Flood Forecasting of an Ungauged Trans-boundary Chenab River Basin Using Distributed Hydrological Model Integrated Flood Analysis System (IFAS)

Riaz, M.[1], A. Aziz[1, 2], S. Hussain[1]

Abstract

River Chenab at rim station Marala covers 97 % of its catchment in India while the only 3 % in Pakistan. The trans-boundary basin is ungauged and during the real time flood and it is difficult to collect the information from India hence used satellite rainfall data for flood prediction. Three different flood events have been studied to make the IFAS model applicable for the flood forecasting of Chenab River so that the losses and damages due to flooding could be minimized. The results of Tuned IFAS (Peak discharge error= 7 %, wave shape error= 29.5 %, volume error= 8.5 %) are much better as compared to IFAS with default parameters (Peak discharge error= 82 %, wave shape error= 15.7 %, volume error= 53 %). The Satellite rainfall data namely Global Satellite Mapping of Precipitation GSMaP_NRT (Near Real Time) has been used by hydrological model Integrate Flood Analysis System (IFAS) for rainfall runoff modeling. The results of Satellite GSMaP_NRT with tuned parameters showed good agreement with the observed discharge values at the ground measuring station. The Satellite GSMaP_NRT captured flood duration and flood peak with reliable accuracy. The IFAS showed the capability to generate sufficient lead time flood forecast for the local downstream population. This tuned IFAS model is practically helpful for the flood early warning and to save the lives and movable properties of the downstream local communities.

Key Words: Satellite Rainfall, Flood Forecasting, Trans-boundary Chenab River, IFAS, Pakistan

Introduction

There is a growing consensus that the impacts of climate change may well lead to an increase in both the frequency and magnitude of floods (Kennedy, 2004). Flooding is a common phenomenon every year in Pakistan since last three decades. River Chenab is one of the largest rivers of the Indus basin. Floods in Chenab result from heavy rainfall in the upper drainage basin. This basin falls under the most active monsoon belt Pir Punjal range beyond Akhnoor which is ideally located to cause the necessary orographic lifting along its windward slopes. The snow melt contributions which is on the average 40 % of the total flow in July synchronizes with the early monsoon in July but not with the peak values occurring in August and September. During the monsoon, particularly the Jammu and Munawar Tawis contribute considerably to the flood flows at Marala (Awan, 2003). Chenab is joined near the border by two major tributaries, the Munwar Tawi and Jammu Tawi both draining some 2,800 Km^2 of land on both side of the two rivers. Chenab enters in Pakistan just upstream of rim station Marala (32°- 40/ N and 76°-29/ E). The river slopes from the source to the mouth vary strongly with the steepest part about 25 m/km upstream of Tandi while Tandi to Akhnoor the slop is 5m/km and it drops to about 0.4 m/km when the river flows out into the plains (Awan, 2003). Below Akhnoor it becomes wider and the flood plain is enormous. The river Chenab above the rim station Marala flows in a rugged and hilly terrain and all its upper drainage basin is situated in Himachal Pradesh (its origin) and Indian state of Jammu Kashmir. The river has no major dam or head works above Marala, therefore it maintains a free flow at Marala head works. As Pakistan could not get the point-rainfall observations from India, therefore the flood forecasting division Lahore has to depend on the QPM radar observations of Lahore & Sialkot. Because of Indus Treaty agreement between Pakistan and India, the discharge data of Chenab at main Akhnoor (India) and also at Jammu (India) for Jammu Tawi the main tributary of Chenab River is available which gives a good clue of the existing conditions at cross

[1] Pakistan Meteorological Department, Flood Forecasting Division, 46 Jail Road, Lahore, Pakistan.
[2] azizpmd@gmail.com

border points. This information plays a vital role for flood forecasting at Marala and river routing downstream up to the confluence of the river, where it enters river Indus. The brief descriptions of historical floods have been shown in the table 1.

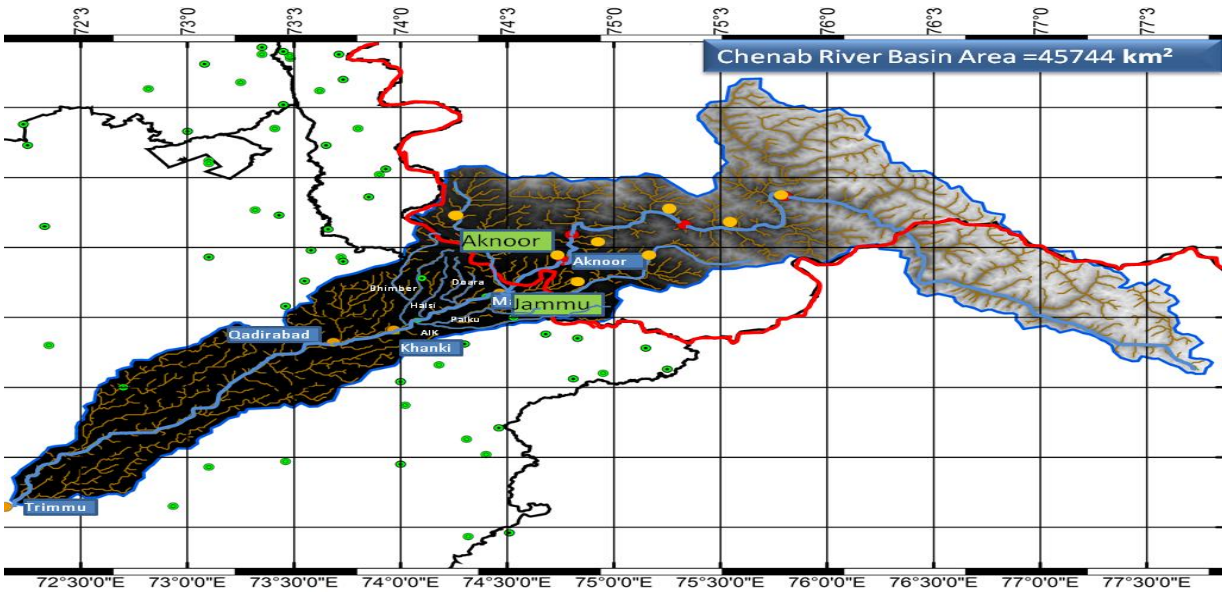

Figure 1: The catchment of trans-boundary Chenab River Basin shows its origin in India to the confluence point at Trimmu with the River Jhelum. The catchment shows the position of Aknoor where it has been calibrated and the rim station in Pakistan.

