent decades the frequency and severity of flood has been observed to rise in many countries. The modern development in almost all countries has led to destruction of forest cover, the draining of natural wetlands and the spread of towns across the countryside and many other human interventions have reduced infiltration leading to more frequent and higher floods.

The Tenth Plan (2003) for the year 2003 to 2008 has identified natural and human-induced disaster management as the core need of sustainable and broad-based economic growth. It has adopted policy on disaster risk reduction in Nepal. The plan has included preparedness activities for disaster management: national and community levels. It provides local bodies, NGOs, community based organizations (CBOs) and the private sectors opportunity for preparedness actions including rescue and relief. The plan has integrated the objectives of making development and construction works sustainable, reliable, effective, and mitigating disasters to secure life of common people through appropriate strategies and programmes.

Vaidhya (2004) have presented the brief history of flood in Kathmandu Valley since 1988

S.No.	River	Affected area	Date
1.	Bagmati	Sankhamul	1988
2.	Bishnumati	Sobhabhagwati	1989
3.	Bagmati	Thapathali	1991
4.	Manahara	Bhaktapur highway	1993
5.	Bishnumati	Naya Bazaar, Balaju	1994
6.	Bishnumati	Near National trading Corporation	1995
7.	Bagmati	Tinkune, Koteshwor	1995
8.	Bagmati	Jhamsikhel	1996
9.	Tukucha	Army barrack, Kumarigal	1998
10.	Tukucha	Kamladi	1998
11.	Bagmati	Under Balkhu Bridge	1999
12.	Tukucha	Tukucha bridge, Tripureshwor	1999
13.	Dhobikhola	Devinagar, Ghatteykulo Anamnagar	2000
14.	Tukucha	Baghbazzar	2000
15.	Bishnumati	Samakhusi and Dhapasi	2000
16.	Dhobikhola	Patan Balkumai bridge	2000
17.	Manahara	Patan Balkumai bridge	2000
18.	Kodku	Gwarkhu area	2002
19.	Balkhu	Oriental colony and Metro cinema Hall	2002

According to the Disaster Review Report published by Department of Water Induced Disaster Prevention (DWIDP), the major water induced disasters from the history in Nepal are as depicted below.

The most significant disaster events recorded in the year 2002 (Pradhan & Shrestha 2002) were-

- Landslide at Sugdel VDC of Khotang District, July 13, 2002
- Landslide and debris flow at Matatirtha VDC in Kathmandu District, July 23, 2002
- Landslide at Badbhanjyang VDC of Kathmandu District, July 23,2002
- Flood & Landslide at Raksirang VDC of Makwanpur District, July 24,2002
- Landslide & Flood at Kakada VDC of Makwanpur District, July 24,2002

- Landslide at Bamti VDC of Ramechhap District, August 21, 2002

The most significant disaster events recorded in the year 2003 (Pradhan & Shrestha 2003) were-

- Flood & inundation at Hadiya VDC of Udayapur District on June 27, 2003
- Flood and inundation at Beltar VDC of Udayapur District on July 9, 2003 which inundated 237 ha. of land.
- Landslide at Manakamana VDC in Gorkha District on July 31, 2003 that claimed 23 death causalities
- Flood & inundation at Inarwa and Bhasedhawa VDC of Rauthat District on July 31, 2003
- Flood & inundation at Gamhariya VDC of Rauthat District on July 31,2003.
- Landslide at Ramche VDC of Rasuwa District on August 16 ,2003 that claimed 18 death causalities.

The most significant disaster events recorded in the year 2004 (Pradhan & Shrestha 2004) were-

- Landslide at Makawanpur District on July 9-10, 2004 that claimed 24 death casualties in total
- Flood and inundation of Katari VDC of Udayapur District on July 10, 2004 which inundated 100.68 ha. of land.
- Flood & landslide at Deurali VDC of Ramechhap District on July 10, 2004, which caused an estimated loss of NRs. 27,271,500.
- Landslide at Okhaldhunga District on July/August 2004 that claimed 21 death causalities in total

The most significant disaster events recorded in the year 2005 (Pradhan et al. 2005) were-

- Landslide at Kapilbastu District on July 14, 2005 that claimed 39 death casualties in total
- Flood & inundation at Itahari of Sunsari District on August 24, 2005, which caused an estimated loss of NRs. 345,00,000.
- Landslide at Dadeldhura District on Sep. 24, 2005 that claimed 32 death causalities in total
- Flood and inundation of Chandani VDC of Kanchanpur District on Sept. 24, 2005 which inundated 474.04 ha. of land.

The most significant disaster events recorded in the year 2006 (Pradhan et al. 2006) were-

- Landslide of Dangsing at Kaski District on July 14, 2006 that claimed 21 death casualties in total
- Landslide at Baitadi District on Aug. 22, 2006 which claimed 10 death, at Banke District on Aug. 27, 2006 which claimed 7 death causalities in total.
- Flood and inundation of Nawalparasi District in different Villages on Aug. 25, 2006 which inundated 1451.73 ha. of land.
- Flood & inundation at Doti and Achham Districts of different villages on August 2006, which caused an estimated loss of NRs. 713.36 million

Sutardi (2006) described the natural factors responsible for flood events are; high intensity and long duration of rainfall, existence of a meandering river and some natural contraction river channels cause a bottle neck for river flow, abrupt change of land terrain from hilly area to flat areas also causes overflowing of river flow over river banks.

Pathak (2007) has estimated the effect of disasters in Nepal for 2001 to 2005. He gave the following data.

Table 2: Annual loss due to disaster for year 2001 to 2005

Year	Affected persons			Affected families	Houses destroyed	Estimated losses (in million US $)
	Dead	Missing	Injured			
2005	204	30	31	2088	1102	3.8
2004	192	11	220	16997	4818	4.6
2003	310	58	160	11730	6819	13.4
2002	461	21	287	40486	19836	7.1
2001	418	45	134	16054	6260	7.3
Total	1585	165	832	87355	38835	36.2

Shakya et al (2007), urban flooding in Nepal is much lightens up as the capital city Kathmandu Valley got flooded badly with large death/missing of 27 people in 2002. The massive downpour of 22nd-23rd July 2002 in Kathmandu Valley was the highest recorded rainfall in the capital in 3 decades. During that period, the point rainfall of Thankot recorded was 300 mm in 24 hours whereas the last highest rainfall was 173.2 mm recorded in July 1954 in Indian Embassy's rain gauge, Kathmandu.

Table 3: Loss of lives by disaster in Nepal (1983 - 2006)

Year/Types	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
Earthquake						721				2		
Flood & landslide	293	363	420	315	391	328	680	307	93	71	1336	49
Fire	69	57	52	96	62	23	109	46	90	97	43	43
Epidemics	217	521	915	1101	426	427	879	503	725	1128	100	626
Windstorms, hailstorms & Thunderbolts					2		28	57	63	20	45	47
Avalanche						14	20					
Stampede						71						
Total	579	941	1387	1512	881	1584	1716	913	971	1318	1524	765

Year/Types	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Total
Earthquake		3					1		0	0	0	0	727
Flood & landslide	203	258	83	273	193	173	196	441	232	131	141	114	6466
Fire	73	61	65	54	39	37	26	11	16	10	28	3	1153
Epidemics	520	494	951	840	1207	141	154	0	0	41	34	0	11875
Windstorms, hailstorms & Thunderbolts	34	75	49	23	22	26	38	6	62	10	18	15	535
Avalanche	43	4	12		5				0	0	21		98
Stampede									0	0	0		71
Total	873	895	1160	1190	1466	377	415	458	310	192	242	132	20925

Source: (Pradhan *et al.* 2006)

Capter III

Study Area

This study is focused whole Nepal as the study area. Altogether 20 rain gauge stations are taken as the reference sites throughout Nepal for the validation of Satellite Rainfall Estimation. The locations and station index are depicted in table 4 (below).

