# INCORPORATION OF SNOW AND GLACIER MELT PROCESSES IN RRI MODEL FOR ESTIMATING PEAK RIVER DISCHARGES AND INUNDATION ANALYSIS IN NEELUM RIVER BASIN

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**ABSTRACT**

There is no hydrological model that can produce inundation by simulating rainfall, snow and glaciermelt together. In this study, Neelum river basin was studied where extreme monsoon weather events augmented by snow and glacier melts trigger the flood frequently and cause damages because of narrow flood plain, residential and commercial activities within the flood plain. There is considerably less ground rainfall information in the Neelum basin for it is a transboundary basin having only one rain gauge at Muzaffarabad. Therefore, the RRI-snow-Glacier (RRI-SG) model was developed in Gilgit basin that has three rain gauges inside the basin. The snow and glacier melt algorithms were incorporated in RRI Model based on degree-day method and satellite snow images. After having confidence that the new model was working well, the model was applied in Neelum river basin to analyse the flood 2010. In order to address the non-gauging and transboundary issue of the basin, satellite observed rainfall (GSMaP-NRT) was corrected by a method proposed by JAXA based on ground rainfall data. The model simulation results showed that the new developed RRI-SG model is a simple, effective and easily applicable to produce flood warning and inundation by simulating the combine effects of rainfall, snow and glacier melts. Lastly, the inundation analysis of the Neelum River basin was accomplished using RRI-SG Model and validated using remote sensing technique. A flood hazard map for Muzaffarabad, based on a 100-year return period future extreme event, was developed. The results showed that both the banks of the Neelum River are under risk of future extreme events.

Keywords: RRI Model, Snowmelt, bias correction, Flood Plain Management

## INTRODUCTION AND BACKGROUND

About 85% of the annual flows of Indus River is due to snow and ice melts while 11.5% of the total area of Upper Indus Basin i.e. 22,000 Km$^2$ is covered by perennial glacial ice (Hewitt, 2001). Like other many developing countries, Pakistan is also facing impacts of floods. In Pakistan, generally heavy concentrated rainfall during Monsoon period cause the flooding. However, in Northern areas of the country, heavy rainfall events augmented by snow and glacier melts cause the river flooding. The main reasons for flood damages are either poor or absence of integrated flood risk management in many flood prone basins.
The main objectives of the study were;

- To incorporate and investigate the combine effects of rainfall, snow and glacier melts in RRI model.
- To accomplish the inundation analysis of River Neelum for better flood plain management, adaptation and mitigation.

For this study, Neelum river basin was selected as a study area. It lies in the North East of Pakistan. It is a part of Mangla Basin and a transboundary basin for some of its part lies in Indian held Jammu Kashmir. The River Neelum originates from a lake known as Vishansar Lake, in Indian held Jammu Kashmir. The mouth of Neelum River lies in Muzaffarabad City at Domail. The basin topography is mostly mountainous, covered with thick forests.

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Key information of Neelum River Basin are appended in Table I.

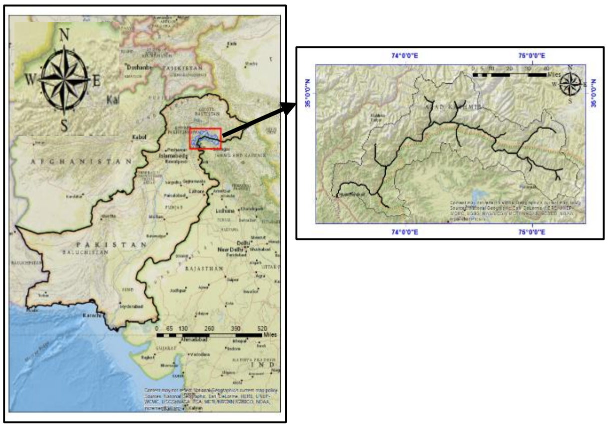

Fig 1: Location of Study Area in Pakistan
(Source: Author created using GIS Tools)

Table I: Study area information

| Neelum River Basin | |
|---|---|
| River Flow Gauging Station | Muzaffarabad |
| Latitude | 34°22'3''N |
| Longitude | 73°27'47.88''E |
| Elevation of Gauging Station | 670 m |
| Drainage Area | 7278 $Km^2$ |
| Mean Elevation | 3363 m |
| No. of Meteorological Stations | 01 (Installed by PMD) |
| | Muzaffarabad<br>670 m |