Table 1: Historical Floods Recorded at Marala during last 46 years.

Day/ Month /Year	Discharge (in Thousands of Cusecs)	Flood Level	Day/ Month /Year	Discharge (in Thousands of Cusecs)	Flood Level
2/ 7/1970	203.7	High	9/ 9/1990	213.3	High
9/ 8/ 1973	769.6	Ex. High	10/ 9/1992	845.0	Ex. High
16/ 7/1975	582.6	Very High	11/ 7/1993	409.4	Very High
2/ 8/1976	549.4	Very High	20/ 7/1994	412.5	Very High
5/ 7/1977	437.1	Very High	27/ 7/1995	439.9	Very High
2/ 8/1978	460.3	Very High	23/ 8/1996	766.8	Ex. High
2 /8/1979	248.1	High	28/ 8/1997	775.5	Ex. High
15/ 8/1980	217.3	High	22/ 7/2000	247.6	High
25/ 7/1981	529.3	Very High	14/8/2002	240.2	High
5/ 8/1982	282.9	High	7/7/2005	345.5	High
4/ 8/1983	232.5	High	3/9/2006	330.4	High
7/ 8/1985	274.1	High	6/8/2010	315.3	High
27/ 7/1986	308.5	High	15/8/2013	377.3	High
25/ 9/1988	750.9	Ex. High	6/9/2014	861.5	Ex. High
30/ 7/1989	407.8	Very High	7/8/2016	412.1	Very High

The Classification of Flood Limits

The classification of flood limits (High, Very High and Exceptionally High) has actually been devised to indicate the river/channel flow conditions with respect to embankments/spillover scenario, alertness

& watch to be maintained by the river management authority and for population awareness. These limits also indicate whether floods are contained within the banks or spillover is expected. The different flood levels can be described as under;

High Flood

The high flood limit indicates the position of river when it is almost fully submerging islands and flowing up to high banks but without encroachment on the freeboard.

Very High Flood

The very high flood limit depicts the river situation when it is flowing between high banks with encroachment on the freeboard.

Exceptionally High Flood

The very high flood limit shows the river situation when there is imminent danger of overtopping or a breach has actually occurred or high bank areas become inundated.

The Flood Limits (in thousands cusecs) for Marala have been shown in the table 2.

Table 2: Flood Limits for Marala

Station	Design Capacity (in thousands of cusecs)	High (in thousands of cusecs)	Very High (in thousands of cusecs)	Ex. High (in thousands of cusecs)
Marala	1100	200-399	400-599	600 & above

Classification of Hydrological Models

The hydrological models are basically developed for the two purposes of which one is the understanding of the catchment hydrological phenomena and effect of catchment change on the phenomena and the other one is the generation of the synthetic sequences of hydrological data for use in flood forecasting. Recently, mathematical models have taken over the most important tasks in problem solving in hydrology (UNESCO, 1985). The purpose of hydrologic models development is according to the requirement and therefore the form of the model is different in each case.