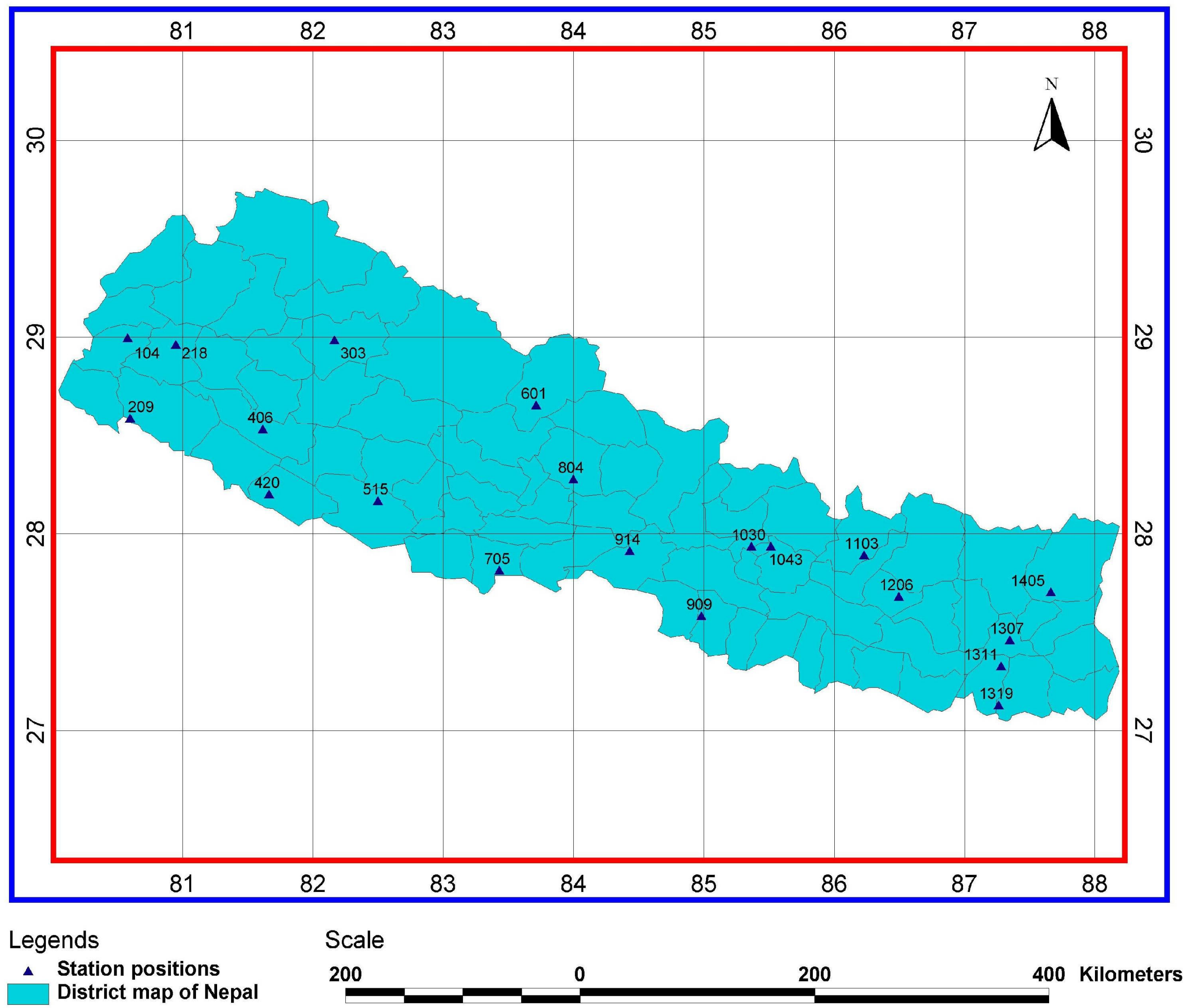
The selection criterial for the following stations are: representative of different rainfall zones such as low rainfall zone; western Nepal, to high rainfall zone middle Nepal, and from southern Nepal to norther part so that they can revel the whole Nepal.

Table 4: List of sample stations for rainfall analysis

Latitude	Longitude	Station index	Station Name
29.3000	80.5833	104	Dadeldhura
28.6833	80.6000	209	Dhangadi
29.2500	80.9500	218	Dipayal (Doti)
29.2833	82.1667	303	Jumla
28.6000	81.6167	406	Surkhet (Birendranagar)
28.1000	81.6667	420	Nepalganj (Airport)
28.0500	82.5000	515	Ghorahi (Dang)
28.7833	83.7167	601	Jomsom
27.5167	83.4333	705	Bhairahawa
28.2167	84.0000	804	Pokhara (Airport)
27.1667	84.9833	909	Simara (Airport)
27.6667	84.4333	914	Bharatpur (Airport)
27.7000	85.3667	1030	Kathmandu (Airport)
27.7000	85.5167	1043	Nagarkot
27.6333	86.2333	1103	Jiri
27.3167	86.5000	1206	Okhaldhunga
26.9833	87.3500	1307	Dhankuta
26.4833	87.2667	1311	Dharan Bazar
26.7833	87.2833	1319	Biratnagar (Airport)
27.3500	87.6667	1405	Taplejung

The distribution of above sations in Nepal are given on the map in following page.

Distribution of sample stations



Chapter IV

Research gaps and thesis objective

The utility of rainfall data depends on the timely availability of the same. In Nepal, rainfall data are not available on time. Different rain gauge stations in Nepal cannot share the rainfall data on time to the Department of Hydrology and Meteorology. In this case, the SRFE is available very rapidly with few hours time delay. Satellite rainfall concept is new in Nepalese context. Shakya et al (2007), used SRFE in disaster review of 22nd-23rd July 2002 in Kathmandu Valley. Similarly, Shakya (2007) used the SRFE in flood estimation without validation in Lothar Kola in Churiya region of Nepal for department of road. It is because, few reports shows that SRFE is well detected during heavy rainfall.

Grid rainfall (SRFE) of 12X12 km^2 directly is used by Shakya without validation. However, he explained that, it is close to the ground truth. Papers presented in Documentation workshop at ICIMOD (Documentation Workshop on SRFE Validation, ICIMOD 2007 October 1st to 5th) did not consider Depth-Area Relation & actual point rainfall. Thus, this research's objectives focus on further validation of SRFE using DAD and point rainfall.

The objectives are as follows:

- Reliability test of satellite rainfall (downscale) with reference to rainfall that is converted from point to aerial by DAD.
- Study of possible applications of SRFE on disaster management.

