Pak. J. Engg. & Appl. Sci. Vol. 17, Jul., 2015 (*p.* 64–79)

Estimation of Snowmelt Contribution for Kalam Catchment

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Abstract

Snowmelt flows are key source for river discharges that is used for agriculture, hydropower generation and domestic use in snow-fed regions. Nature has sanctified Pakistan with the frozen peaks of the Hindu Kush Himalayan (HKH) in the northern part of the country. Mountain ranges receive heavy snowfall in winter playing a dynamic role in water supply estimation and management. Flows in Kalam catchment are mainly generated due to snowmelt. Since foreseeing and understanding the time-space variation of snow magnitude plays an important role in watershed hydrology, it is necessary to simulate snow accretion and melt precisely. Due to the availability of Moderate Resolution Imaging Spectroradiometer (MODIS) data for snowcover area and Rainfall Estimates (RFE) for precipitation records, it is now possible to identify the portion of the snowmelt that may contribute to the flood hydroghraph. The investigation of MODIS snow product (MOD10A1) for the past 14 years (2000-2013) record shows an average snow cover variation in Kalam Catchment ranges from 5% to 99% in September & March, respectively. A correlation is developed between RFE and Kalam rainfall station by extracting the pixel information of RFE coming over the Kalam station showing a monthly and yearly (2000-2012) correlation coefficient of 0.70 & 0.77, respectively. The research employs, water balance approach and SRM for estimating snow melt contribution (Snowmelt Runoff Model). Results from water balance approach gives an overall snowmelt contribution of 65% with an average groundwater and average rainfall runoff contribution as 19% and 16% respectively. The SRM is well calibrated and validated using regular stream flow 2000 to 2012 (average correlation coefficient for Calibration ~0.95 & for validation ~0.89, annual volume bias<6.5%). Snowmelt from SRM is estimated by separating rainfall days on basis of critical temperature. Results of the study reveals that average snowmelt contribution in the Kalam is about 72%, whereas, average contribution from rainfall is 17%. Results from conventional method is compared with SRM to inspect and assess the performance of a model in the Kalam catchment.

Key Words: Kalam; MODIS; NOAA; RFE; SRM; Water balance method

1. Introduction

Northern Pakistan is one of the biggest sources of snow-glaciated ice outside Polar areas. Snowmelt flows can also be a significant flood risk. Khyber Pakhtunkhwa has the strongest relief and highest precipitation of the four provinces in Pakistan; consequently it has a considerable hydropower potential in the narrow gorges downstream of Kalam. Even when the two other large catchments in the North of Pakistan (Upper Indus Basin and Jhelum River) have an even higher potential, as Kalam is totally snowfed catchment so it is important to monitor or calculate snow discharge that can provides sustainable supply of flows to stream discharge and to downstream irrigation canals. Pakistan has sufficient human and land resources but insufficient water resources. The impact of shortage of water is further intensified due to its non uniform distribution with respect to time and space. Over 80 percent of the flow in rivers occurs in the summer making the agricultural production and optimum use of land resources difficult during rest of the year. The development of the world's largest contiguous irrigation system with large dams and thousands of miles long irrigation canals is the outcome of human efforts for harnessing of water for meeting the ever increasing demand for food, fiber, fodder and fuel.

There is an urgent need for adequate efforts for conservation, optimization and assessment of water flows. Snowmelt assessment is essential where snow melt is a major contribution to river discharge so there is robust requirement of observing snow related processes.

The core purposes of this research is to investigate spatial distributions of snow cover over the catchment, comparison of RFE precipitation with Kalam station data and estimation of snowmelt contribution from conventional as well as from Model approach.

2. Literature Review & Related Work

Snowmelt has significant impacts on flood hydrograph especially during monsoon season; snow data and information within the Swat river basin are not available. Due to the lack of snow data, it is difficult to accurately identify the portion of the snowmelt that may contribute to the design flood at the proposed Munda dam site [1].

Singh et al., [2] anticipated the annual part of snow & glacier-melt flows in the annual river flow of the Chenab stream at Akhnoor for a data length of 10 years using the water balance approach.

Hydrograph-separation methods are applied to stream records of the Kosiat Tribeni (57000km^2) and Chyurlia measured that snowmelt accounts for about 20%, 50%, 70% and 40% in March, April, May and June respectively [3].

Hydrograph separation analysis has been done for years to approximate ground water flows [4]. These studies used graphical and analytical methods to separate base-flow from total river discharge [5]. The components of hydrograph can be divided into: Quick flow from rainfall, interflow from snowmelt and a baseflow which is from groundwater. In order to estimate rainfall runoff volumes, results from two methods i.e., SCS-CN method and Volumetric rainfall volume analysis are used and for groundwater flow volume like constant flow method, constant, concave method and Slope method to get respective volumes.