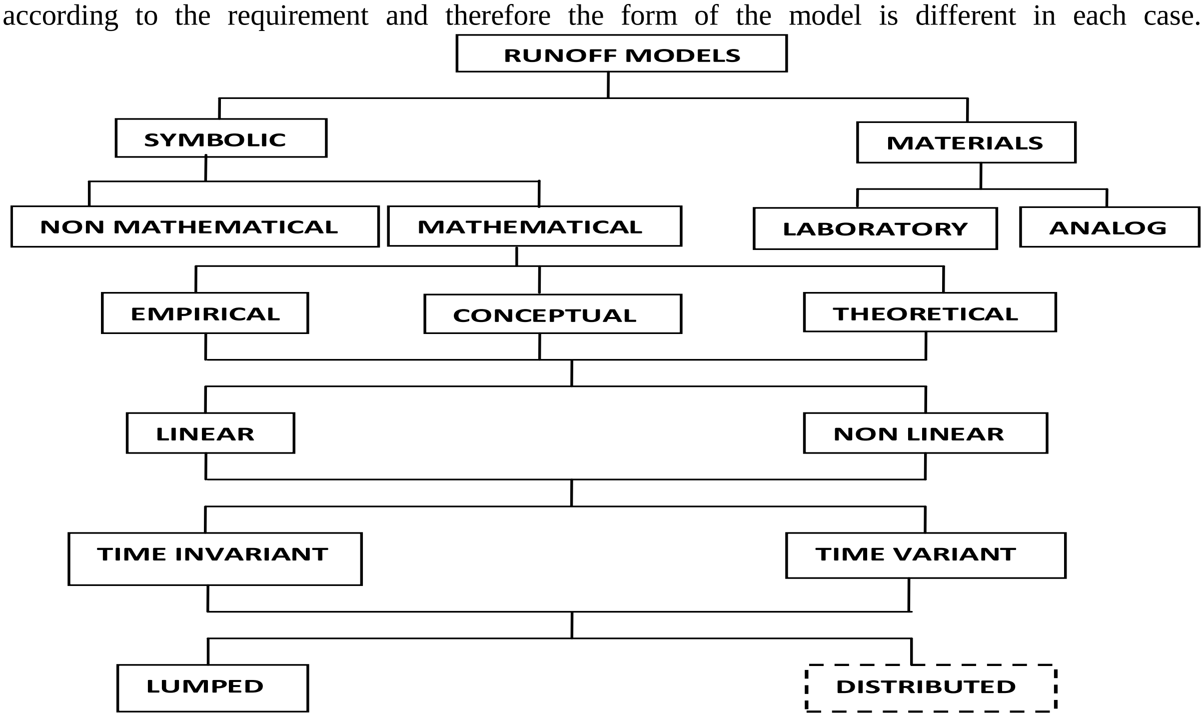

Figure 2: Classification of hydrological models

The hydrological models are useful to study the potential impacts of changes in land use or climate. The rainfall runoff modeling was originated in the 19th century to find the solution of problems like reservoir spillway design, land reclamation drainage system design and urban sewer design. The design discharge had been considered the major parameter of interest. An Irish engineer, Mulvaney (1850), introduced the concept of rational method for determining flood peak discharge from rainfall depth. In 1932, Sherman introduced the concept of unit hydrograph on the basis of superposition principle. The unit hydrograph helped to calculate flood peak discharge as well as the whole hydrograph. Actually the Conceptual models were originated during the period 1950's. The unit hydrograph could then be expressed in terms of few parameters to be estimated from catchment characteristics (Parsad, 1967). Since the late 1980s macro-scale hydrological models were developed for a variety of operational and planning purposes especially to estimate the variability of water resources over larger areas at a spatial resolution and the sources of pollutions leading to streams. The hydrologic models can be variously classified. One of the classification methods used by Singh is used here which distinguishes hydrologic models as material and symbolic or formal as shown in Figure 2 (Singh, 1988).

Study Area

The Chenab River up to rim station Marala has been discussed in this study. The total catchment area up to Marala is 29192 square kilometers and length is about 438 kilometers. It is located in eastern Pakistan and its annual average flow is 12.38 MAF. It flows from northeast to sotheastern direction through the Punjab province. The catchment area of this trans-boundary river spans over India and Pakistan.

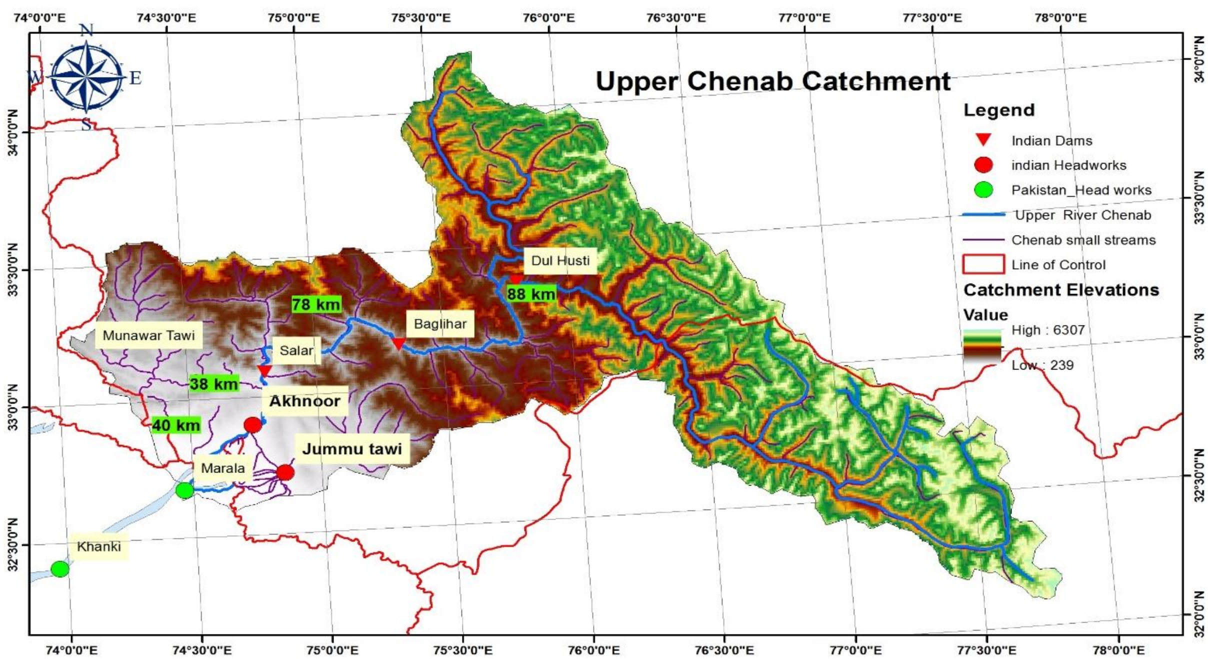

Figure 3: Catchment of the trans-boundary basin depicts the dams, head works, small streams and line of control between India & Pakistan.

Data and Methodology

The three flood events during the flood seasons 2013, 2014 and 2016 have been discussed in this study. The IFAS model has been calibrated on the flood event of 2014 and then validated on the two seasons 2013 and 2016 respectively. The Global Satellite Mapping of Precipitation (GSMaP_ NRT) near real time hourly rainfall data are used for the period from August 01 to Sep 30, 2014. The hourly GSMaP data then converted into six hourly by using the IFAS function (Project time interval). The GSMaP project was promoted for a study of production of a high precision, high resolution global precipitation map using satellite data sponsored by Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency (JST) during 2002-2007. Science 2007, GSMaP project activities are promoted by the JAXA Precipitation Measuring Mission (PMM) science team. The specifications of the satellite data are shown in the table3, (IFAS manual, 2009).