Rationale of the Study

Quick rainfall data is vital statistics for getting control over the flash flood, dam operation, agriculture and others. The existing rain gauges measure the cumulative rainfall over 24 hour (Shakya 2004). This measurement is not enough supportive in those activities. Besides this, establishment of rain gauges countrywide in mountainous region is not reasonable. On the other hand the local irregular terrain, winds velocity and direction, rain drop size will produce some errors in rainfall measurements in rain gauge (Garg 2005). These are some difficulties on ground-based rain gauges over the satellite rainfall estimation. The other weak point of this rain gauge is the time lag in data transport. Due to the lag time, there are many difficulties in hydrologic analysis. On the other hand, the satellite rainfall estimation gives very quick rainfall estimation. This can give six hourly, 12 hourly or 24 hourly rainfalls estimates as per requirement. Hence, it makes easier in hydrological analysis and flash flood prediction, reservoir or dam monitoring, etc. Hence, the satellite rainfall could be used in disaster management.

Chapter V

Materials and Methodology

The objective of the study was to test the reliability of the satellite rainfall estimates CPC_RFE product provided by NOAA. CPC_RFE are the product of 24 hours cumulative rainfall measurements obtained daily at 0-Z from a set of AMSU-B, SSM/I, GPI and rain gauges.

A. Data Preparation

Estimated Rainfall

The estimated rainfall was provided by NOAA for the period 2001 onward. This data was in girded gif format. For the current scope of the study, the estimated rainfall data set from NOAA CPC_RFE for the period from 2007 January to September was obtained from the online source.

Observed Rainfall

The observed point rainfall dataset for the period 2007 January to September was obtained from the rain gauge station of the DHM. It is online available on www.mfd.gov.np.

The rain gauge data provided by DHM were in html format and have been converted to Microsoft excel format. The latitude and longitude of the rain gauge station provided by DHM was converted to degree decimal format then converted to GIS (point shape file) format and transformed to same projection parameter as CPC_RFE data set. This point shape file was joined with daily rainfall data set in excel format.

B. Data Quality Control

1) The gauge data were quality controlled by removing duplicates
2) Remove rain gauge data that contribute to GTS
3) Station information (especially location) was verified, where the details are available
4) The precipitation data were checked for typing error
5) Few data that give high deflection were removed

C. Validation Methodology

a) **Visual analysis**: The point shape file of sample raingauge stations on GIS was overlaid over the estimated (NOAA CPC_RFE data or SRFE) data file along with the district map of Nepal for ease on visual interpretation. All of the above three maps were before hand converted to the same projection system. For ease on interpretation, the files were zoomed up to pixel size. Now the corresponding eastimted rainfall amount on the CPC_RFE was visually interpreted for all of the sample stations. This estimated rainfall amount was tabulated (annex II & III). To reduce the manual errors in visual interpretation, the RGB value of SRFE pixel and RGB value on scale pixel were compared for exacet rainfall value of the pixel. On the other hand, the observed rainfalls at the rain gauge station were pre-hand tabulated in excel.

b) **Data conversion**: The point rainfall that measured in rain gauge were to be converted into area rainfall. For the conversion of the point rainfall into area rainfall, the Depth Area Duration (DAD) interpolation was used. Boyer 1957 (cited in Shakya 2004) developed the formula for the construction of DAD. The equation is

$$P = P_0 e^{-bx}, \qquad \text{eq (1)}$$

Where, P_o is the rainfall at the center of the storm for any duration, P is maximum average depth of rainfall over an area “A” covered by radius “x” in km & “b” is coefficient equal to 0.0235. This equation is valid for drainage basin area more than 260 km^2. The area for the spatial distribution calculation on DAD, the same area of a pixel of CPC_RFE 144 Km^2 was taken and radius was calculated as $A = \pi \ r^2$, i.e. **r** is equal to 6.7702 km. The daily rainfall and monthly rainfalls for selected samples were converted into area rainfall by DAD interpolation method. Then averages of all the stations for daily and monthly rainfall were estimated. The average rainfall of CPC_RFE Vs DAD was plotted.

The SRFE was obtained in class range. The mid value of each class was taken for the analysis after few hit and trial on validation. Besides this, the rainfall value on rain gauge beyond the SRFE class was adjusted to the upper most class value of SRFE.

c) **Statistical Analysis**:

It was assumed that the satellite estimates were independent of the gauge values. The statistical measures and definitions used to compare the satellite estimates with the gauges were taken from the results of the 3rd Algorithm Inter-Comparison Project of the Global Precipitation Climatology Project (GPCP) (Ebert 1996 Cited in; Vila *et al.* 2004).

Continuous verification statistics measure the accuracy of a continuous variable such as rain amount or intensity (Ebert 2005). In the equations to follow S_i indicates the estimated value at grid box i, G_i indicates the observed value, and N was the number of samples.

The mean error (bias) measures the average difference between the estimated and observed values. The mean absolute error (MAE) measures the average magnitude of the error. The Root Mean Square Error (RMSE) also measures the average error magnitude but gives greater weight to the larger errors.

$$Bias = \frac{\sum_{i=1}^{N}(S_i - G_i)}{N} = \overline{S} - \overline{G} \qquad \text{eq (2)}$$

$$\mathrm{MAE} = \frac{1}{\mathrm{N}} \Sigma \left| G_i - O_i \right| \qquad \text{eq (3)}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N} \Sigma (S_i - O_i)^2} \qquad \text{eq (4)}$$

The correlation coefficient *r* measures the degree of linear association between the estimated and observed distributions. It is independent of absolute or conditional bias, however, and therefore must be used along with other measures when verifying satellite estimates.

$$r = \frac{N \sum_{i=1}^{N} G_i S_i - (\sum_{i=1}^{N} G_i)(\sum_{i=1}^{N} S_i)}{\sqrt{N \sum_{i=1}^{N} {G_i}^2 - (\sum_{i=1}^{N} G_i)^2} \sqrt{N \sum_{i=1}^{N} {S_i}^2 - (\sum_{i=1}^{N} S_i)^2}} \qquad \text{eq (5)}$$

Any of the error statistics can be used to construct a skill score that measures the degree of improvement over a reference estimate.

$$Skill = 1 - \frac{\sum_{i=1}^{N} \frac{\left| G_i - S_i \right|}{\left(G_i + S_i \right)}}{N} \qquad \text{eq (6)}$$

This normalized parameter takes into account the absolute error between estimation and the ground truth divided by the sum of both. The best performance of the model is when the skill is near one.

Chapter VI

Analysis

The SRFE was projected in ArcView software. The rain gauge stations were overlaid over the satellite rainfall image. The respective SRFE for each rain gauge was tabulated by visual observation in software. The satellite rainfall was considered as the observed rainfall and the rainfall data from the rain gauge stations were taken as the expected rainfall over the point.

The in-situ rainfall of rain gauges were interpolated with the Boyer formula for Depth Area equation (1) ($P = P_0 e^{-bx}$). Then, the DAD value for each in-situ rainfall data was compared with the SRFE rainfall data tabulated.

The correlation between SRFE and in-situ rainfall for monthly cumulative & daily rainfall of 20 stations' average were analyzed and the following figure 6.1 and 6.2 were obtained respectively. In figure 6.1 & 6.2 analysis, the correlation value were 0.966 and 0.403 respectively.

