SIGNIFICANCE OF REMOTE SENSING BASED PRECIPITATION AND TERRAIN INFORMATION FOR IMPROVED HYDROLOGICAL AND HYDRODYNAMIC SIMULATION IN PARTS OF HIMALAYAN RIVER BASINS

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ABSTRACT:

The Himalayan region are home to the world's youngest and largest mountains, and origins of major rivers systems of South Asia. The present work highlight the importance of remote sensing (RS) data based precipitation and terrain products such as digital elevation models, glacier lakes, drainage morphology along with limited ground data for improving the accuracy of hydrological and hydrodynamic (HD) models in various Himalayan river basins such as Upper Ganga, Beas, Sutlej, Teesta, Koshi etc. The satellite based rainfall have mostly shown under prediction in the study area and few places have are also showing over estimation of rainfall. Hydrological modeling results were most accurate for Beas basin, followed by Upper Ganga basin and were least matching for Sutlej basin. Limited ground truth using GNSS measurements showed that digital elevation model (DEM) for carto version 3.1 is most accurate, followed by ALOS-PALSAR 12.5 DEM as compared to other open source DEMs. Major erosion and deposition was found in Rivers Bhagirathi, Alakhnanda, Gori Ganga and Yamuna in Uttarakhand state and Beas and Sutlej Rivers in Himachal Pradesh using pre and post flood DEM datasets. The terrain data and river cross section data showed that river cross sections and water carrying capacity before and after 2013 floods have changed drastically in many river stretches of upper Ganga and parts of Sutlej river basins. The spatio-temporal variation and evolution of glacier lakes was for lakes along with GLOF modeling few lakes of Upper Chenab, Upper Ganga, Upper Teesta and Koshi river basin was done using time series of RS data from Landsat, Sentinel-1 and Google earth images.

1. INTRODUCTION AND OBJECTIVES

1.1 Introduction

The mountainous catchments of Himalayan Rivers are constantly under change due to geological, geomorphological, climatic and extreme weather events. The remoteness, ruggedness and inaccessibly of Himalayan terrain poses great challenge for accurate and complete assessment and monitoring of various hydro-meteorological and cryosphere related parameters such as precipitation, air and land surface temperature, river flows, snow and glacier dynamics, glacier lakes and topographical changes (Mukherji et al., 2015; Bharti et al., 2016; Thakur et al., 2019; Maurer et al., 2019; Dimri et al., 2020). The major driving parameter for all hydrological studies in any basin or watershed is accurate spatial and temporal representation of precipitation. Traditional methods of measuring precipitation using rain or snow gauges gives accurate and temporal point based estimates of rainfall, but fails to represent spatial variations in precipitation, especially in mountainous regions or river basins such as in Himalayas, where such field instruments are sparse (Bhatt and Nakamura, 2005; Khandelwal et al., 2015; Thakur et al., 2017). In such scenarios, gridded rainfall products from satellites, climate and weather models, re-analysis data and interpolation gauge data have gained significance in the last 20 years and these rainfall products are used extensively in many validation and hydrological studies in Himalayas (Bookhagen and Burbank, 2006, 2010; Shukla et al., 2014b; Thakur et al., 2015; Bharti et al., 2016; Li et al., 2018; Banerjee et al., 2020).

The second most important parameters for hydrological and river hydraulics study in hilly catchments is topography. The watershed of basin terrain is stable over longer time periods, whereas, river bed or flood plain is highly dynamic with yearly variations. The satellite based DEM have proven to be indispensable for any hydrological and hydrodynamic study in complex rivers basins of Himalaya (Saran et al., 2010; Achleitner et al., 2012; Tan et al., 2015; Dhote et al., 2019). Many parts of upper Himalayan river basin have witnessed large scale river bed erosion and deposition during the major flood events of recent past, which have changed their river bed profile in both lateral and longitudinal directions (Kale and Pramod, 1997; Singh et al., 2014; Shukla et al., 2014a; Devrani et al., 2015; Tombrink, 2017; Paul and Biswas, 2019; Turzewski et al., 2019) after occurrence of each major flood event (figures 14, 19 and 20 in appendix-1).

1.2 Objectives

Therefore, the present work have been taken as part of ISRO sponsored project on flood early warning system for North West Himalaya (NWH). The main objective of the present work are to evaluate the weather research and forecasting (WRF) model with Indian meteorological department (IMD) and satellite based tropical rainfall measuring mission (TRMM) and global precipitation mission (GPM) gridded rainfall datasets and quantify there impact on hydrological models. The other objective is to evaluate the various DEM for watershed hydrology, flood prone area mapping and river hydraulics study especially before and after major flood event of 2013. Lastly, glacier lakes are mapped for few river basins of Himalaya and GLOF modeling is done for few GLOF susceptible lakes of Eastern Himalaya.

