SIMULATING HYDROLOGICAL RESPONSE OF SNOW AND GLACIER MELT AND ESTIMAING FLOOD PEAK DISCHARGE IN SWAT RIVER BASIN, PAKISTAN

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ABSTRACT

Pakistan is a flood prone country and undergo flood almost every year. In this research Swat River Basin which originates from the foothills of Hindu Kush mountain range has been studied. Havoc caused by frequent flooding and flash flooding because of narrow flood plain and concentrated residential and commercial activities into flood plain is a major issue of this basin. Structure countermeasures are very poor, therefore this research has been carried out to strengthen the non-structural measures of flood early warning system. In the past no hydrological model in which snow and glacier melt have been addressed, used for simulation of hydrological response for flood forecasting. Therefore the applicability of Integrated Flood Analysis System (IFAS) snow model, based on the degree day approach and Moderate Resolution Imaging Spectroradiometer (MODIS) snow data for flood forecasting was evaluated and improved. The simulated snowmelt runoff was reliable for 2005, but for 2007&13 years of validation, the model results were unsatisfactory. The model was validated after fixing the bug of IFAS import function of minimum temperature. Based on the snow cover and the average temperature of the grid, the rainfall has been separated from precipitation as snow is recorded as rain. The lack of the sufficient number of rain gauge stations is a major factor of disruption of hydrological study of the basin, in order to address this issue, corrected GSMaP rainfall has been used for rainfall runoff, as a result the model gave simulated discharges best fit to observed one with Nash-Sutcliffe Coefficients 0.71, 0.42 & 0.63 respectively for 2005, 2007 & 2013 and Correlation Coefficient 0.84, 0.68 & 0.91 respectively. After developing the model, IFAS snow model is easily applicable model for flood forecasting.

Keywords: IFAS, Degree Day Approach, Bifurcation of Precipitation, Bias Correction of Satellite Rainfall

INTRODUCTION

The northern Pakistan is considered as home of snow and glacier after Polar Regions, received heavy snowfall in winter playing a dynamic role in water budget (Muhammad Umar et al., 2015). Snow and glacier melt runoff contribute about 80 % to Indus river discharge (Young & Hewitt, 1990). Although snow and ice are great water resources, when melt abruptly, a flood occurs. Pakistan is a flood prone country and undergoes from medium to high level flood almost every year. Mainly floods in Pakistan are caused by heavy concentrated rainfall during summer monsoon season, augmented by snow and glacier melt in Upper Indus Basin (UIB) Rivers. Both poor structural and non- structural countermeasures cause flooding in. The main objectives of this research are

- Investigation of the applicability of Degree Day Model of IFAS and MODIS snow data for reliable flood forecasting.
- Estimation of snowmelt and glacier melt runoff contribution to total river discharge.
- Investigation of the applicability of satellite rainfall data for reliable flood forecasting.

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In this research Swat River Basin is selected as study area. The location of the study area is shown in Fig.01. Th PMD observatories & Water and power Development Authority (WAPDA) stream gauge station used in this research has been shown in table I & II.

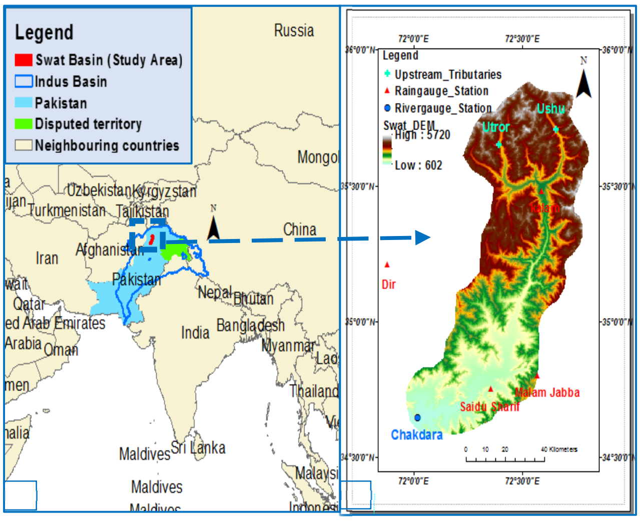

Fig. 1: Location of study area inside the Indus Basin

Table I: PMD observatories used in study area

Station Name	Latitude (°N)	Longitude (◦E)	Elevation (m)
Saidu Sharif	34°45′00″	72°21′18″	950
Kalam	35°28′42″	72°35′19″	2000
Malam Jaba	34°47′59″	72°34′11″	2450
Dir	35°12′36″	71°52′48″	1400

Table II: WAPDA steam gauge s used in study area

Station Name	Latitude (°N)	Longitude (◦E)	Elevation (m)
Chakdara	34°38′40″	72°01′30″	676

THEORY AND METHODOLOGY

IFAS Model

Two layer tank model was used for this study. The configuration of two layer tank model is given in table III, below.