## METHODOLOGY AND THEORY

Rainfall Runoff Inundation model is a two dimensional model that can simulate rainfall-runoff and flood inundation simultaneously (Sayama et al., 2012). The flow on the slope grid cells is calculated with the two dimensional diffusive wave model, while the channel flow is calculated with the one dimensional diffusive wave model. The model simulates also lateral subsurface flow, vertical infiltration flow and surface flow. The vertical infiltration flow is estimated by the Green-Amp model (RRI User's Manual). However, the model does not include the snow and glacier melt processes. Therefore, snow and glacier melt processes based on the Degree day method were incorporated in the model. Temperature at each cell was calculated from the following equation based on the observed average temperature and Temperature Lapse Rate (TLR).

$$Lapse\ Rate = -\frac{change\ in\ Temperature}{change\ in\ Elevation} \quad \text{(A)}$$

Snow and glacier melts (mm/day) at each grid cell, if snow count was one, was calculated from the following relation;

$$Melt = (T_a - T_b)\ X\ DDF \quad \text{(B)}$$

Where DDF=Degree Day Factor, $T_a$= mean daily air temperature in °C and $T_b$= base temperature in °C

Where value of Degree Day Factors (DDF) for snow and glacier were set as 2 mm/°C/day.

The model source code was modified to ensure that both the snow and glacier melt at each cell, calculated as per above mentioned physics, were added to the ground observed rainfall (mm/day or mm/hr) and model was run to simulate the 2010 flood event in the study area. In order to tackle the transboundary basin and under gauging issue, Near Real Time Global Satellite Mapping of Precipitation (GSMaP_NRT) was corrected by a method proposed by Japan Aerospace Exploration Agency (JAXA) based on ground rainfall data.

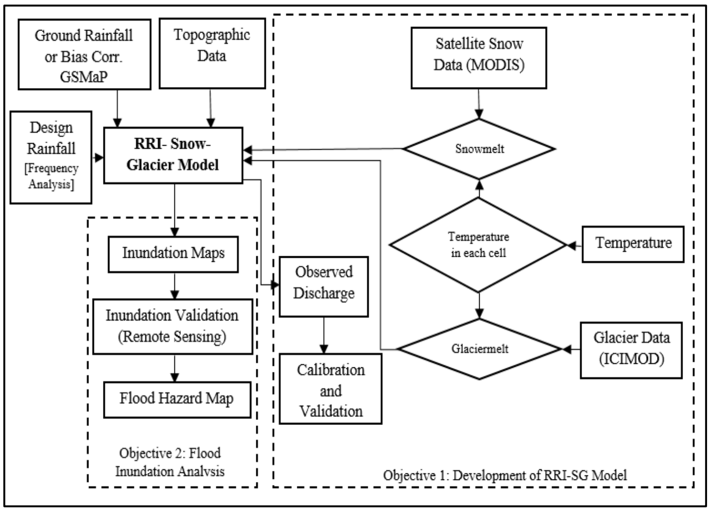


Fig 2: Study Methodology

## DATA

Inundation analysis is one of the objective set for this study therefore, Rainfall-Runoff Inundation (RRI) Model was used for this study. The original model requires topographic and precipitation data as its basic inputs. The model does not consider the snow and glacier melt processes. As discussed earlier, the study area also receives the snow during winter season therefore the model was required to be modified by incorporating the snow and glacier melt processes based on degree day method and satellite snow data. Therefore, in addition to basic inputs, MODIS snow cover data, glacier cover data and temperature were also required for this study.

### *Topographic Data*

Digital Elevation Model for Asia was acquired from United State Geographical Survey (USGS) HydroSHEDS to delineate the study area. The study area was delineated using GIS techniques. Then ASCII format files of DEM, flow direction and flow accumulation for the study area were prepared.