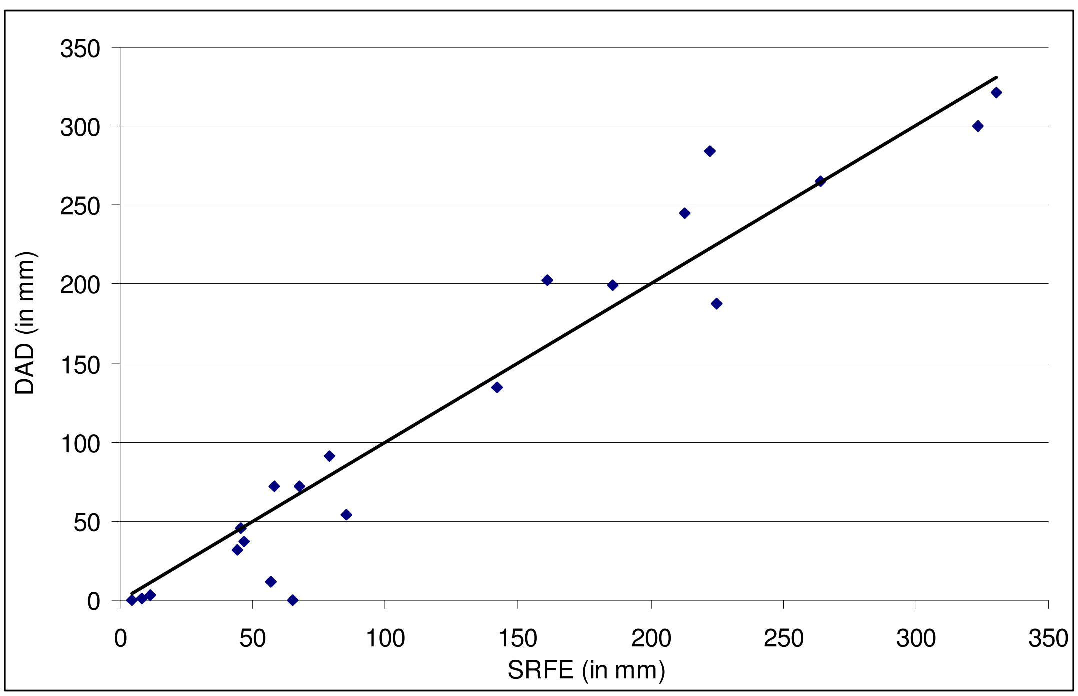


Figure 6.1: Linear regression analysis between SRFE & DAD interpolation in scattered diagram for monthly cumulative average for total of all the sample stations.

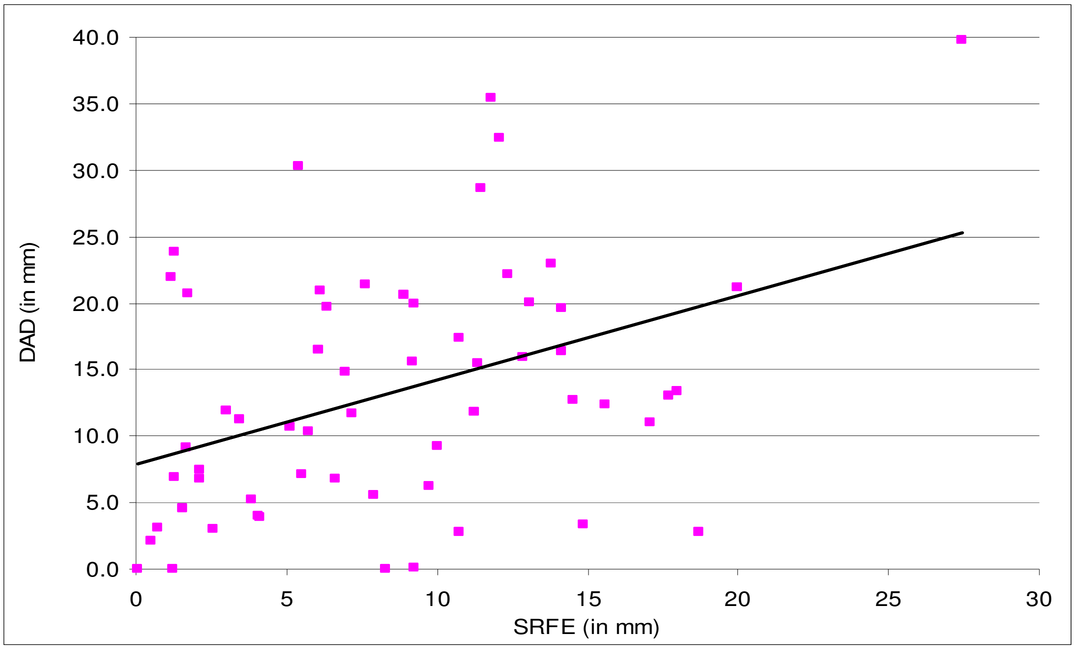


Figure 6.2: Linear regression analysis between SRFE & DAD interpolation in scattered diagram for daily rainfall for average of all the sample stations.

The deviation between SRFE and in-situ rainfall analysis for average of 20 stations obtained the following analysis (figure 3).

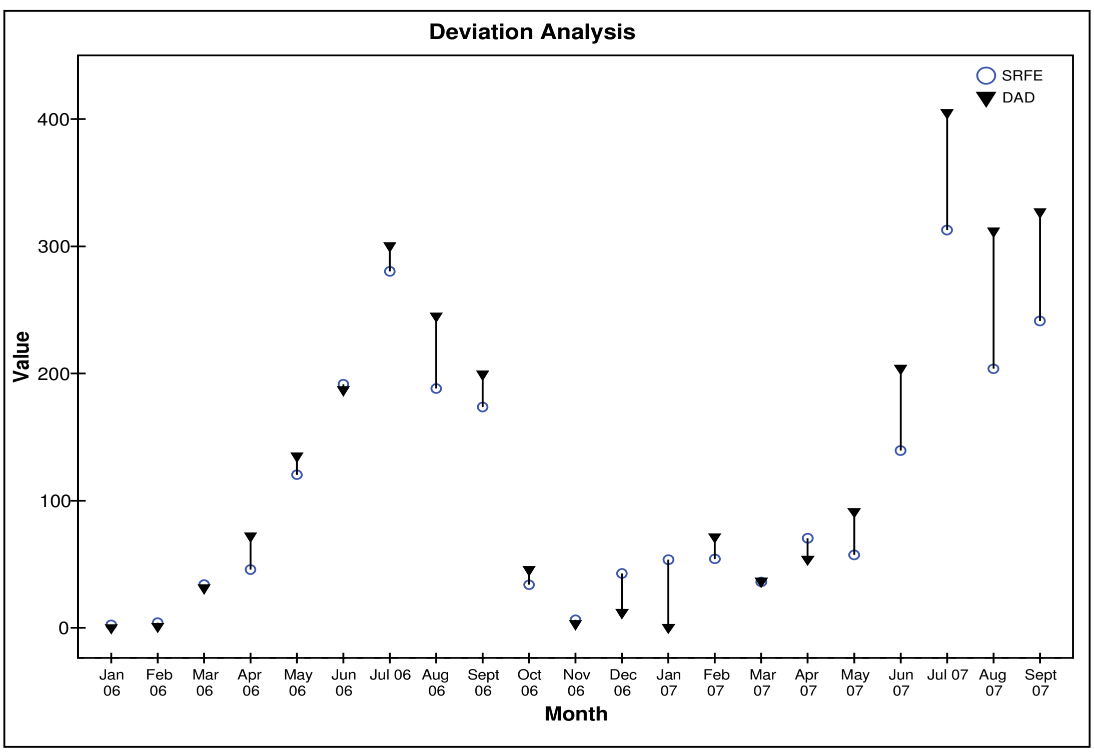


Figure 6.3: Graphical deviation comparison between monthly cumulative SRFE and DAD interpolation for rain gauge measured data.