Table III: Model configuration

Model	Function
Surface Tank Model	Infiltration to unsaturated layer, surface runoff, surface storage, evapotranspiration, rapid intermediate outflow
Aquifer Tank Model	Outflow from aquifer, aquifer loss
River Tank Model	River course discharge

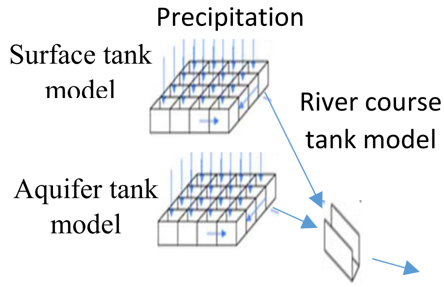

Fig. 2: Schematic representation of Two layer tank model

Degree Day Model:

By using this approach snow and glacier melt can be estimated, regardless of location and elevation of snow and glacier cover area (Hagg et. al., 2007). Snowmelt is a function of temperature lapse rate, degree day factor and critical temperature (Archer, 2003). First temperature is estimated at each grid cell by the equation

$$T_{est(i,j)} = T_{obs} + dE * \left(-\frac{dT}{dE}\right) \quad \ldots\ldots (1)$$

Where $T_{est(i,j)}$ is average estimated temperature in each grid, T_{obs} is average observed temperature of the station, dE is the difference of elevation of grid from nearest station and (- dT/dE) is the temperature lapse rate (TLR). The snowmelt can be calculated at each grid cell by the equation

$$Snowmelt_{(i,j)} = Snow\_Count_{(i,j)} * (T_{est(i,j)} - T_{cri}) * DDF \quad \ldots\ldots (2)$$

Where T_{cri} is critical temperature for melting snow and DDF is degree day factor.

DATA

Topographic Data: the following topographic data has been used in this study.

Table IV: Topographic data used in the study

Division	Name	Creator	Spatial Resolution	Coordinate	Data Format
DEM	Global Map	ISCGM	Horizontal Grid (1km mesh), Spacing is 30 arc seconds	Horizontal direction WGS84, Vertical direction meter unit from average sea level	Data of each tile are provided in bil format
Land Use	Global Map/ Land cover	----do---	----do----	----do----	----do----

Meteorological Data: The rainfall, maximum and minimum temperature data of the four stations as mentioned in the study area for years 2005, 2007 & 2013 has been collected from PMD.
Stream Gauge Data: The stream gauge data of the outlet at chakdara location as mentioned in the study area for years 2005, 2007 & 2013 has been collected from WAPDA through PMD.
Satellite Rainfall Data: Global Satellite Mapping of Precipitation (GSMaP) data has been downloaded from Japan Aerospace Exploration Agency's (JAXA) website. JAXA devised tool GSMaP_IF(2.0) was utilized for bias correction of rainfal**l.**
Snow Cover Data: MODIS snow cover data (MOD10A1 Terra Daily L3 Global 500m SIN V05) for years 2005, 2007 &2013 has been downloaded from NASA's website of 500 m resolution.
Glacier Data: Glacier data was obtained from International Centre for Integrated Mountain Development.