Table 3: Specifications of the Satellite GSMaP_NRT data

Product Name	GSMaP_NRT	Product Name	GSMaP_NRT
Resolution	0.1^0 (L=11km, A=120km^2)	Coordinate System	WGS
Resolution Time	1 (hour)	Historical Data	Dec 2007
Coverage	60^0N-60^0S	Developer and Provider	JAXA/EORC
Time Lag	4 (hours)	Sensors	TRMM/TMIAqua/AMSR-EADEOS II/AMSRSSM/IIRAMSU-B

Estimation of missing data

The rainfall stations are sparsely located in the catchment area. The uppermost part of the study area contains a few and the Himalayan portion has almost no rainfall station. The estimation of missing data is made by comparing the data from nearby rain gauge stations. Thiessen Tessellation method is employed for this job. There are three observatories (A, B and C) inside the target area whose rainfall distribution has to be made uniform or estimate the missing rainfall data. The rainfall data of observatories A and B is known while the rainfall data of observatory C has to be determined. The observatories D and E are out of the target area as shown in the Figure 4(g). According to Thiessen Tessellation, grid precipitation calculation is the area which is surrounded by two perpendiculars and two bisectrix lines between one of following observation spot and the other observation spots, is assigned as effecting extent of the observation spot and the area is extent cell for distributed precipitation of observation spot.

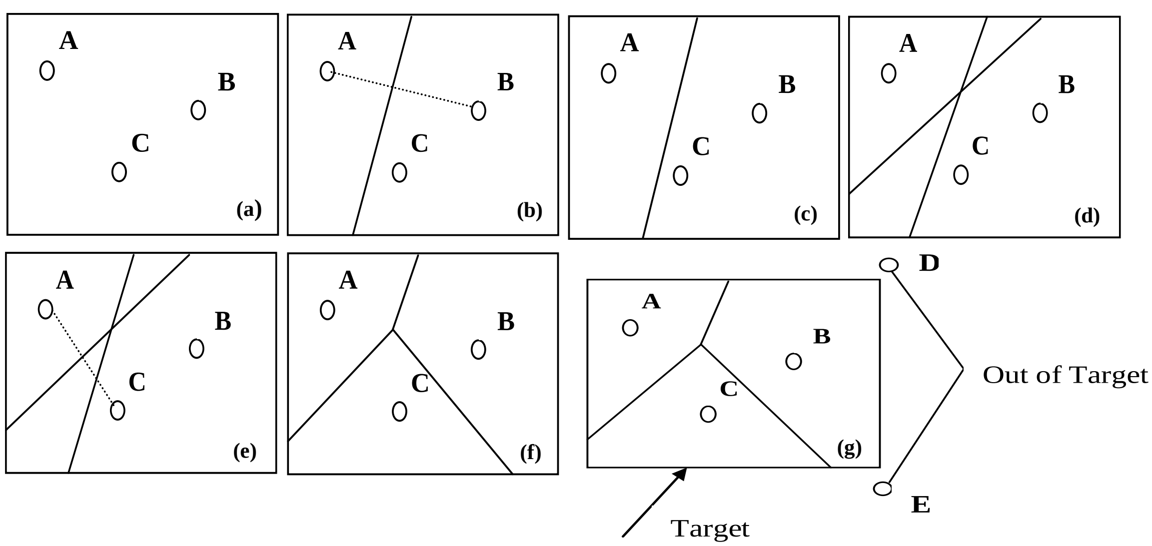

Figure 4: (a, b, c, d, e, f) shows the Thiessen Tessellation method and (g) depicts the Precipitation observation spot that becomes subject.

The Configuration of PWRI Distributed Model

The PWRI Distributed Model version 2 contains the configuration of two tanks on vertical direction; the surface tank and the underground water tank and the third one is the river channel tank as shown in the Figure 5.

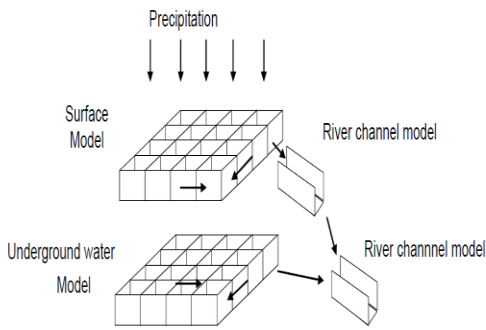

Figure 5: Scheme image of the model.

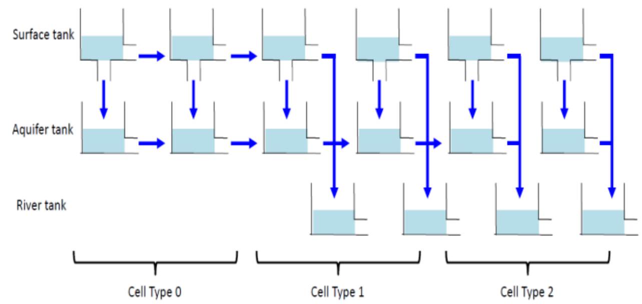

Figure 6: Cell type outline chart

The structure of PWRI Distributed model

The PWRI Distributed model consists of three models. The features of each model can be described as follows.

Surface model

The surface model is a model used to divide the rainfall to surface, rapid intermediate, and ground infiltration flows. The top right, bottom right and central bottom orifices represent the surface, rapid intermediate and ground infiltration flows, respectively. The surface outflow is estimated as a fraction (3/5) of storage capacity based on the Manning Law. The rapid intermediate flow is also estimated as a fraction of storage capacity. The ground infiltration is estimated as a fraction of storage capacity based on the Darcy Law.