The correlation between SRFE and in-situ rainfall for monthly cumulative & daily rainfall of 20 stations were analyzed and the following figure 6.4 and 6.5 were obtained respectively.

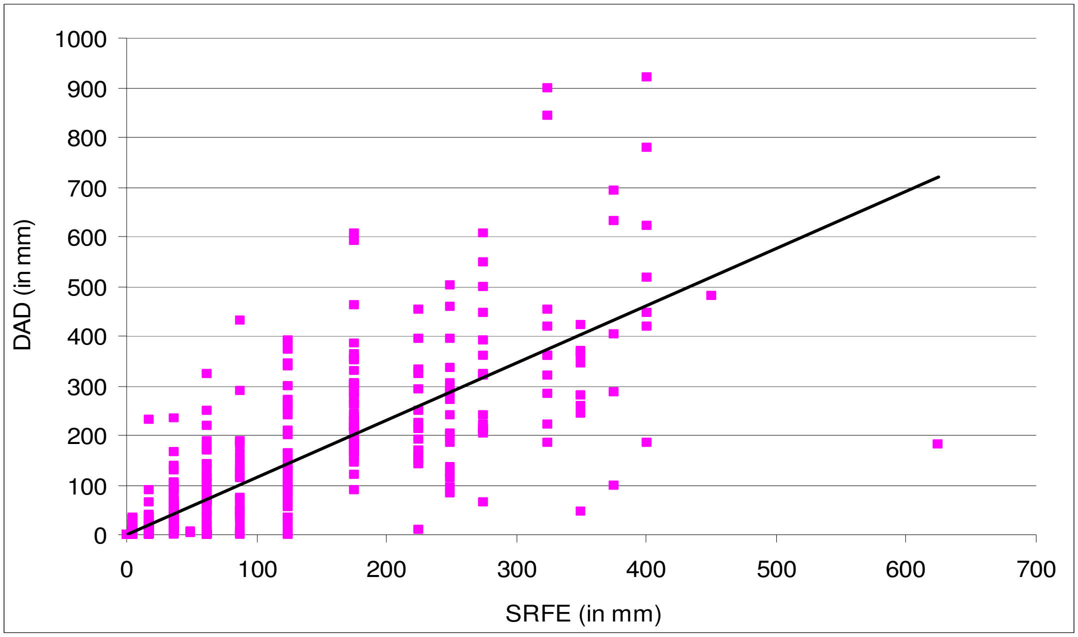


Figure 6.4: Linear regression analysis between SRFE & DAD interpolation in scattered diagram for monthly cumulative rainfall of sample stations

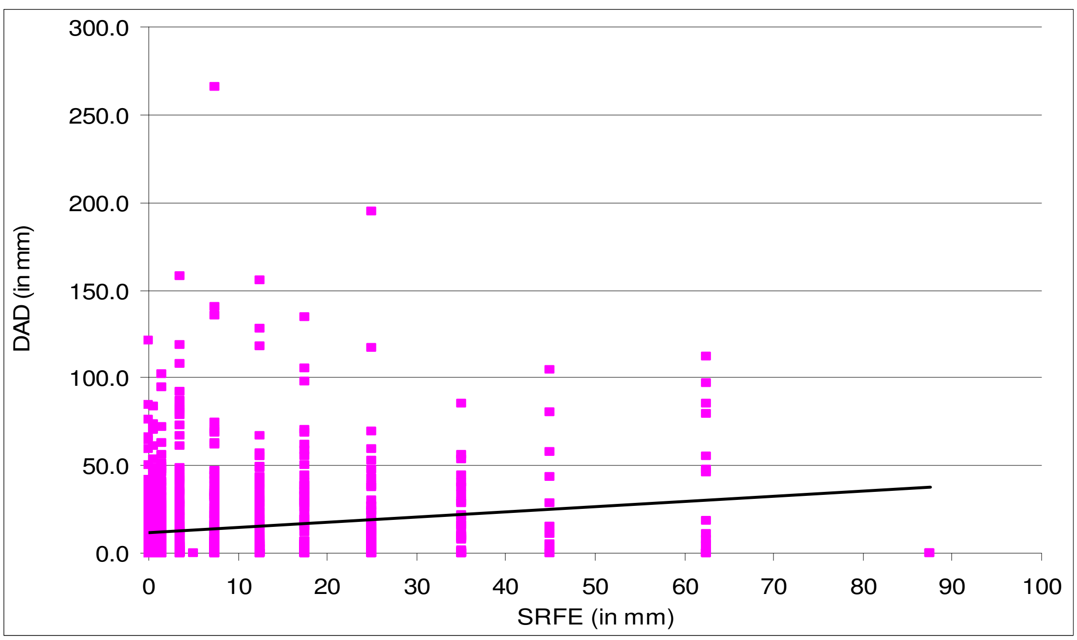


Figure 6.5: Linear regression analysis between SRFE & DAD interpolation in scattered diagram for daily cumulative rainfall of sample stations.

The scatter diagram gave the following equations and correlation values depicted in table.

Table 5: Output from charts in

	Equation	Correlation
SRFE Vs Point rain DAD for monthly cumulative rainfall	$R_{DAD} = 1.1517\, R_{SRFE}$ ---------(A)	0.764526
SRFE Vs Point rain DAD for daily rainfall	$R_{DAD} = 0.2914\, R_{SRFE} + 11.792$ ----(B)	0.14491
SRFE Vs Point rain DAD for monsoon 2006 and 2007	$R_{DAD} = 0.888\, R_{SRFE} + 77.427$ ------(C)	0.52915
SRFE Vs Point rain DAD for monsoon 2007	$R_{DAD} = 0.9506\, R_{SRFE} + 88.966$ ----- (D)	0.55
SRFE Vs Point rain DAD for monsoon 2006	$R_{DAD} = 0.7848\, R_{SRFE} + 73.39$ ------(E)	0.2634

Using the above equation in second column in table 5, the corrected rainfall can be estimated using the SRFE data. The constant in equation was the average value hence will not fit in all the cases.