SCS [6], which is extensively used and proficient method for estimating rainfall runoff in a certain area. Formulation for converting rainfall into discharge is:

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \tag{1}$$

Where

$$\mathbf{S} = \frac{1000}{\mathbf{CN}} - 10 \tag{2}$$

$$\mathbf{S} = \frac{25400}{\mathbf{CN}} - 254 \tag{3}$$

where, Q is flows is in millimeters, P is rainfall in millimeters (mm) and S is possible retention after runoff begins (mm).

SCS CN depends on Hydrological Soil Group (HSG), Land use and Antecedent moisture state of area of interest. HSG is usually estimated as of soil texture data developed by International Soil Reference Information Centre (ISRIC). Equation (3) is used for estimating weighted CN on basis of land cover data.

$$CN = \frac{\sum A_i \, CN_i}{\sum A_i} \tag{4}$$

The Curve Number is adjusted for different AMC based upon the equations (5) and (6) shown below:

$$CN(I) = \frac{4.2CN(II)}{10-0.058CN(II)} \tag{5}$$

$$CN(III) = \frac{23CN(II)}{10+0.13CN(II)} \tag{6}$$

Volumetric rainfall runoff analysis estimates runoff volume on the basis of runoff coefficient “Cv” which depends on type of soil in the catchment. Tables are available that relates the soil type with the rainfall in mm [7]. Table 1 shows the runoff coefficient values for vatious rainfall depths. If soil surface is not available, adopt a value of 0.5

Table 1 Typical volumetric runoff coefficients for Loamy clay soil condition

Rainfall (mm)	Loamy Clay	Rainfall (mm)	Loamy Clay
10	0.2	60	0.74
20	0.43	70	0.77
30	0.56	80	0.79
40	0.63	90	0.81
50	0.69	100	0.83

There are many ways for groundwater estimation, few are based on the guess that groundwater discharge peak is synchronized with river flow peak, while some considers that recession of flows remains after the time when surface flow starts [8] [9]. Some approaches basically use an interpolation method to approximate groundwater between beginning and end of surface flow i.e., (a) constant flow approach considers that ground discharge is constant throughout the storm & uses minimum river flow instantly before rising limb as a constant [9]; (b) constant slope approach links the beginning of rising limb with inflection point on receding limb & considers instantaneous response in ground discharge to rainfall incident; (c) concave approach attempts to represent the approximated preliminary decrease in ground discharge during rising limb by projecting declining hydrographic trend evident former to rainfall incident to directly under the crest of storm hydrograph [10].

According to Sharma [11], the snow fed rivers show a distinct rise in the pre monsoon period (April to mid-June) with melt water contribution exceeding 30% in May.

Mohsin [12] employed SRM from 2000-2006 on Astore catchment with a correlation coefficient of 0.87 and volume difference of 1.8%. The results explain that SRM can produce best results when MODIS snow data is used as a input to SRM.

Bashir et al., [13] applied SRM successfully on Gilgit basin showing good results with the use of MODIS snow cover data for year 2003.

Nabi [14] applied SRM on Astore catchment with very high model efficiency of 0.96 and suggested that snow cover mapping is an efficient technique for catchment having difficult terrain and large areas.

Satluj watershed has a catchment area of 22,275 km^2, snowmelt contribution is estimated by Singh and Jain [15] to about 59% on annual term while in summer it contributes to about 75% for 1980 period.

Rango [16] suggested that snowcover area obtained from satellite can be used to simulate the river flows in River Indus and River Kabul.

Tahir [17] employed Snowmelt model on snow catchments of Upper Indus produced good results with the use of snow data from MODIS.

Snowmelt Runoff Model

Snowmelt Runoff Model (SRM) was developed in Switzerland by Martinec in 1975 [18]. It is used for simulating and forecasting daily stream flow data with an incorporation of satellite data [19]. SRM has been successfully applied on more than hundred (100) catchments and produced high accuracy results. SRM is basically a degree-day approach model that incorporates temperature, snow covered area and precipitation as primary input to model. Detailed description of model is given in SRM manual [20]. Results and comparison of SRM with various models can be seen in World Meteorological Organization report which tells about the accuracy and validity of model [21].

General Equation

SRM simulates the daily discharges by incorporating the snowfall and rainfall, the results from these two components are overlaid by use of recession with the use of following equation:

$$Q_{m1} = [C_{Sn} a_n (T_n + \Delta T_n) S_n + C_{Rn}] \frac{10000}{86400} A(1 - k_{n+1}) + Q_n k_{n+1} \tag{6}$$

where, Q is daily discharge [m^3/s], C is loss coefficient for rain and snowmelt, a is Degreeday factor [cm/°C/d], T is number of degree-days [°C d], ΔT is lapse rate of temperature adjustment factor for considering hypsometric mean elevation [°C d], S is snow covered area/Total area , P is precipitation that contributes directly to runoff [cm], A is basin area or zonal area [km^2], k is coefficient of recession that takes periods without snow melt and rainfall runoff, n is date sequences when flows are computed and $\frac{10000}{86400}$ = conversion factor from [cm·km^2/d] to [m^3/s].