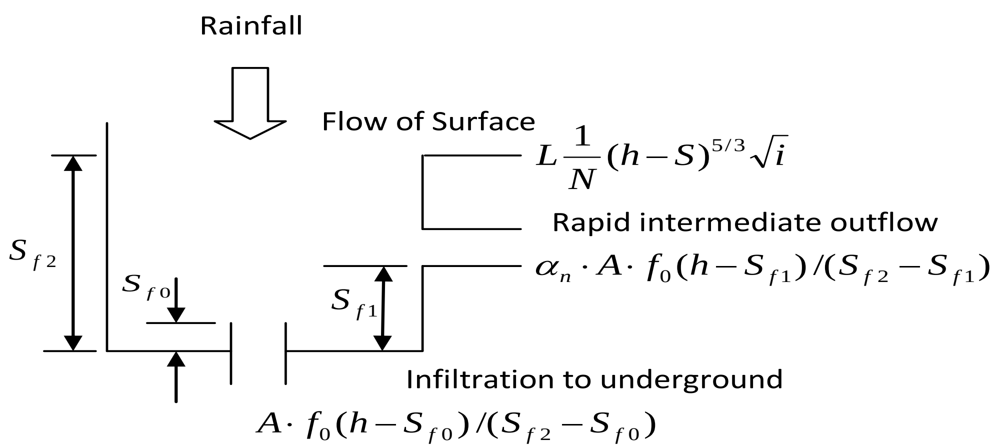

Figure 7: Concept image of the surface model

If $h \geq S_{f2}$, then $\frac{\partial h}{\partial t} = R - E_{ps} - Q_o - Q_{sf} - Q_{ri}$

If $S_{f1} \leq h < S_{f2}$, then $\frac{\partial h}{\partial t} = R - E_{ps} - Q_o - Q_{ri}$

If $S_{fo} \leq h < S_{f1}$, then $\frac{\partial h}{\partial t} = R - E_{ps} / S_{f1} \cdot h - Q_o$

If h$\leq S_{fo}$, then $\dfrac{\partial h}{\partial t} = R - E_{ps} / S_{f1} \cdot h$

Where, R: Rainfall; S_{f2}: Height where surface flow occurs; Q_{sf} : Surface outflow

S_{f1}: Height where intermediate outflow occurs; Q_{ri}: Fast intermediate outflow

S_{fo}: Height where ground infiltration occurs; E_{ps}: Evapotranspiration

Q_o : Infiltration for infiltrate model; h: Storage height for model

Surface Parameters

The default surface parameters used in this study have been shown in the table 4.

Table 4: Surface parameters used for Chenab River

Parameter	Final infiltration capacity fo(cm/s)	Maximum storage height S_{f2}(m)	Rapid intermediate flow S_{f1}(m)	Height where ground infiltration occurs $S_{f0(m)}$	Surface roughness coefficient N(m-1/3)	Rapid intermediate flow regulation coefficient α_n	Initial storage height (m)
1	0.0005	0.1	0.01	0.005	0.7	0.8	0
2	0.00002	0.05	0.01	0.005	2	0.6	0
3	0.00001	0.05	0.01	0.005	2	0.5	0
4	0.000001	0.001	0.0005	0.0001	0.1	0.9	0
5	0.00001	0.05	0.01	0.005	2	0.5	0

Groundwater Tank

The configuration of groundwater model is shown as Figure 8. The top right and bottom right orifices represent the unconfined and confined groundwater flows, respectively. Outflow of ground water is considered as a fraction of confined ground water to h, and of unconfined groundwater to h2.

If h$\geq S_g$, then $\dfrac{\partial h}{\partial t} = Q_{in} - Q_{g1} - Q_{g2}$

If h<S_g, then $\dfrac{\partial h}{\partial t} = Q_{in} - Q_{g1} - Q_{g2}$

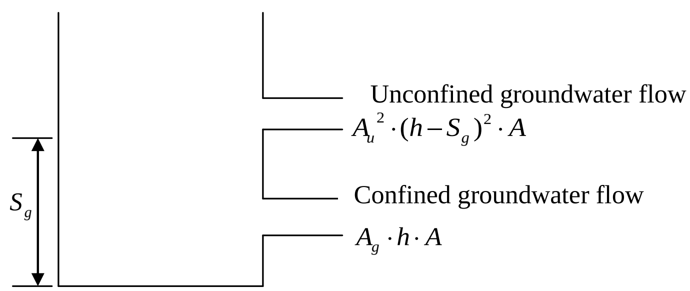

Figure 8: Concept image of the groundwater model

Where, S_g: Height where unconfined groundwater outflow occurs

Q_{in}: Inflow from infiltration mode; Q_{g1}: Unconfined groundwater outflow

h: Storage height of model; Q_{g2}: Unconfined and confined groundwater outflow

Aquifer Parameters

The default aquifer parameters used in this study have been shown in the table 5.

Table 5: Aquifer parameters used for Chenab River

Parameter	Symbol	Notation	Units	Parameter value
Runoff coefficient of unconfined acquifer	A_u	AUD	(1/mm/day)	0.1
Runoff coefficient of confined acquifer	A_g	AGD	1/day	0.003
Height where the unconfined acquifer runs off	S_g	HCGD	m	2
Initial water height	-	HIGD	m	2

River Channel Model

The configuration of river channel model is shown in Figure 9. Outflow is based on Manning equation.

$$LB\frac{\partial h}{\partial t} = Q_{in} - Q_r$$

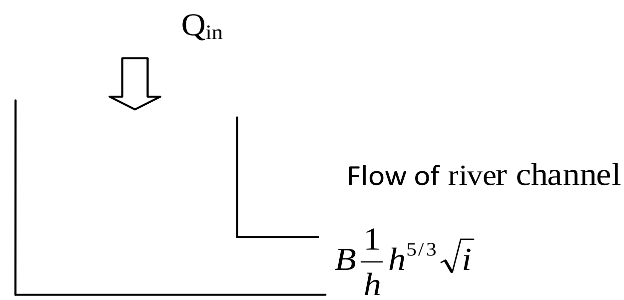

Figure 9: Concept image of the river channel model

Where, Q_r : Outflow of river channel ; L: Length of river channel; B: Breadth of river channel
Q_{in} : Inflow from ground water and upstream river channel models

River Tank Parameters

The default river parameters used in this study are shown in the table 6.