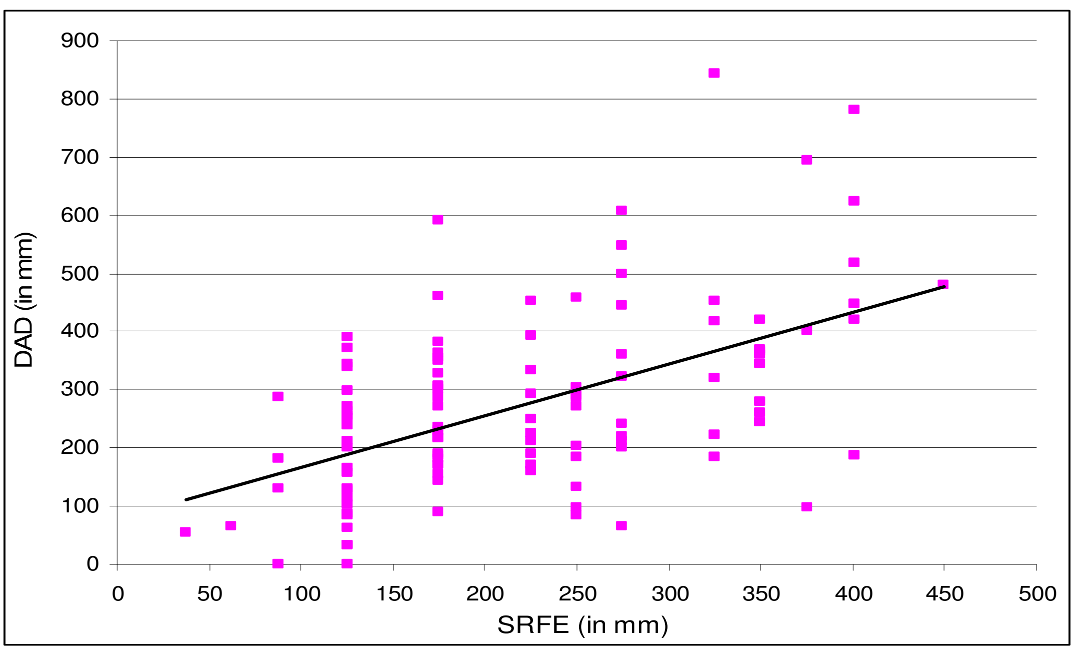


Figure 6.6: Combined scatter plot for the year 2006 and 2007 for the monsoon season

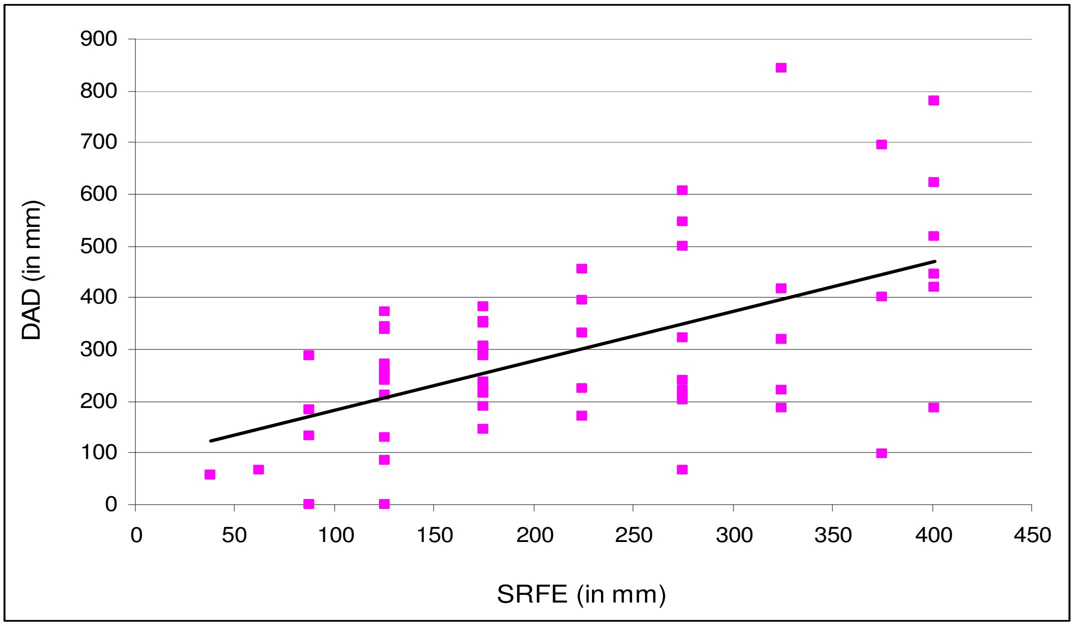


Figure 6.7.: The scatter plot of monsoon 2007; the above analysis shows that, the SRFE was improving compare to preceding year 2006.

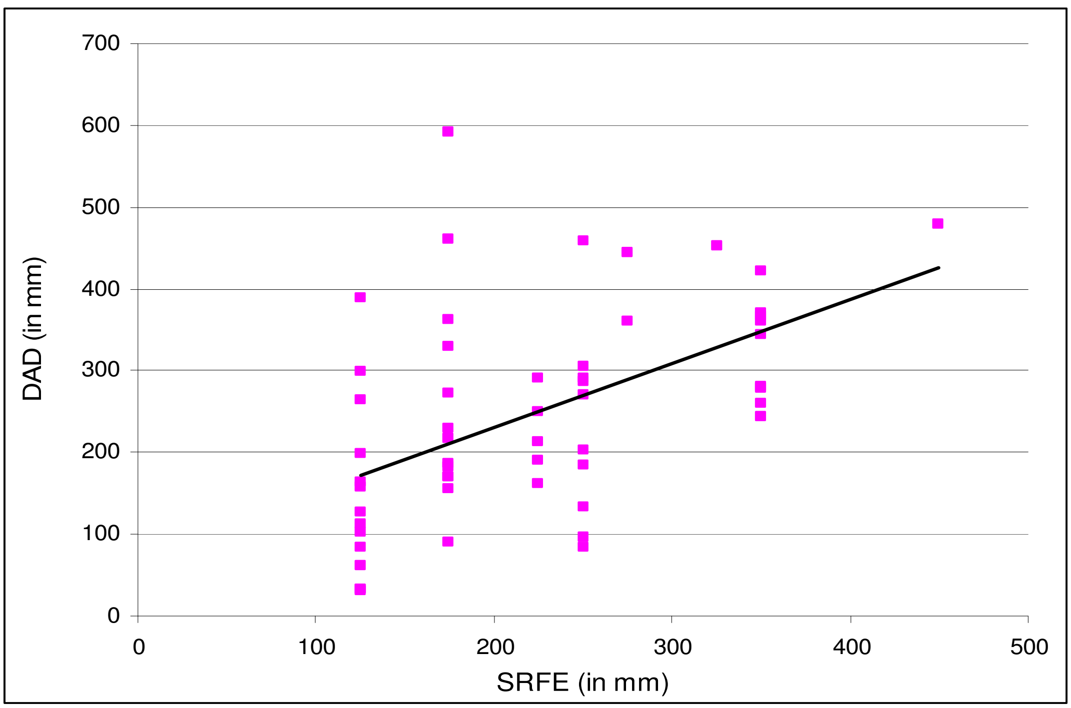


Figure 6.8: The Scatter plot of monsoon 2006

The outcome equations and the correlation values were depicted in the table 5. The equations in the second colum can be used in obtaining improved SRFE.

Chapter VII

Results and Discussions

The plot between the average rainfall of SRFE and DAD interpolation was analyzed. The monthly cumulative analysis (figure 6.1) showed the correlation factor 0.966 while the daily SRFE analysis (figure 6.2) gave only 0.403 with the DAD interpolation of in-situ rainfall. The monthly cumulative SRFE seemed to follow the rain gauge measured rainfall.

The figure 6.3 showed that the SRFE was under estimating the rainfall in most of the case. And, the over-estimation was with low deviation. While in case of under estimation, the deviation from the in-situ measurement was high.

The statistical calculation on daily rainfall and monthly cumulative rainfall resulted the following values.