RESULTS AND DISCUSSIONS

Contribution of Snowmelt to River Discharge

The daily MODIS10A1 snow cover data of year 2005, 2007 and 2013 has been processed through MODIS

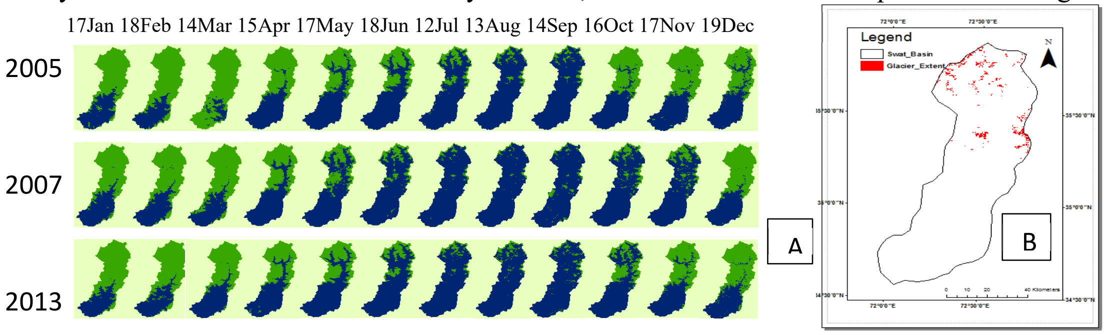

Fig. 3: Spatiotemporal distribution of snow cover area (A) & glacier extent (B) for Swat River Basin

Reproduction Tools (MRT) and binary header files were obtained. These files were converted into text and then ASCII. Finally the ASCII files were processed through GIS tool and the projection of snow cover area has been obtained, as shown in the figure 03(A), which implies that snowfall start in October continue till March and then start melting from April till August. These observations show that Swat river basin is predominantly snow-fed and hence snowmelt contribution to river discharge is significant.

Contribution of Glacier melt to River Discharge

The glacier data from ICIMOD was clipped for study area through GIS tool and by using raster calculator tool of GIS, the conditional raster was obtained. It was found that glacier cover is only 3 % of the total area of the basin, as shown in figure 03(B). Therefore contribution of glacier melt runoff is negligibly small.

IFAS Simulation for 2005

The rainfall data of 2005 was simulated, the comparison of observed & simulated discharges are shown in fig. 04. Two issues have been observed. One issue is overestimation of simulated discharge during snowfall season (Oct- Mar) as snow is recorded as rain. Second issue is well underestimation during summer monsoon season, as original IFAS ver. does not have snow module and hence did not include snowmelt contribution.

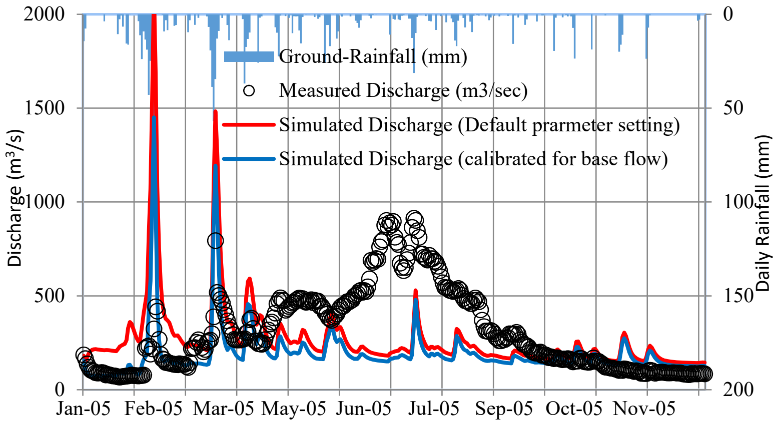

Fig.4: Daily Obs & simu discharges at basin outlet for model calibration of 2005

In the above figure, red color hydrograph represents IFAS default simulation. The model has been calibrated for base flow, as base flow is high, by adjusting the value of parameter HIGD (initial water height on aquifer tank) to 1.80 m (default value is 2.00 m), as represented by blue color hydrograph.

To fill the gap during summer monsoon season, IFAS Snow Model based on Degree Day Approach has been applied to the basin to simulate ground rainfall and MODIS snow cover data together. The results of simulation as shown in the figure 5.