2. MATERIAL AND METHODS

2.1 Study area

The study area for this work are Himalayan river basins such as Upper Ganga, Beas, Sutlej, Teesta, Koshi (in Nepal) etc. The NWH region and its selected river basins (figure 1) are used for extensive rainfall analysis, hydrological/hydrodynamic (HD) and DEM based erosion/deposition study. The Koshi and Teesta river basins (figure 3) are mainly used for glacier lake related studies.

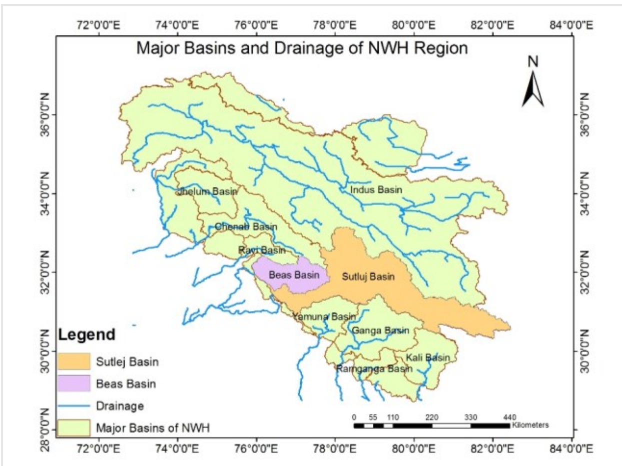

Figure 1. Overall study area in NWH with major River basins and Beas & Sutlej highlighted having good ground data.

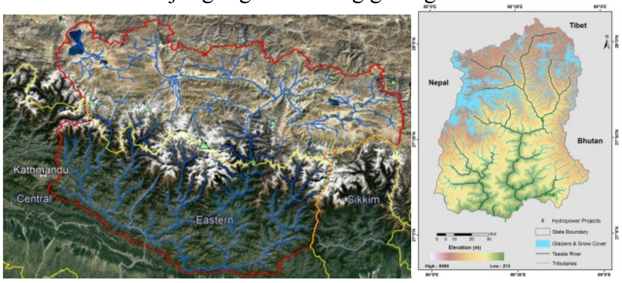

Figure 2. Koshi River basin of East Nepal for glacier lakes mapping and monitoring study & Teesta river basins of Sikkim for glacier lakes mapping, monitoring & modeling study.

2.2 Material and data used

The main data types used in this work are, ground observation data from hydro-meteorological stations, remote sensing based data of rainfall, terrain and multi-temporal multi-spectral images and weather forecast and climate data. The rainfall data from rain gauges and automatic weather stations of IMD and IIRS-ISRO. The discharge data for major rivers from Bhakra Baes Management Board (BBMB) for Beas and Sutlej river basins and Central Water Commission (CWC) for Ganga and Teesta river basins. The satellite based rainfall data is primarily taken from Hydro Estimator Model (HEM), Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) gridded rainfall products. The elevation data from CartoDEM v3 from NRSC, Shuttle Radar Topography Mission (SRTM) 30m, ASTER global 30 m DEM, ALOS 30m DSM, Tandem-x 90m, ALOS-PALSAR 12.5m DEMs and MERIT 90m DEM are used. High Mountain Asia (HMA) 8-meter Digital Elevation Models (DEMs) from NASA's National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC) were utilized for the pre (20 March 2012) and post (17 March 2015) June 2013 floods to quantify the flood inundation, river morphological and topographical changes for Alakhnanda rivers downstream of Badrinath. The mapping and monitoring of glacier lakes is done using the time series of Landsat data from United States Geological Survey (USGS) and Cartosat-1 data from national remote sensing centre (NRSC).

2.3 Methodology

The methods used in this work is divided into three parts. First, method of rainfall data comparisons and hydrological modeling are briefly given. Next, the terrain data analyses and hydrodynamic modeling methods are provided. Finally, the method for Glacier Lakes mapping, monitoring and modeling are given.

2.3.1 Methods for satellite based rainfall comparison and hydrological modeling

A comparative study is also done to check the validation of forecasted data with different meteorological data. For comparative study different parameters are calculated using the contingency table (table 1). The parameters that are calculated for comparative study are given below:

2*2 Contingency Table		Event Observed	
		Yes	No
Event Forecast	Yes	a (hits)	b (false alarms)
	No	c (misses)	d (correct negatives)

Table 1: Contingency table for rainfall statistical computation

- Bias = (a+b)/(a+c)
- Mean Absolute Error = $((1/n\sum_{i=1}^{N}|$referenced value-calculated value$|)$
- Root Mean Square Error= $\sqrt{(1/n\sum(\text{reference value-calculated value})^{2})}$
- False Alarm Ratio = b/(a+b)
- Critical Success Index = a/(a+b+c)
- Probability of Detection = a/(a+c)
- Probability of False Detection = b/b+d