Table 6: River tank parameters used for Chenab River

Parameters	Constant of the Resume Law	Constant of the Resume Law	Manning roughness coefficient	Initial water table of river channel	Infiltration of Aquifer tank	Coefficient of cross shape (RHW)	Coefficient of cross shape (RHS)	Coefficient of cross shape (RBH)	Coefficient of cross shape (RBET)	Coefficient of cross shape (RLCOF)
Units	c	s	n ($m^{1/3}/s$)	(m)	(1/day)	non-dim	non-dim	non-dim	non-dim	non-dim
1	7	0.5	0.035	0.2	0	9999	1	0.5	0.05	1.4
2	7	0.5	0.035	0.2	0	9999	1	0.5	0.05	1.4
3	7	0.5	0.035	0.2	0	9999	1	0.5	0.05	1.4

Objective Function

Efficiency criteria (objective function) are defined as mathematical measures of how well a model simulation fits the available observations (Beven, 1999). Krause (Krause et al, 2005) mentioned the reason of evaluation of model as, to provide a means for evaluating improvements to the modeling approach through adjustment of model parameters values, model structural modifications, the inclusion of additional observational information, and representation of important spatial and temporal characteristics of watershed. The performance of the IFAS model can be evaluated by three indices like wave shape error, volume error and peak discharge error which are defined by the Japan Institute of

Construction Engineering (JICE). The each and every indicator can be described as shown in the table 7.

Table 7: Indicators for the error analysis of IFAS

Wave Shape Error	Volume Error	Peak Discharge Error
$E_w = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Q_{O(i)} - Q_{C(i)}}{Q_{O(i)}}\right)^2$	$E_v = \frac{\sum_{i=1}^{n} Q_{O(i)} - \sum_{i=1}^{n} Q_{C(i)}}{\sum_{i=1}^{n} Q_{O(i)}}$	$E_P = \frac{Q_{OP} - Q_{CP}}{Q_{OP}}$

Where, E, E_w, E_v and E_P represent Error, Wave Shape Error, Volume Error and Peak Discharge Error respectively; n : The number of calculating time

$Q_{O(i)}$: Measured run-off at time I; $Q_{C(i)}$: Calculated run-off at time I

Q_{CP} : Calculated maximum run-off; Q_{OP} : Measured maximum run-off

Results and Discussion

The present study has been conducted for the flood forecasting of the Chenab River. Pakistan Meteorological Department is already using the Flood Early Warning System (FEWS) hydrological model as a nonstructural counter measure for the flood forecasting but this model failed to show better performance during the flood 2014. In this scenario a reliable flood forecasting model is need of the hour. Therefore, in this study an attempt is made to parameterize the IFAS and make it applicable for the flood forecasting of the Chenab River. The results of the IFAS have been analyzed for the flood 2014. The flood peaks calculated by the IFAS on the Chenab River have shown well synchronization with the observed ones for the flood 2014.

The IFAS with default parameters showed no synchronization with the measured discharge values, therefore, it cannot be reliably applied for the flood forecasting of the Chenab River. The surface parameters like surface roughness coefficient (N)-to slow the surface outflow, and height where rapid intermediate outflow occurs (Sf1)-to slow the peak flow, are increased while rapid intermediate flow regulation coefficient (α n)-to small the rise part of wave form, and final infiltration capacity (f o)-to increase the storage height of groundwater tank, are decreased in the parameterized IFAS. The aquifer parameter, slow intermediate flow regulation coefficient (Au)-to enlarge the set part of wave form, is increased in the parameterized IFAS. The river parameter, surface roughness coefficient (n), is increased in the parameterized IFAS. The discharge results of IFAS for Chenab at Marala are shown in the table 8.

Table 8: Results of GSMaP_NRT for Marala 2014, 2013 & 2016

GSMap_NRT	Wave Shape Error (EW)	Volume Error(Ev)	Peak Discharge Error(Ep)
Marala (default) 2014	0.16	0.53	0.82
Marala (tuned) 2014	0.30	-0.09	-0.07
Marala 2013	0.45	-0.26	0.10
Marala 2016	0.27	-0.23	0.16

Results of Satellite GSMaP_NRT for 2014 with default Parameters

The upstream rainfall data for the period from Aug 01 to September 30, 2014 have been analyzed. The IFAS calculated discharge by using rainfall data of the Satellite GSMaP_NRT. The model runs well during the normal period. The flood duration captured by the satellite GSMaP_NRT have well synchronization with the observed one. The peak calculated by GSMaP_NRT for Marala have errors of Peak discharge error= 82 %, wave shape error= 15.7 %, volume error= 53 % which show the poor results of the satellite with default parameters. The discharge results of IFAS for Chenab at Marala are shown in the Figure 10.