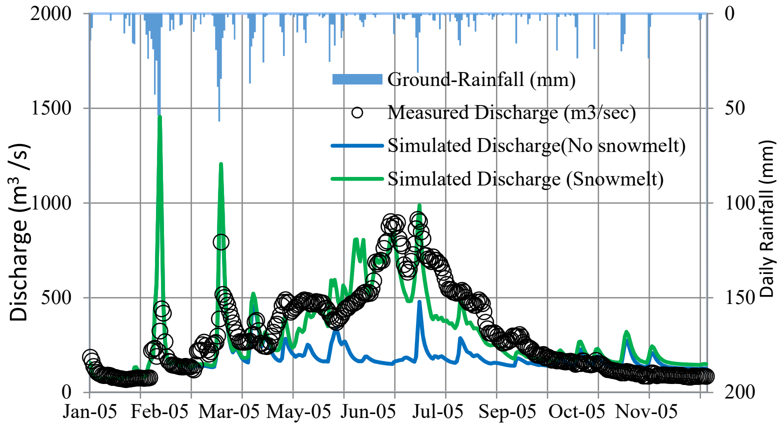

Fig. 5: Daily obs & simu discharges at basin outlet after adding snowmelt for 2005

Parameter Setting: Temperature Lapse Rate, Degree Day Factor & Critical Temperature

For the following parameter setting the simulated discharges were best fit to observed discharges.

Table V: Temperature Lapse Rate (°C/km) & Degree Day factor mm $°C^{-1}$ day^{-1}) on monthly basis

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
TLR	7.2	7.2	7.0	6.6	6.2	5.8	5.3	5.0	6.0	6.7	6.9	7.2
DDF	1.0	1.0	1.0	4.0	4.0	8.0	8.0	8.0	1.0	1.0	1.0	1.0

Critical temperature for melting snow was chosen as 0°C.

IFAS Snow model's validation for 2007

The same model setup was applied to simulate rainfall and snow cover data of 2007 as shown in fig 6, but no rise in discharges has been observed after addition of snowmelt. The same situation was observed for 2013. The model gave reasonably well results by simulating snowmelt runoff for 2005 but the results were not satisfactory in case of 2007 &13. So distribution of temperature, snow cover and snow melt have been compared for investigation in order to find out the malfunction.

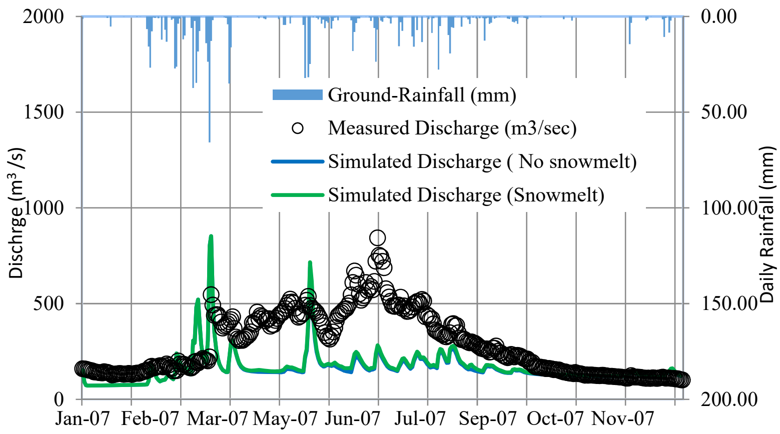

Fig.6: Daily obs & simu discharges at basin outlet after adding snowmelt for 2007

Investigation of temperature (max., min. & mean), snow cover and snowmelt distribution

Fig. 7, shows distribution of temperature, snow cover & snowmelt on May 06 for 2005 versus 2007.

Fig. 7, shows that min and hence mean temperature of 2007 is well below than 2005 which is against the ground reality. Therefore the bug on IFAS import function of minimum temperature data was checked closely by importing the mean temperature through bug on IFAS import function of max temperature data and then copied the imported mean temperature data from max temperature folder into min temperature folder and finally run the model, the simulated discharges were increased, implied that bug of IFAS import function of minimum temperature data was out of order.

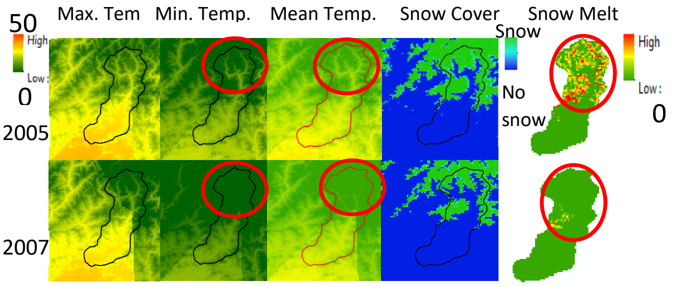

Fig.7: Distribution of temp, snow cover & melt on May 6 for 2005 vs 2007

Simulation after fixing the bug of IFAS import function of min temperature data & bifurcation of rainfall

After fixing the bug, the model gave reliable results as was observed from fig. 8. On the basis of snow cover and average temp of grid, an attempt was made for separation of rainfall from rated precipitation of rain gauge. The basic empirical equations developed in Fortran source code are summarized as, for any snow-fed grid if average temp is greater than critical temp, then rainfall is equal to rated precipitation otherwise rainfall is equal to fraction of precipitation.