The forecasted precipitation from WRF model, or from IMD, AWS and TRMM/GPM data are used in semi-distributed,

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watershed based Hydrological Modeling System (HMS) hydrological model (HEC-HMS, 2010) or at 2.5 km grid scale using fully distributed variable infiltration capacity (VIC) model (Wood et al., 1997). The basic maps like land use land cover (LULC), soil, DEM are also used in both hydrological models for creating necessary input layers (Roy, 2018). The watershed and terrain processing in done using HEC-GeoHMS tool in ArcGIS environment for watershed delineation, stream network pattern and catchment characteristics estimation. The calibration and validation of both the models is done for Beas, Sutlej, Jhelum and Upper Ganga basins.

2.3.2 Methods for satellite based terrain data and hydrodynamic modeling

The elevation accuracy of various DEMs are accessed GNSS based ground control points in parts of upper Ganga basin. The comparison of DEM based delineated watershed and rivers is done using Sentinel-2, Landsat-8 and Google Earth images. For the river morphology study, the Post-Event and Pre-Event DEMs were subtracted using the “Raster Calculator” in GIS environment for quantifying the erosion/deposition before and after 2013 flood event of Uttarakhand. By their subtraction, positive and negative digital values were generated corresponding to each pixel (figure 3).

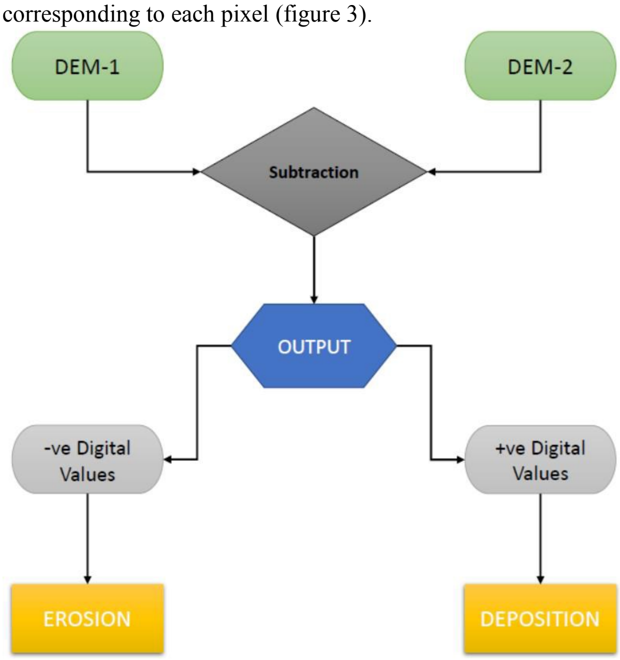

Figure 3. DEM differencing method for river erosion/deposition study using pre-post flood event DEM data.

The stream parameters and river cross sections are derived using ALOS 12.5 and CartoDEMs in HEC-GeoRAS tool of ArcGIS and Mike hydro tool of Mike-11 HD model. The generated river network and cross-sections are used in Mike-11 HD model along with boundary condition and HD parameter settings to simulate the river flows due to heavy rainfall events based flash floods (flood hydrographs as input boundary condition are output of hydrological model) GLOF (glacier lake breach scenarios) events (Thakur et al., 2016, 2017). Evaluation of terrain data from DEMs is also utilized in the Height Above Nearest Drainage (HAND) tool (Renno et al., 2008) to identify the flood prone areas of NWH region.

2.3.3 GLOF mapping, monitoring and modeling

The mapping of glacier lakes is done using Normalized Difference Water Index (NDWI), which delineates open water features and enhances their presence in the remotely sensed digital imageries like Landsat, Resourcesat and Sentienl-2. The NDWI makes use of reflected near-infrared radiation and visible green light to enhance the presence of water bodies (McFeeters, 1996). The NDWI map time series to map glacier lakes are generated using Google Earth Engine (Gorelick et al., 2017).

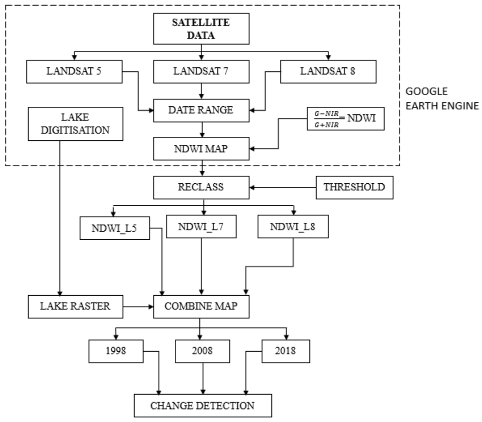

Figure 4. Glacier lake mapping using NDWI method and GEE.