Table 6: Statistical calculation for daily and monthly cumulative rainfall

Parameters	Daily rainfall	Monthly rainfall	Monsoon Seasonal
MAE	14.4833	62.1	114.5
RMSE	25.8559	105.5392	154.6
Bias	-5.8729	-21.4882	-57.1487
Correlation	0.145	0.764526	0.52915
Skill	0.29106	0.636388781	0.8
Total Cases	1105	408	117

Table 7: Statistical calculation for monsoon seasonal rainfall

Parameters	2006	2007
MAE	88.9	138.7
RMSE	124	178.9
Bias	-24.3057	-88.34
Correlation	0.513	0.55
Skill	0.8	0.7
average DAD	244.2618	307.0
Average SRFE	219.9561	218.6
Total Case	57	60

The Mean Absolute Error was 14.4833 for daily rainfall and 62.1 for monthly cumulative. The RMSE was 25.8559 & 105.5392 for daily and monthly cumulative rainfall respectively. The errors in case of cumulative rainfall could be termed as insignificant as these values were very less compare to the total rainfall. The SRFE was underestimating the rainfall by -5.8729 mm and -21.4882 mm bias for daily and monthly cumulative rainfall. While the correlation coefficient for daily and monthly cumulative rainfall was 0.145 and 0.764 respectively with skill 0.291 and 0.851 for daily and monthly rainfall respectively. Table 5 showed that, SRFE need to add nearly 1.15 times of value in average for the monthly cumulative rainfall and nearly 12 mm of value in average for the daily rainfall.

The table 7 showed that monsoon in year 2006 had good estimation compare to the monsoon in year 2007 in all the statistical tests except the correlation coefficient. It might be due to low rainfall in monsoon season in year 2006 compare to the year 2007. The monsoon season had more than 25% of rainfall in year 2007. This result showed that the SRFE has high errors during high rainfall and it can capture the low or medium rainfalls.

Bajracharya et al (2007) found, SRFE underestimated the average rainfall by an amount of -11mm, 2mm & -2mm in the case of intense, medium and less rainfall respectively. The averaged RMSE was 26.78, 11.21 & 0.34 mm in heavy, medium & low rainfall respectively not much deviating from the present study. The average correlation coefficient was 0.45, 0.2 & 0.6 in heavy, medium & low rainfall respectively. Sharma (2007) found, the grid-wise daily correlation between CPC grids and observed rainfall was rather low in most of the rain regimes, CPC under estimated (negative bias) the rain for most of the rain regimes in monsoon period except Trans-Himalayan region (positive bias), Hussain (2007) found that, in winter SRFE underestimated the average rainfall by an amount of -30 mm while in summer SRFE underestimated by an amount of -2mm, the averaged correlation coefficient was 0.701 in winter rainfall, 0.73 in summer rainfall and zero in low rainfall. Das (2007) observed that the NOAA estimated over the northeast Indian region was significantly underestimated the error ranging from 40% to 60%.

Chapter VIII

SRFE Applications

Applicability in Disaster management

SRFE can be used in landslide monitoring. There are different factors that determine whether any landslide will occur or not. One of them is water content of the soil in slope. If all the conditions are already in favour of landslide, and the failure-determining factor is water content in soil, the land is stable until water is not percolated. If at this condition, precipitation occurs at sufficient amount, the land slides. Geologist can calculate the water amount required for sliding the land from different tests and by SRFE the amount of rainfall can be determined where there are no nearby rain gauges. With these data, landslide probability can be determined. Hence, disaster could be prevented. In this case, the cumulative rainfall is to be used and it is more reliable compared to the daily SRFE as the cumulative SRFE has high correlation values and insignificant errors.

High amount of rainfall in upstream will give flood in downstream with lag of '*concentration time'*. For the flood warning system, the real time and reliable data is must. The SRFE is not so strong enough yet, to use in flood warning system even though it provides real time data, since the daily SRFE has low correlation coefficient and significant errors. At this stage, the flood warning system will fail to predict the flood intensity and occurrence time.

The cumulative SRFE is correlating with the in-situ rainfall data measured by the rain gauge. In this case, the cumulative SRFE data can be used to predict the inundation by continuous rainfall over long time. This can support in agricultural practice for managing the drainage. Beside this, the cumulative rainfall can be used on water balance study. This will give the idea for the irrigation system in agriculture.

Other Applications

Application in Rainwater Harvesting

Limbu (2005) described that 40% population of Nepal lacks drinking water supply and over 70% are denied safe drinking water. The rainwater is one of the best and chief options for safe drinking water supply at decentralized level. Collection of rainwater as it falls is termed as rainwater harvesting. For the rainwater harvesting, one of the primary requirement is the amount of falls that could be collected. For the estimation of amount of water collection, the rainfall data is must. At the places where there are no rain gauges for rainfall measurement system, the SRFE could be the better option. In case of rainwater harvesting, the cumulative rainfall data is used. Hence, as the cumulative rainfall of SRFE is much closer to the rain gauge measured data, the SRFE could be used in rainwater harvesting.

Application in Irrigation Management

In large-scale agriculture, the water balance is required. For rainfall measurement data, where there is no mechanism for rainfall measurement, the SRFE can be used. With correct rainfall data, the possibility of water logging or over flooding and water deficiency is determined. In extensive agricultural practice, monthly rainfall and seasonal rainfall is essential. Hence, the SRFE is applicable in irrigation management; wherever the means of rainfall measurement mechanisms are absent.

Application in Watershed Management

The SRFE can be used in discharge monitoring in watershed. The SRFE can be used in water balance equation, sedimentation study and soil loss study; as these studies need cumulative rainfall data. Since the SRFE is yielding good estimation in cumulative rainfall estimation it can be used in watershed management and related studies.

Chapter IX

Conclusions

As discussed above, there are wide fields where the SRFE can be used. At present, the SRFE is not estimating the precipitation precisely. The SRFE should be improved. As there was good correlation coefficient and skill value in cumlative rainfall, it is clear that SRFE can be improved. In Africa and many other regions, the SRFE has good estimation. In case of Nepal, the SRFE was not capturing very good estimation in case of daily rainfall. It was estimated that SRFE need to add nearly 1.15 times of value in average for the monthly cumulative rainfall and nearly 12 mm of value in average for the daily rainfall. On the other case, the cumulative rainfall estimation showed quite good estimation. However during the monsoon season, the SRFE had very significant errors and medium correlation values. In all case, there were problems of over- & under-estimation on SRFE and the cumulative estimation has very limited uses in practice. It is clear that SRFE cannot be used in flood warning mechanisms at present condition with existing bias, low correlation coefficient and significant errors. The SRFE can be used in fields where the cumulative rainfalls are applicable.

References

Bagchi A. K. (1982) Orographic Variation of Precipitation in a High-Rise Himalayan Basin. In: *Hydrological Aspects of Alpine and High Mountain Areas* pp. 138. IAHS Publication

Bajracharya S. R., Shrestha M. & Mool P. K. (2007) Validation of Satellite Rainfall Estimates over the Hindu Kush Himalayan Region. International Center of Integrated Mountain Development, Kathmandu, Nepal.

Balkundi H. V. (1996) *Rigvedatil Hawaman*. Pushpak Prakashan, Pune, India.

Balkundi H. V. (1998) Measurement of Rainfall in Ancient India. *Asian Agri-History* 2: 37 - 48.

Bhat M. R. (1993) *Varahmihira's Bruhat-Samhita*. Motilal Banarasidas Publishers Pvt. Ltd.

Bhave H. A. (1991) *Chanakya Charitra*. Varada Books, Pune.

Chalise S. R. & Khanal N. R. (1996) Hydrology of the Hindu Kush Himalayas. In: *Regional Workshop*. ICIMOD, Kathmandu.