SRM Flow Chart

Schematic working of snowmelt runoff model describing the inputs preparation for SRM and its parameters is presented in Figure 1:

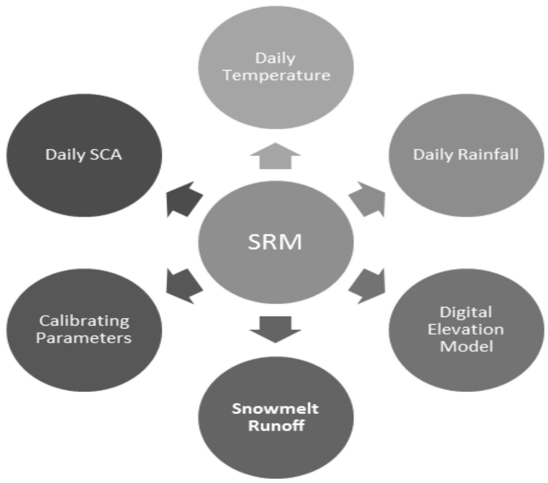


Fig. 1 SRM Inputs and its parameters

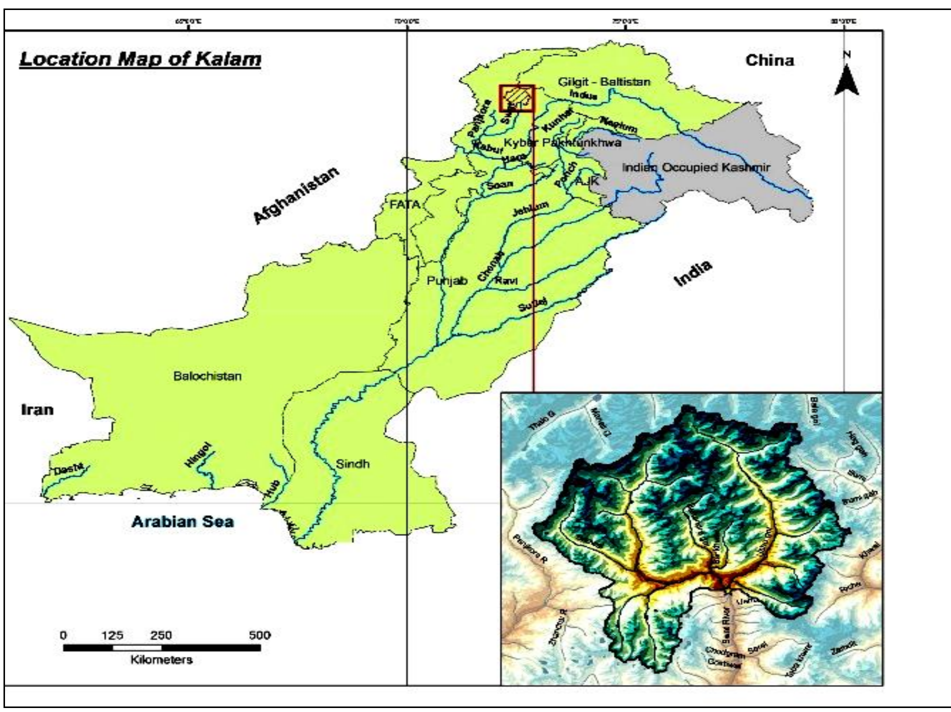
First part of general equation (6) is used for estimating snowmelt discharge. As SRM calculates melt depth by using temperature as degree days and degree day factor (usually calibrated) which then multiplied with daily snowcover area (extent) while Cs is used to take into account the losses in snowmelt.

2. Characteristics of Study Area

Swat River basin consists of three sub-basins (i) Upper Swat (6579 km^2) (ii) Panjkora (5724 km^2) and Ambahar (1347 km^2). Snow line fall away to 2500 m during winter and regresses to about 4000 m during summer. Monsoon brings 30% of annual precipitation while its effect is significantly low in upper most region. Kalam lies on the upper most reaches in Swat valley in Khyber Pakhtunkhwa Province of Pakistan. It lies 30 kms from Bahrain & about 2000 masl. In Kalam, Ushu and Gabral streams meets to form River Swat.

Study area is surrounded by Ghizar district in North, Chitral in the North West, Upper Dir in the West, Swat in South and Kohistan in East. Approximately latitude of $35^{0}10'$ – $35^{0}58'$ North and longitude of $72^{0}00$ – $72^{0}50'$ bounds the catchment as shown in Figure 2.