The susceptible glacier lakes are identified using multi-criteria methods (Aggarwal et al., 2017). The modeling of critical GLOF susceptible lake is accomplished using one dimensional 1-D HD model (Thakur et al., 2016).

3. RESULTS AND DISCUSSION

The results and discussion are arranged in three sub-sections. In the first sub-section, inter comparison of forecasted, IMD satellite based gridded rainfall products is given along with its use and impact on hydrological simulations in selected NWH river basins. In 2nd part, results of DEM accuracy assessment, terrain, watershed parameters, erosion/deposition from flood events and impact on river cross-sections and profiles is presented. In final part, glacier lake mapping and modeling results are presented.

3.1 Results of satellite based rainfall and its impact on hydrological modeling

The satellite based precipitation products such as Tropical rainfall measuring mission, TRMM and global precipitation measurement mission, GPM are first compared with gridded rainfall data from IMD (figure 6), weather forecast models and limited ground based automatic rain gauge datasets and later used for generating flood hydrographs using hydrological models.

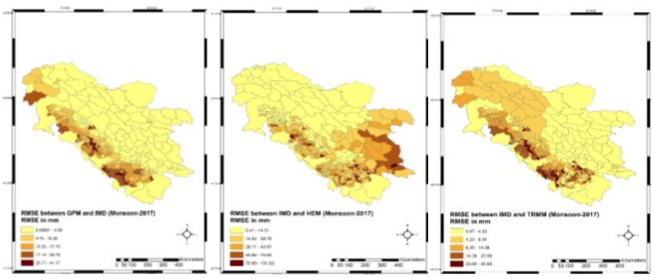

Figure 6. RMSE maps for 2017 Monsson for GPM, HEM and TRMM rainfall data as compared with IMD datasets.

The satellite based rainfall have mostly shown under prediction in the study area and few places have are also showing over estimation of rainfall. The GPM, TRMM errors are comparable which shows high difference in rainfall in lower and middle elevation ranges of NWH, whereas, HEM data more mismatch in Tibet region of Sutlej and Indus basins (figure 6). Overall at basin scale, comparative maps of different parameters shows that WRF data is well suited for rainfall forecasts, provided proper physics options and elevation option are chosen (table 2 and figure 7, Dhote et al., 2018; Navalea and Singh, 2020).

Comparative Values For TRMM, WRF &GPM(Year-2015)

		TRMM&WRF							GPM&WRF						
BASIN NAME	DATE/COMPARATIVE PARAMETERS	RMSE	MAE	MBE	FAR	CSI	POD	POFD	RMSE	MAE	MBE	FAR	CSI	POD	POFD
	22july-26jul	10.05	8.89	6.11	1.00	0.00	0.00	0.29	8.10	6.99	6.99	1.00	0.00	0.00	0.50
	28jul-30jul	7.38	4.94	4.39	0.00	1.00	1.00	0.00	4.28	4.01	4.01	1.00	0.00	0.00	1.00
	11aug-17aug	1.75	1.41	1.37	NA	0.00	0.00	0.00	1.57	1.29	1.29	0.00	0.00	0.00	0.00
	18aug-25aug	1.78	1.25	0.86	NA	0.00	NA	0.00	2.11	1.58	1.58	0.00	0.00	0.00	0.00
Ganga Basin	27aug-31aug	2.45	1.54	1.51	0.00	0.00	0.00	0.00	0.03	0.02	0.02	0.00	0.00	0.00	0.00
	22july-26jul	17.38	14.12	13.50	0.67	0.25	0.50	0.29	11.99	10.86	10.86	0.75	0.20	0.50	1.00
	28jul-30jul	10.91	7.28	5.51	0.00	1.00	1.00	0.00	8.06	7.87	7.87	1.00	0.00	0.00	1.00
	11aug-17aug	4.99	3.77	3.59	1.00	0.00	NA	0.75	4.88	3.66	3.66	1.00	1.00	1.00	0.43
	18aug-25aug	3.30	1.80	0.46	NA	0.00	0.00	0.00	1.16	0.84	0.84	0.00	0.00	0.00	0.00
Yamuna Basin	27aug-31aug	4.12	2.09	2.09	0.00	0.00	0.00	0.00	0.04	0.02	0.02	0.00	0.00	0.00	0.00
	22july-26jul	10.20	9.20	4.64	1.00	0.00	0.00	0.75	9.86	8.83	8.83	0.40	0.60	1.00	1.00
	28jul-30jul	12.66	11.12	11.12	0.66	0.33	0.33	1.00	15.37	12.65	12.65	1.00	0.00	0.00	1.00
	11aug-17aug	2.08	1.65	1.28	0.00	0.00	NA	0.00	2.56	1.80	1.80	0.00	0.00	0.00	0.00
	18aug-25aug	2.96	2.41	0.89	0.00	0.00	0.00	0.00	1.90	1.67	1.67	0.00	0.00	0.00	0.00
Sutlej Basin	27aug-31aug	8.68	5.48	5.47	0.00	0.00	0.00	0.00	0.90	0.76	0.76	0.00	0.00	0.00	0.00

Table 2. Rainfall data comparison for WRF model with GPM and TRMM hourly datasets.