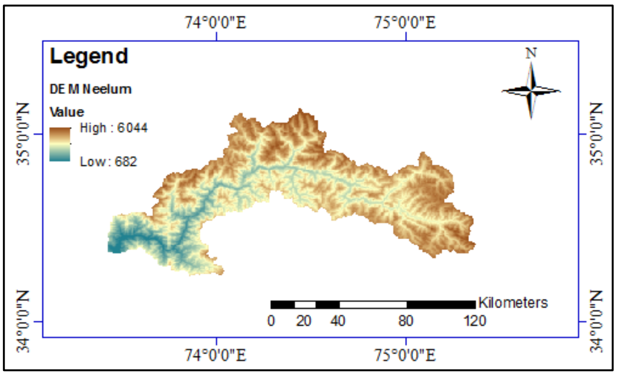


Fig 3: Digital Elevation Model of Neelum River Basin (HydroSHEDS)

### *Precipitation Data*

There is only one meteorological station in the basin at Muzaffarabad, therefore, ground rainfall from Eight basin outside laying rain gauges were used initially.

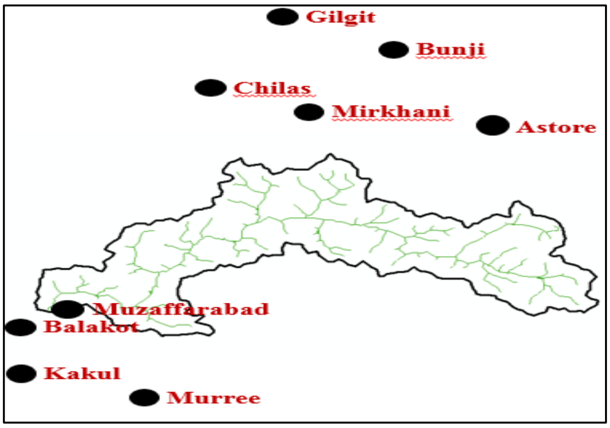


Fig 4: Location of Meteorological Stations in Study Area

### *Snow and Glacier Cover Data*

Snow Cover data was obtained from Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS/Terra Snow Cover Eight-Day L3 Global 500 m Grid (MOD10A2) for year 2010 were used for this purpose. Out of the eight bands, only first band was used. Glacier Data was acquired from International Centre for Integrated Mountain Development (ICIMOD).

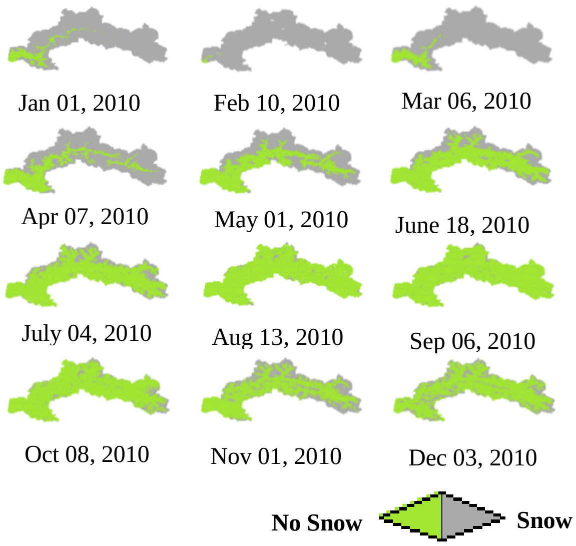


Fig 5: Snow Cover Maps for Study area (MODIS)

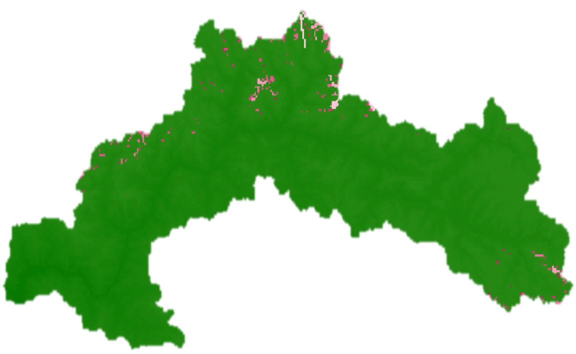

Fig 6: Glacier Map of Neelum River Basin (ICIMOD)

## RESULTS AND DISCUSSION

### *RRI Simulations in Gilgit River Basin*

From the MODIS snow cover maps for the study area, it was clear that snow melt was also contributing to the Neelum river runoff, therefore, incorporation of snowmelt process in RRI model was required. However, since Neelum river basin has very less ground rainfall inside the basin even in Pakistan's territory, therefore, the RRI-SG model was developed in Gilgit basin which is a part of upper Indus river basin and has three rain gauges inside the basin. The results are shown in Fig 7.