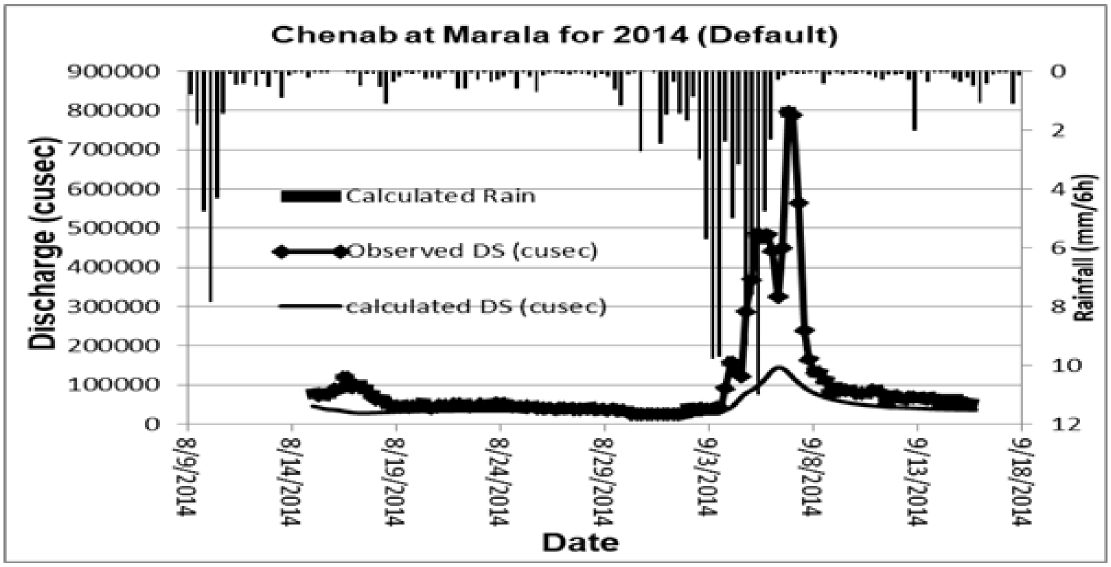

Figure 10: Satellite GSMaP_NRT (default) for Marala 2014

Results of Satellite GSMaP_NRT for 2014 with Tuned Parameters

The upstream rainfall data for the period from Aug 01 to September 30, 2014 have been analyzed. The IFAS calculated discharge by using rainfall data of the Satellite GSMaP_NRT. The flood peak and flood duration captured by the satellite GSMaP_NRT have well synchronization with the observed one. The model runs well during the whole flood period. The flood duration captured by the satellite GSMaP_NRT have well synchronization with the observed one. The peak calculated by GSMaP_NRT for Marala has error= 7 %, wave shape error= 29.5 %, volume error= 8.5 % which shows the very good results of the satellite with tuned parameters. The error analysis shows the best results by the satellite GSMaP_NRT. The discharge results of IFAS for Chenab at Marala are shown in the Figure 11.

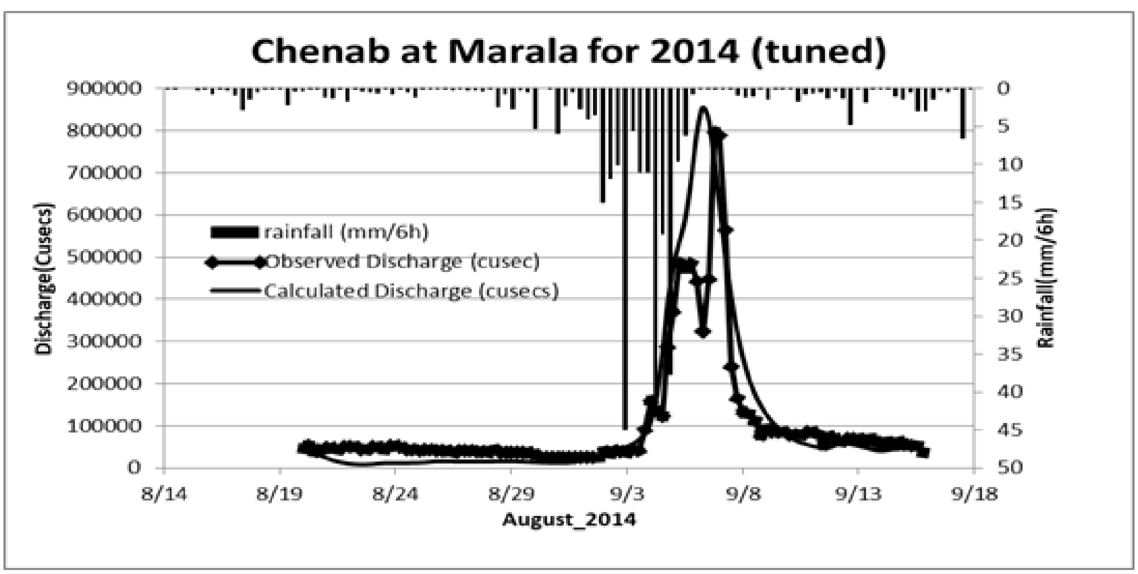

Figure 11: Satellite GSMaP_NRT (tuned) for Marala 2014

Results of Satellite GSMaP_NRT for 2013

The upstream rainfall data for the period from Aug 05, 2013 to Aug 20, 2013 have been analyzed. The IFAS calculated discharge by using rainfall data of the Satellite GSMaP_NRT. The flood peak captured by the satellite GSMaP_NRT have well synchronization with the observed one. The flood duration captured by the satellite GSMaP_NRT have no synchronization with the observed one. The flood wave calculated by GSMaP_NRT for Marala have errors of Peak discharge error= 0.1 %, wave shape error= 0.45 %, volume error= -0.26 % which shows the good result for flood peak only. The discharge results of IFAS for Chenab at Marala are shown in the Figure 12.