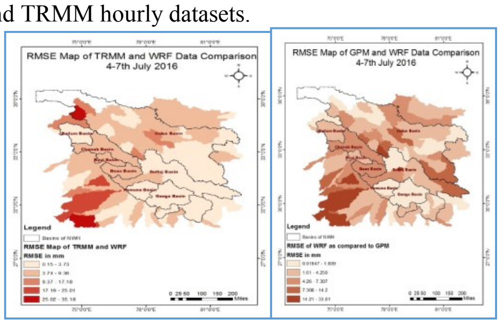

Figure 7. RMSE map between WRF-TRMM rainfall data for one of the 2016 monsoon rainfall event.

When this rainfall data from satellites and WRF model are used for hydrological simulation in Upper Ganga basin, part of Alakhnanda basin showed over estimation/prediction of rainfall resulting in high runoff generation, but for the Beas basin difference between satellite and ground based rainfall was less, which resulted in high accuracy of simulated flood hydrographs. Hydrological modeling results were best for Beas basin, followed by Upper Ganga basin and were least matching for Sutlej basin. The HMS model (with rainfall from TRMM and ground based AWS network) was used for simulating the 3 hourly flood event of August 2014 and 2015 in Beas basin and gave high accuracy in terms of R^2 of 0.93 and 0.89 resp.

Station Name	Basin Name	R^2	N-S Efficiency	RMSE (cumecs)	Annual Discharge (cumecs)	Monsoon Average Flow (cumecs)
Rampur	Sutlej	0.66	0.46	303.98	238.12	668.42
Kasol		0.65	0.52	810.14	244.95	694.85
Sunni		0.69	0.35	536.43	243.52	686.87
Sujanpur Tira	Beas	0.83	0.738	410.03	251.88	565.29
Nadaun		0.82	0.799	353.80	267.28	598.53

Table 3. Hydrological model validation results for Beas and Sutlej river basins as simulated by VIC model (Roy, 2018).

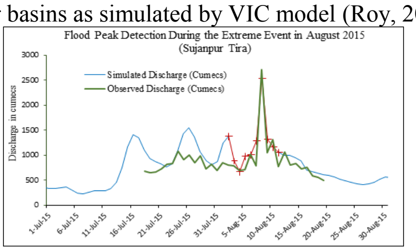

Figure 8. Hydro model results in WRF forecast mode.

3.2 Results of satellite based terrain data and its impact on hydrodynamic modeling

Limited ground truth using GNSS measurements showed that ALOS-PALSAR 12.5 DEM (mean bias of 0.285 m) followed by carto DEM version 3.1 (mean bias of 1.65 m) and ALOS 30 m (mean bias of 2.086 m) are found to be most accurate as compared to other open source DEM such as MERIT, SRTM, and ASTER DEMs. The watershed delineation by ASTER 30m (2011), Tandem-x 90m (2016) and SRTM 90 DEM (2000) for Koshi basin showed slightly different watershed areas (57680.8 km², 57639.90 km² and 57658.1 km² respectively. There was no change in number of sub-watersheds and streams in all three DEMs, but river length varied in each DEM, mainly due to shifting and erosion/deposition of river course and bed material between different DEMs.

Similarly, the major erosion and deposition was found in catchments of river Bhagirathi, Alakhnanda, Gori Ganga and Yamuna in Uttarakhand state and Beas and Sutlej river catchments in Himachal Pradesh using HMA and other terrain datasets. The river cross-section and longitudinal profile data showed that river cross sections before and after 2013 floods have changed drastically in many river stretches of upper Ganga and parts of Sutlej river basins. Similarly, flood events of 2014, 2015, 2016 and 2018 have impacted Beas River and its tributaries cross sections and longitudinal profiles as well. The results of HMA 8 m DEM (post flood, 2015 time) and Aster 30 m DEM (pre flood, 2011 time) on river bed is shown in figure 9, showing areas of erosion and deposition. The sediment deposition area is much higher than the eroded area in this part river stretch.

Figure 9. Impact of 2013 flood in parts of Alakhnanda River elevation near Hanuman Chatti and Govindghat, Uttarakhand.