Chen S. (1991) Characteristics of Flood Damages in Monsoon Asia. *Bulletin of Flood Damage Evaluation Information System and Wetland Use*.

Chyurlia J. P. (1984) Water Resources Land Resource Mapping Project, Kathmandu.

Coppola E., Tomassetti B., Verdecchia M., Marzano F. S. & Visconti G. (2005) A Rainfall Estimation Algorithm For Hydrological Purpose Using Satellite And Radar Data. *Geophysical Research Abstracts* 7: 2.

Das P. J. (2007) Validation of Satellite Rainfall Estimates for Northeast India. North East Center for Environmental Research and Development, Guwahati, Assam, India.

Datar A. V. (1991) *Achary Vishnugupta Virachit Shree Kautilya Arthashastra*. Sampurnand Sanskrit University, Varanasi, India.

Ebert E. E. (1996) Result of the 3rd Algorithm Intercomparison Project (AIP-3) of the Global Precipitation Climatology Project (GPCP) pp. 199. Bureau of Meteorology Center, Melbourne, Australia.

Ebert E. E. (2005) Methods for Verifying Satellite Precipitation Estimates. Bureau of Meteorology, Melbourne, Australia.

Garg S. K. (2005) *Hydrology and Water Resources Engineering*. Khanna Publishers, Delhi.

Hussain S. P. (2007) Application of Satellite Rainfall Estimates in the Hindu Kush Himalayan Region. Flood Forecasting Division, Pakistan Meteorological Department, Pakistan.

Islam N. & Uyeda H. (2006) Use of TRMM in Determining the Climatic Characteristics of Rainfall Over Bangladesh. *Remote Sensing of Environment* 108: 393 - 405.

Kidd C., Kniveton D. R., Todd M. C. & Bellerby T. J. (2003) Satellite Rainfall Estimation Using Combined Passive Microwave And Infrared Algorithms. *Journal of Hydrometeorology* 4: 17.

Laurent H., Jobard I. & Toma A. (1998) Validation of Satellite and Ground Based Estimates of Precipitation over the Sahel. In: *Atmospheric Research* pp. 25. Laboratoire de Meteorologie Dynamique, CNRS, Ecole Polytechnique, Palaiseau, France.

Limbu B. (2005) Assessment of Rainwater Harvesting Potential in Kathmandu Valley. Schems, Pokhara University, Kathmandu.

Liu G. R., Liu C. C. & Kuo T. H. (2000) Rainfall Intensity Estimation by Ground-Based Dual-Frequency Microwave Radiometers. *Journal of Applied Meteorology* 40: 7.

Michaelides S. C., Gabella M., Perona G., Theofilou K., Papadakis M. & Constantinides P. Validation of TRMM Satellite Rainfall Measurements with In-Situ Rain Gauges in Cyprus. Meteorological Services Nicosia, Cyprus.

Miller J. B. (1997) Floods- People at risk, strategies for prevention. UN New York and Geneva.

Mishra J. K. & Sharma O. P. (2001) Cloud Top Temperature Based Precipitation Intensity Estimation Using INSAT-1D Data. *International Journal of Remote Sensing* 22: 969 - 985.

Pathak P. K. (2007) Country Approach to Disaster Risk Reduction in Nepal. Ministry of Home Affairs /GoN, Kathmandu.

Pradhan L. C., Kyoju S. K. & Shrestha P. M. (2005) Disaster Review 2005. Department of Water Induced Disaster Prevention/GoN, Kathmandu.

Pradhan L. C., Kyoju S. K. & Shrestha P. M. (2006) Disaster Review 2006. Department of Water Induced Disaster Prevention/GoN, Kathmandu.

Pradhan L. C. & Shrestha P. M. (2002) Disaster Review 2002. Department of Water Induced Disaster Prevention/GoN, Kathmandu.

Pradhan L. C. & Shrestha P. M. (2003) Disaster Review 2003. Department of Water Induced Disaster Prevention/GoN, Kathmandu.

Pradhan L. C. & Shrestha P. M. (2004) Disaster Review 2004. Department of Water Induced Disaster Prevention/GoN, Kathmandu.

Rajbhandari R. (2007) Validation of NOAA/CPC Satellite Rainfall Estimates Over Nepal in the Hindu Kush Himalayan Region. Department of Meteorology, Trichandra College, Tribhuvan University, Kathmandu.

Shakya B. (1998) Problems due to some severe floods and other catastrophic events associated with synoptic situation in Nepal. In: *Polish Polar Studies – 25th International Polar Symposium*, Warsza.

Shakya B. (2004) *Elements of Practical Hydrology and Meteorology for Environmental Studies*. Dongol Printers, Kathmandu.

Shakya B. (2007) Application of Satellite Rainfall Estimate in Flash Flood Estimation. Department of Road, Government of Nepal, Kathmandu.

Shakya B., Ranjit R., Shakya A., Bajracharya S. & Khadka N. (2007) Estimation of 2002 Extreme Flood over Balkhu River Using NOAA Based Satellite Rainfall and HEC-HMS Hydrological Model, and Assessment of Flood Education of People Living Near the Flood Risk Zone of Balkhu River. In: *International Symposium on GEO-Disasters, Infrastructure Management and Protection of World Heritage Sites*.

Sharma R. R. (2007) Validation of CPC-RFE Data for Nepal. Department of Hydrology and Meteorology, Nepal, Kathmandu.

Shih S. F. (1989) Potential Application of Satellite Data for Rainfall Estimation. In: *Remote Sensing and Large-Scale Global Processes*. IAHS, Baltimore, M.D.

Sutardi (2006) Action Report Toward Flood Disaster Reduction Indonesian Case. Indonesia Water Partnership.

Suzuki Y., Nakakita E., Hasebe M. & Ikebuchi S. (2004) Study on Rainfall-Topography Relationships in Japan with Regard to the Spatial Scale of Mountain Slopes. In: *Sixth International Symposium on Hydrological Applications of Weather Radar*, Melbourne, Australia.

Tenth Plan (2003). Ministry of Home Affairs and National Planning Commission / GoN.

Tsonis A. A. & Georgakakos K. P. (2005) Observing Extreme Events in Incomplete State Spaces With Application To Rainfall Estimation From Satellite Images pp. 6. Nonlinear Processes in Geophysics.

Vaidhya H. R. (2004) Brief history of flood in Kathmandu since 1988. In: *Kantipur Daily*, Kathmandu.

Vicente G. A., Fmandez J. M., Urunuela J. J. & Rubio M. A. M. (2001) Satellite Rainfall Estimation For Flash Flood Application European Basic Auto Estimator Within The Frame of The SAFNWC pp. 17. SAFNWC/INM.

Vila D. A., Scofield R. A., Kuligowski R. J. & CDavenport J. C. (2004) Satellite Rainfall Estimation Over South America: Evaluation of Two Major Events. Sistema de Alerta Hidrologico / NOAA/NESDIS/Office of Research and Applications / I M Systems Group, Inc.

Wei C. & Cheng K. S. (2005) Study on Rainfall Forecasting by Using Weather Satellite Imagery in a Small Watershed Located at Mountainous Area of Central Taiwan. National Taiwan University, Taiwan, China.

Zongyi F., Naimeng L. & Cheng L. (2004) Preliminary Introduction of NSMC in the Monitoring of Precipitation and Flooding Area with NOAA/AVHRR Data pp. 4. National Satellite Meteorological Center, CMA, Beijing.

Annex