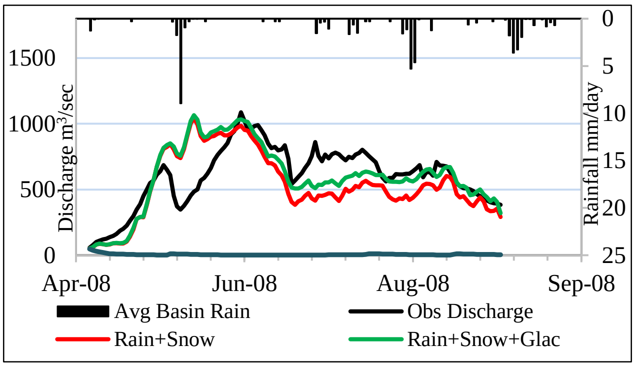


Fig 7: Observed and simulated discharge hydrographs at Gilgit Station (Ground Rainfall, snow & Glacier)

### *RRI Simulations in Neelum River Basin*

Having confidence that the model was working well, it was applied in the Neelum river basin. Fig 8 shows RRI simulation based on ground rainfall only that shows there was underestimation during March to June because snow melt was not considered. Figure 9 shows the RRI-SG model simulation based on ground rainfall, snow and glacier melt together. However, due to less glacier cover map, the contribution from glacier melt was not prominent.

Since, most of gauges were outside the basin, therefore, GSMaP-NRT was corrected based on JAXA's correction method. The method proved to be effective to obtain good rainfall distribution maps inside the basin with the help of basin outside lying rain gauges. RRI-SG simulation for bias corrected GSMaP-NRT, snow and glacier melt together is shown in fig 10.

After that, through sensitivity analysis, the model was calibrated and validated. The fig 11 and 12 show the results.

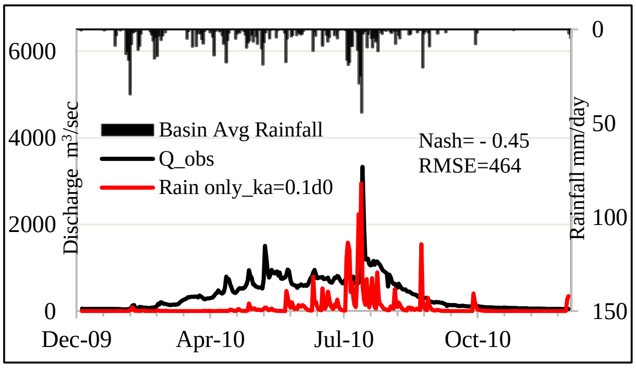


Fig 8: Observed and simulated discharge hydrographs at Domail Station (Ground Rainfall only)

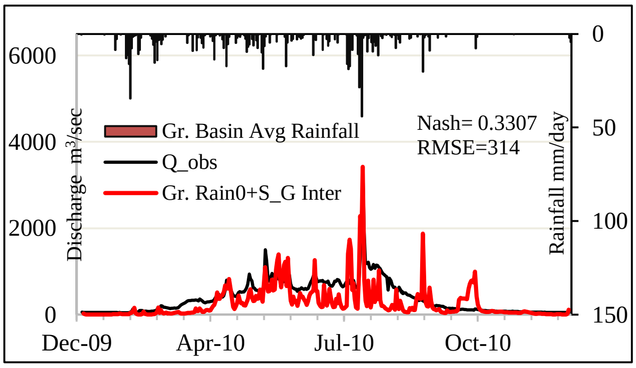


Fig 9: Observed and simulated discharge hydrographs at Domail Station (Ground Rainfall, snow & Glacier)