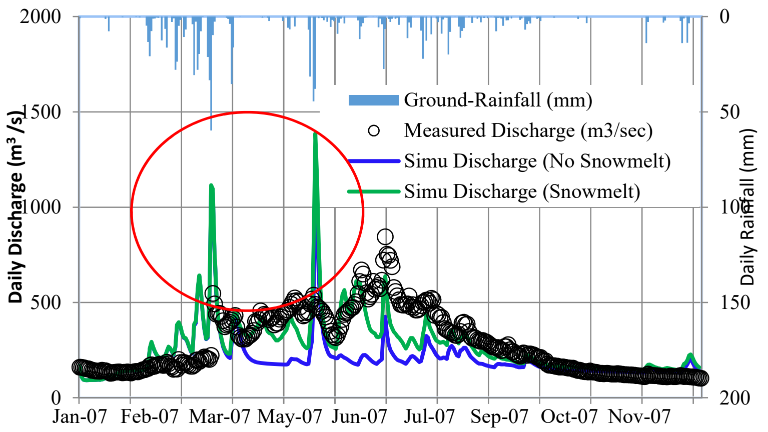

Fig.8: Daily obs & simu at basin outlet after fixing the bug

The simulated discharges after bifurcation of rainfall from rated precipitation are shown in figure 9.

From fig 9, it was cleared that after bifurcation the first peak reduced but second peak did not reduce. The second peak is because of lack of sufficient rain gauge stations inside the basin, for which ground and GSMaP rainfall's distribution were compared.

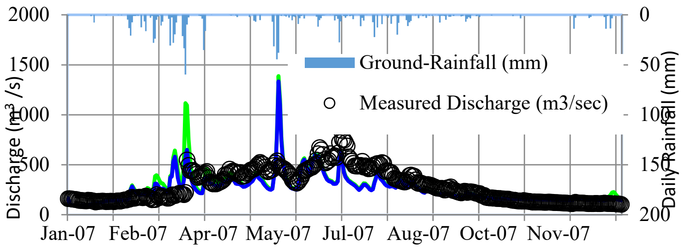

Fig. 9: Daily obs & simu discharges at basin outlet after bifurcation of rainfall

GSMaP Bias Correction

From fig. 10, it was observed that weight of GSMaP rainfall was shifted as well as increased after bias correction. Therefore it is concluded that lack of sufficient number of rain gauge stations is a serious disruption of hydrological study of the basin and GSMaP corrected rainfall data is well applicable to the basin condition.

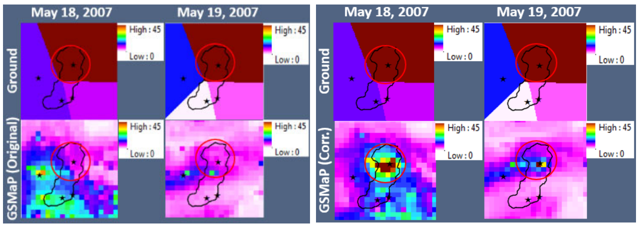

Fig.10: Distribution of gound and GSMaP rainfall before & after corr

RECOMMENDATIONS

- The new version of IFAS snow model after fixing the bug of IFAS import function of minimum temperature data has been working reasonably well after fixing the minimum temperature bug.
- While simulating flood peak discharge, both summer monsoon heavy rainfall and snowmelt can contribute to the total river runoff.
- IFAS model is an easily applicable model for flood forecasting.
- Lack of sufficient information on meteorological condition is a major factor of disruption of hydrological study of the basin.
- The bias corrected GSMaP rainfall gave reliable results to the basin conditions.
- The empirical equations developed for bifurcation of rainfall from rated precipitation of the rain gauge station gave reliable results to the basin.

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