The changed river bed profile and cross sections have significant impact on the HD model results in terms of change in water level and discharge for a given peak flow. In some areas, water carrying capacity of river channel have increased due to erosion and in some places it has shown significant decrease due to sediment deposition.

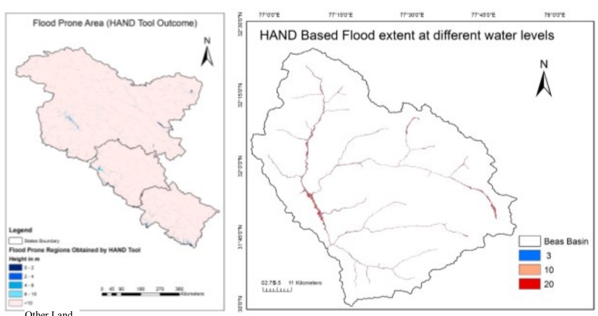

Figure 10. HAND based flood prone areas for NWH region and Beas river basin.

As ALOS-PALSAR 12.5 DEM was found to be most accurate in NWH region, this DEM was used for generating topography based flood prone areas using HAND tool in ArcGIS. The initial results are shown in figure 10 for NWH region and Beas basin upto Pandoh dam.

3.3 GLOF mapping, monitoring and modeling

The spatio-temporal variation and evolution of glacier lakes was for lakes of Upper Chenab, Upper Ganga, Upper Teesta and Koshi river basin was done using time series of RS data from Landsat, Sentinel-1 and Google earth images. Koshi basin of Nepal covering Everest and surrounding region have shown largest increase in the glacier lakes in last 40 years, followed by glacier lakes of Upper Teesta, Chenab and Ganga river basins. Some of these lakes are highly susceptible for glacier lake outburst floods, GLOF. The GLOF modeling at various lake breach scenarios for some of highly vulnerable and large glacier lakes was done using 1-D HD models, with inputs from ALOS 12.5 and Carto-v3.1 DEM.

Year	Number of lakes	Number of Newly formed lakes	Total Area (km^2)	Change in Area (km^2)
1998	297	---	509.8347	---
2008	317	20	518.9355	+9.1008
2018	331	14	521.2359	+2.3004

Table 4. Evolution of glacial lakes at different periods 1998, 2008 and 2018 for Koshi basin, East Nepal.

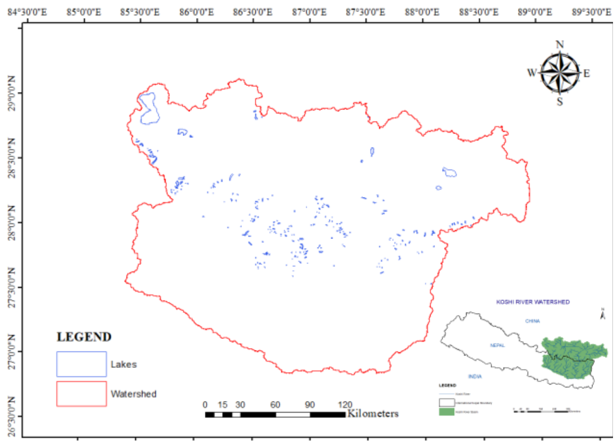

Figure 10. Mapped glacier lakes of Koshi Basin, east Nepal

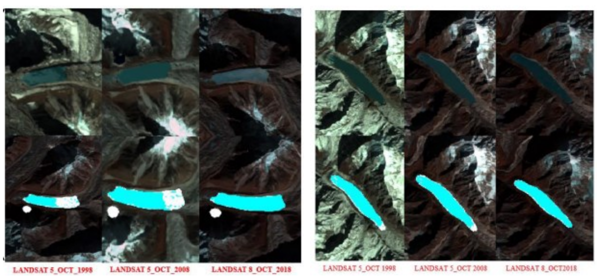

Figure 11. Evolution of Imja and Tsho Ralpa glacier lakes from 1998-2018 using Landsat datasets.

Two major glacier lakes which are susceptible for GLOF, such as Imja lake expanded by 126.6% from 1998 (0.9288 km^2) to 2008 (1.1754 km^2) and by 146% from 2008 to 2018 (1.7154 km^2), whereas Tsho Ralpa lake remained relatively stable from 1998 (1.70 km^2) to 2018 (1.778 km^2). A total 70 numbers of common glacier lakes are mapped during 1998-2018, all showing increase in lake area. The susceptible glacier lakes of Teesta basin of Sikkim are shown in figure 12.