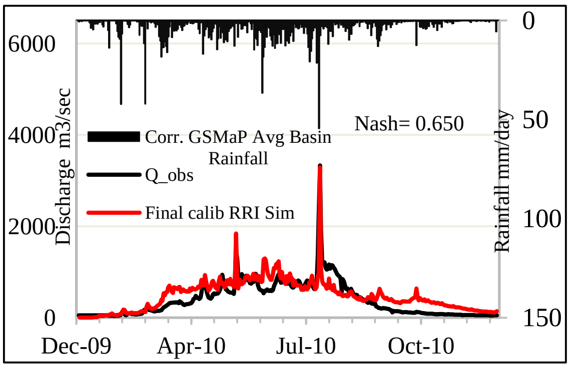


Fig 11: Final Calibrated RRI-SG Simulation

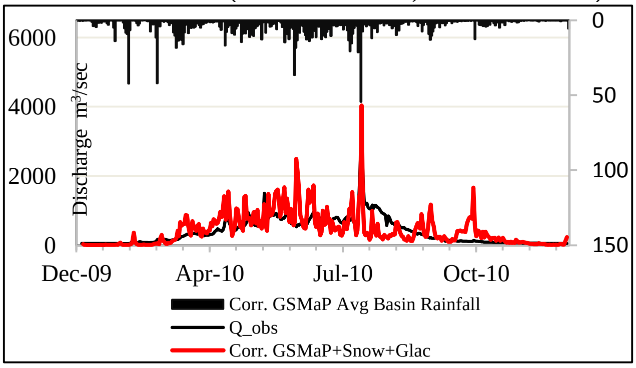


Fig 10: Observed and simulated discharge hydrographs at Domail Station (Corr. GSMaP, snow & Glacier)

*Flood Inundation analysis in Neelum Basin*

In order to achieve the second objective of this study, inundation output from the RRI model was used to produce the flood inundation map for the year 2010 in Muzaffarabad and its surrounding areas. For validation, modified gradient based remote sensing technique was used which although showed overestimation but similar pattern of inundation was observed. The results are shown in fig 13 and 14.

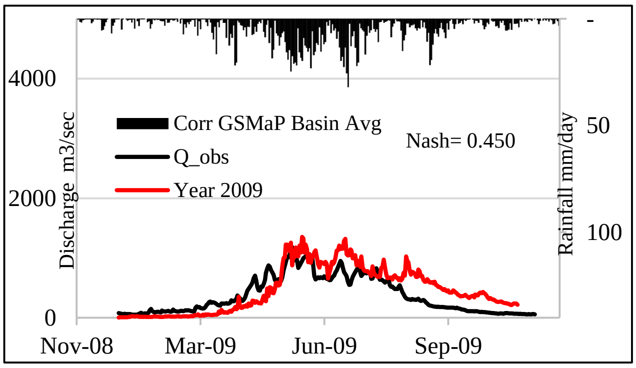


Fig 12: RRI-SG Model Validation (2009)

*Frequency Analysis results*

Annual Maximum Rainfall data for period (2001- 2010) for Muzaffarabad, Balakot and Astore Rain gauge stations were used to calculate 100 year return period extreme rainfall events based on Gumbel and Generalized Extreme Value distributions and cunnane method.

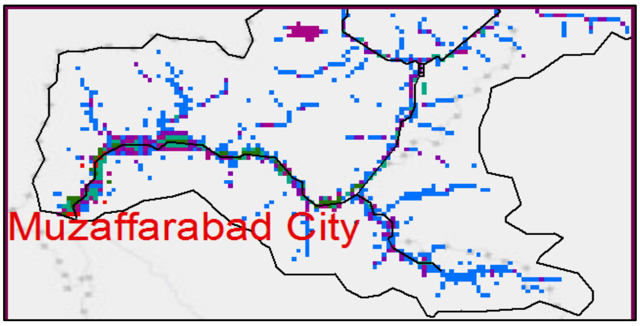


Fig 13: Flood 2010 Inundation in Muzaffarabad and surrounding areas on July 30, 2010

*Future Flood Inundation*

Finally, based on the results of frequency analysis of future extreme event, the inundation from the model was obtained and flood hazard map for Muzaffarabad city and its surroundings based on 100-year return period event was developed. Figure 14 shows the 100-year flood hazard map for Muzaffarabad and its surrounding areas. Its shows the flood plain of the river is under risk of a future flood.