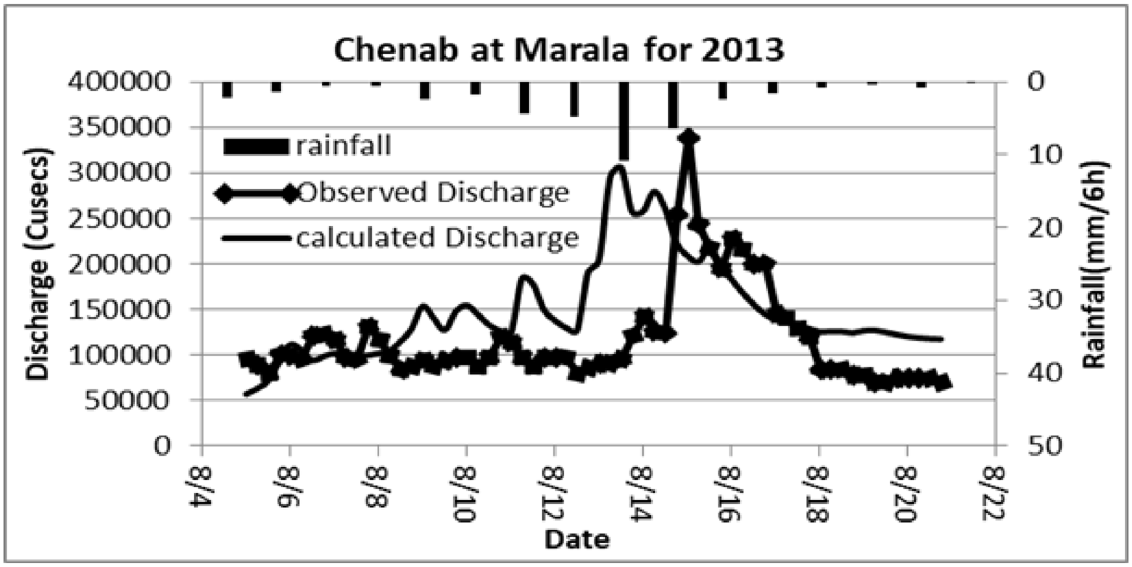

Figure 12: Satellite GSMaP_NRT for Marala 2013

Results of Satellite GSMaP_NRT for 2016

The upstream rainfall data for the period from Aug 01 to Aug 15, 2016 have been analyzed. The IFAS calculated discharge by using rainfall data of the Satellite GSMaP_NRT. The discharge results of IFAS for Chenab at Marala are shown in the Figure. The flood peak and flood duration captured by the

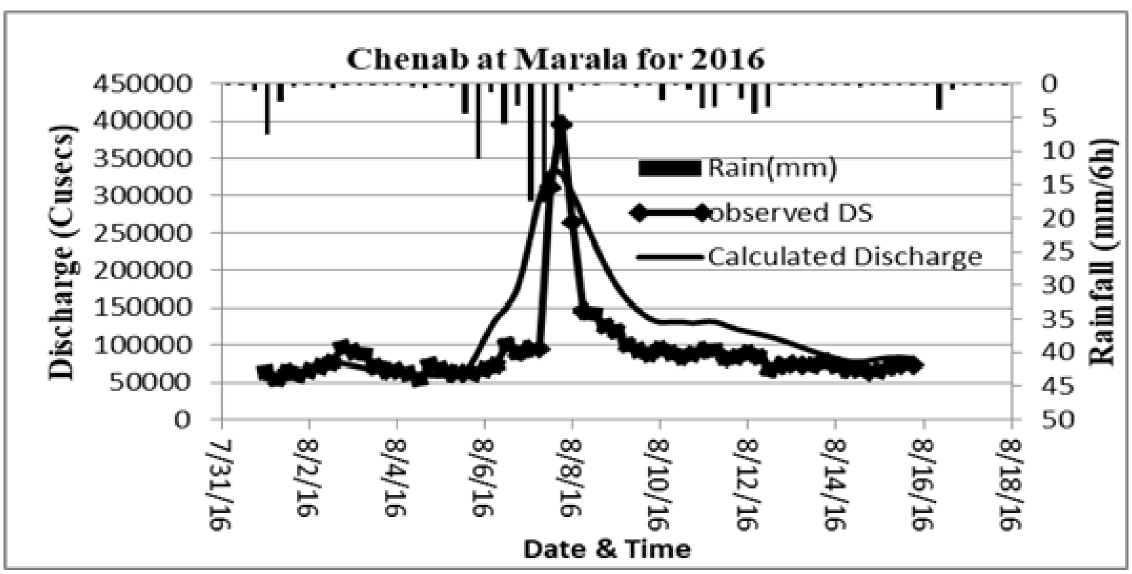

Figure 13: Satellite GSMaP_NRT for Marala 2016

satellite GSMaP_NRT have well synchronization with the observed one. The peak calculated by GSMaP_NRT for Marala have errors of Peak discharge error= 16 %, wave shape error= 27 %, volume error= 23 % which show the good results of the satellite data. The error analysis shows the best results by the satellite GSMaP_NRT.

Conclusion

The IFAS model has been used to calculate discharge by using satellite rainfall data instead of ground rainfall data. The results of calculated discharge for all the cases show well agreement with the measured one. The calculated discharge in each and every case is well synchronized with the measured one both in terms of flood peak and flood duration. The Satellite GSMaP_NRT with corrected rainfall, by using the ICHARM's method for correction of rainfall data, shows the best calculation results for each and every case. The discharge calculated by the Satellite GSMaP_NRT is well synchronized with the measured discharge. This satellite shows the best results while calculating the huge Pakistan flood 2014. The flood duration and flood peak calculated by the Satellite GSMaP_NRT have the best agreement with the observed ones.

Recommendation

The IFAS by using the data set GSMaP-NRT (tuned) can be used for the flood forecast of Chenab River. The results of the GSMaP_ NRT (tuned) for the flood 2014 are, no doubt, very good but may still need to be improved. The mechanism can also be developed for the modification of the satellite rainfall data. The results of IFAS (tuned) even can be made more accurate by tuning different parameters. The present study can also be enhanced to the entire Indus River Basin.

References

Awan, S. A., 2003: Pakistan: Flood Management-River Chenab from Marala to Khanki. WMO/GWD, Associated Programme on Flood Management.

Beven, K. J., 1999: Rainfall-Runoff Modeling (The Primer). Lancester. UK: John Wiley & Sons, LTD.

Kennedy, D., 2004: 'Climate Change and Climate Science'. In Science, 304: 1565.

Krause, P., D. P. Boyle, and F. Base, 2005: Comparison of Different Efficiency Criteria for Hydrological Model Assessment.

Prasad, R., 1967: A non linear hydrologic system response model. J. Hydraul. Div., ASCE HY4.

PWRI Techinical Note No.4148, ICHARM Publication No.14, IFAS Version 1.2, user's manual June 2009.

United Nations Educational, Scientific and Cultural Organization (UNESCO), Courier, Internet Newsletter, October 2001 Ed.