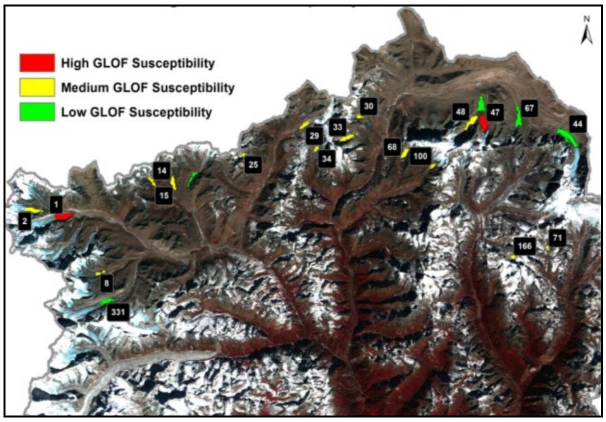

Figure 12. Susceptible glacier lakes of Teesta basin of Sikkim (Aggarwal et al., 2017).

The 1-D HD model simulations (using SRTM 30 m DEM and scenario of 20 m of glacier lake breach) for upper Thangu cascade lakes of North Sikkim showed that peak flow 8548 m^3/s at the lake site within 39 min., followed by peak flow of 7541 and 6147 m^3/s at downstream of army base camp and Thangu village within 3 min and 12 min, respectively (Aggarwal et al., 2017). Similarly GLOF simulations for Chubda glacier lake of Bhutan and Gapang glacier lake of H.P., India was completed using Mike-11 1-D HD model for various lake breach scenario. The figure 13 shows the Chubda glacier lake, river cross-sections and simulated flood inundation at one of the vulnerable road, human settlement and airport site situated downstream of lake on left river bank (Jakar town). In both these cases also SRTM-30 m DEM was used to create river cross-sections. The simulated peak flow at lake sites varied from 17,329 cumec to 34,658 cumec for lake depth of 10 to 20 m (area of lake is 1.38 km^2 in 2016, and volume of 5.54 Mm^3), with 40 mins of flood duration time at lake site. This value will further reduce to 10, 500 cumec if flood duration at lake site is increased to 2-3 hrs.

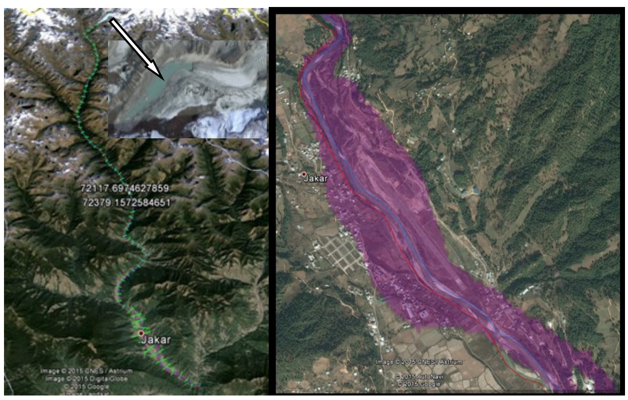

Figure 13. Chubda glacier of Bhutan and its GLOF scenario simulation based inundation at Jakar town, showing possible inundation of human settlements, roads and air strip.

Most of the glacier lake which are prone for GLOF, have hydro-power, road and village settlements as elements at risk.

4. CONCLUSIONS AND FUTURE SCOPE

The present work has highlighted the importance of satellite derived precipitation and terrain information for mountainous catchments of Himalaya. The GPM, HEM and TRMM data can be used along with forecasted WRF data in NWH region with certain degree of confidence. The spatial pattern of satellite and forecasted rainfall data matched more than the single point based AWS based rainfall values. Further improvements, specific to Himalayan region is needed in both satellite and numerical weather prediction models, so as to improve their utility in flood simulation and hydrological forecasting models. In hydrological models, the event based HMS model has given better results for simulating the hourly flood peak as compared to the daily grid based VIC model.

The terrain data given by various global and regional DEM is of good accuracy for operational watershed terrain parameter generation, hydrological simulations and 1-D HD simulations. But the same data, may not be sufficient for temporal time series analysis of pre and post flood event river morphological studies. In that case, high resolution (HR) DEMs such as HMA 8m and ALOS 12.5 m and Carto-10 m DEM shows better potential. In future, use of drones, Icesat-2 and other HR optical and radar/LIDAR based DEM should be generated for critical river and glacier lakes of Himalaya.

In case of glacier lakes, regular monitoring of all susceptible glaciers is most important, as many of these lakes have breached in past (Nie et al., 2018), and have potential to breach again, due to dynamic hydro-glacio-climatic and extreme weather events of Himalaya. At the same time, satellite or ground based glacier lake depth or volume estimate and high resolution terrain data is most critical to get the improved GLOF scenarios. In future use of more open source 1-D and 2-D HD models can be explored in such high relief mountain regions.

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APPENDIX - I

The appendix give information about location of IIRS-AWS sites in NWH, basic model configuration, outputs of models simulations and few field photographs.