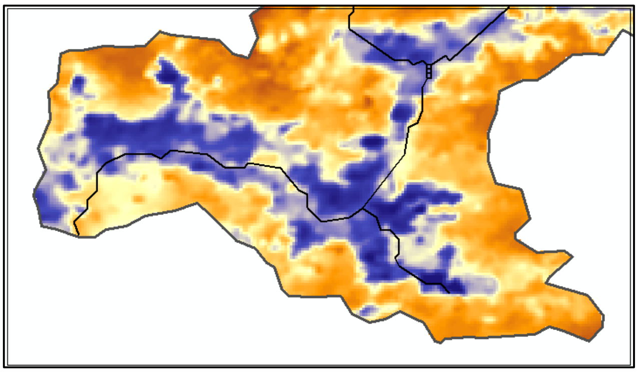

Fig 14: Validation of flood 2010 inundation by modified gradient based method (MOD9A1, 8-day composite 500 meter July 8 to Aug 4, 2010)

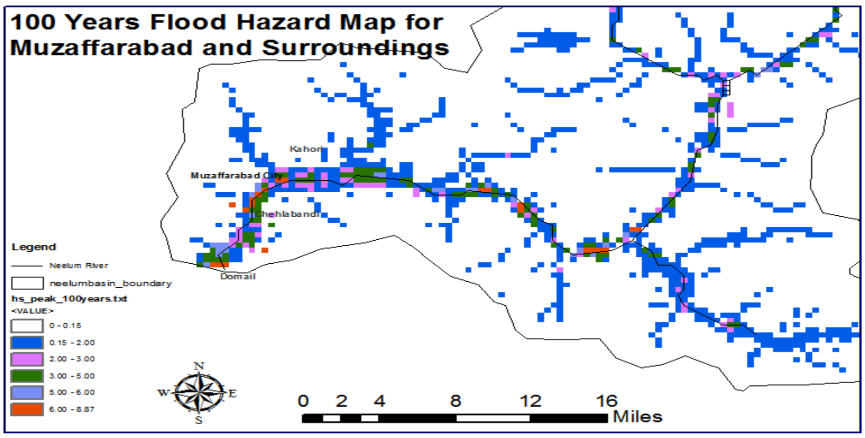


Fig 15: Flood Hazard Map for Muzaffarabad and surroundings (100 Year return period)

## RECOMMENDATIONS

The following are the few recommendations based on this research.

i. Integrated Flood Risk Management in the flood plain of Neelum River is required. Therefore, Early Warning System and contingency planning should be ensured. In addition to that, policies and strategies regarding existing and future settlements should be formulated.

ii. Awareness regarding future possible flood risk and early evacuation may be raised among the community. In addition to it, early evacuation drills may also be conducted.

iii. The RRI-SG model should be applied in the whole Indus River basin for flood forecasting, inundation analysis and detail damage assessment purposes.

iv. A suitable number of meteorological observatories at suitable locations should be installed for flood forecasting purposes.

v. Effectively collaborated institutional arrangements in AJ&K are necessary for observing meteorological and river flow data, forecast and carrying out countermeasures against.

## ACKNOWLEDGEMENTS

All the praise and glory to Almighty Allah Who is the most merciful and beneficial. First of all, I would like to express my gratitude to Japan International Cooperation Agency (JICA) for providing me this mammoth opportunity of my entire life.

This dissertation would not have been possible without the support, worthwhile knowledge and suggestions of many personalities. I have been privileged to accomplish this research under the kind supervision of Associate Professor Dr. Mohamed Rasmy. I acknowledge with my deepest gratitude his endless support, expert guidance, encouragement and motivation in exploring new horizons of research.

I would also like to express my heartedly indebtedness to sub supervisor Prof. Toshio Koike for his guidance, incredible patience, thoughtful questions, comments and valuable suggestions. A time-to-time meeting conveyed with an internationally reputed Professor like him proved a milestone in achieving the objectives set for this study.

In addition, I am deeply thankful to co-supervisors Dr. Morimasa Tsuda and Dr. Liu Tong for their valuable knowledge and suggestions. I am grateful to Mr. Takashi Shirai and Miss Yukie Okawa, who were always readily available to support me with their best.

Last but not the least, I want to thank to all of my family members and specially my mother and wife for their unconditional love. Their support and prayers always made it possible the way I wished.

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