Figure 14. Extensive river bed and channel erosion at Gaurikund, after June 2013 Kedarnath flood event. Picture by (Dr Praveen K. Thakur, Oct., 2013 flood survey).

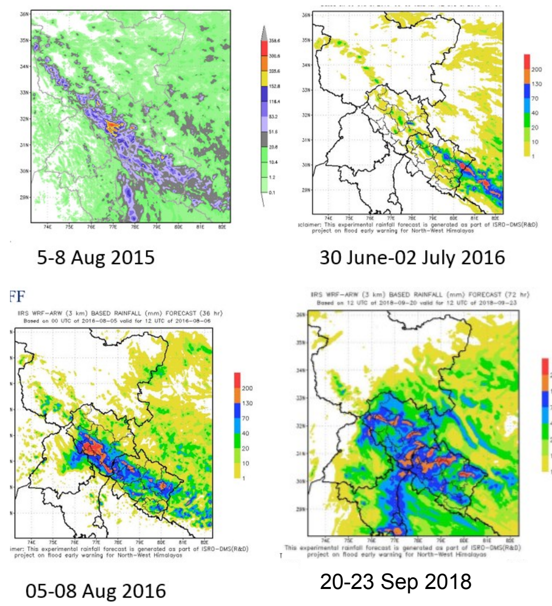

Figure 15. Major flood events simulated by correctly by WRF in NWH during 2015-2018 time period.

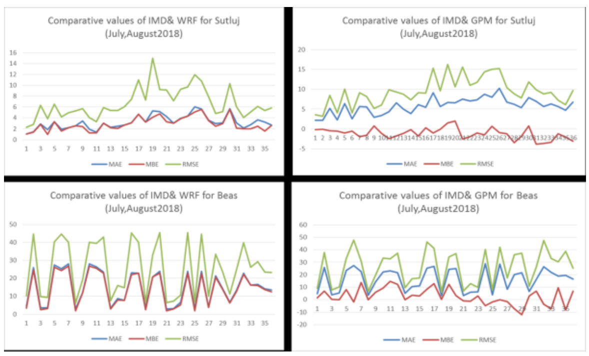

Figure 16. Comparison of WRF and GPM rainfall data with IMD for 2019 Monsoon in Sutlej and Beas basins.

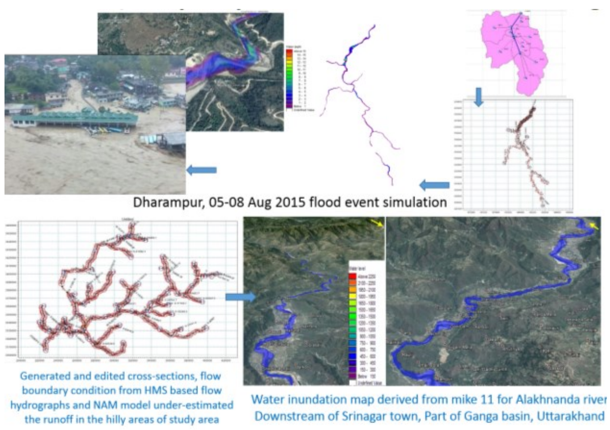

Figure 17. Hydrological and 1-D HD model setup and simulation results of few sites in Beas basin and Upper Ganga river basin

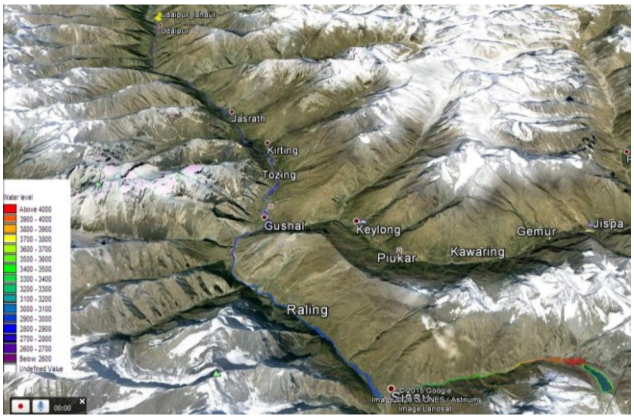

Figure 18. Simulated GLOF scenario (with water level at WRS 84 datum) for Gepang Glacier Lake to Udaipur in H.P., India.

Figure 19. Extensive river bed and channel erosion at downstream of Rambara, after June 2013 Kedarnath flood event (Picture by Dr Praveen K. Thakur, Oct., 2013 flood survey).

Figure 20. Extensive river bed and channel erosion along with landslides at upstream of Rambara, after June 2013 Kedarnath flood event (Picture by Dr Praveen K. Thakur, Oct., 2013 flood survey).

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