A line diagram in Figure 3 shows the major nullahs and tributaries of the Swat River upstream of the Amandara headworks and Panjkora river upto Timargarha. The stations where discharge, suspended sediments and gauge heights are measured, are also marked. (orange circle, green circle, Q, S and G represents town, measuring station, discharge, sediment and gauge measurement respectively).



SALIENT FEATURES	
Location	Khyber Pakhtunkhwa
Latitude Range	$35^{0}10'$ – $35^{0}58'$ North
Longitude Range	$72^{0}00$ – $72^{0}50'$ East
Elevation range	2000 to >4500m.a.s.l
Drainage Area	2018 km^2
Streams	1- Ushu 2- Gabrail

Fig. 2 Kalam Catchment

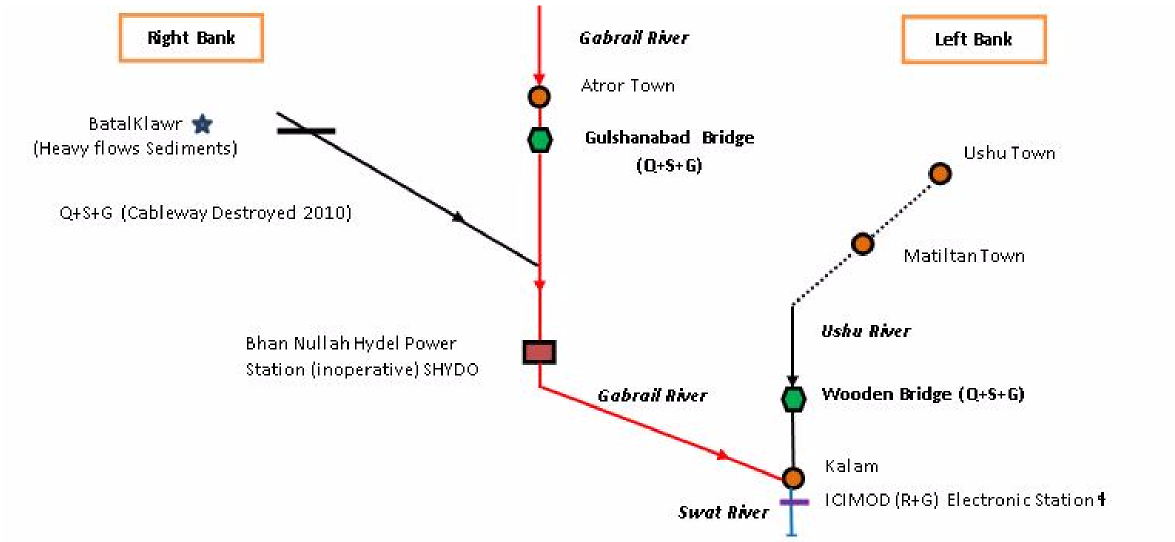


Fig. 3 Line diagram of River Swat catchment

4. Data Type and Acquisition

4.1 Temporal Data

Kalam station data has been acquired from the Surface Water Hydrology Project (SWHP), WAPDA for the period as described in Table 2 (Year 2013 data has not yet published by WAPDA).

Table 2 Data acquired from WAPDA

Sr. No.	Data Type	Lat	Long	Data
				Peruid
1	Discharge	34° 21’	71° 32’	2000-2013
2	Temperature	35° 32’	71° 55’	2000-2013
3	Rainfall	35° 32’	71° 55’	2000-2013

4.2 Satellite Data

4.2.1 DEM

A digital elevation model (DEM) of the Kalam catchment has been set-up to delineate the watershed and to define the elevation zones necessary for the snowmelt runoff modelling. For this purpose the SRTM (Shuttel Radar Topographic Mission) was used, which has a resolution of 3 arc-second (~90x90 m). The downloaded DEM tile is srtm_51_06 that covers the whole catchment area was downloaded and mosaicked. Although ASTER GDEM Version 2 is much improved compared to Version 1, there are still problems with reflecting water bodies [22]. The ‘Hydrology’ toolbox of ArcGIS’s Spatial Analyst was used to delineate the watershed of the Kalam catchment. After the delineation of the watershed, the catchment was divided into 7 elevation zones, which have in general an equal elevation difference of 500 m. Only the lowest and highest zones were extended to the minimum lower respectively maximum upper altitudes, as a further subdivision would have led to disproportional small areas. Area and mean hypsometric elevation of each zone was calculated from the DEM raster through Geographic Information System (GIS). The resulting elevation zones of the Kalam catchment is shown in Figure 4 and hypsometric mean elevation is shown in tabular as well in graphical form.

Table 3 Hypsometric mean elevation

Zones	$Elev_{min}$	$Elev_{max}$	H_{mean}	Area $(km)^2$
1	1501	2000	1989	18
2	2001	2500	2298	69
3	2501	3000	2782	168.5
4	3001	3500	3279	291.5
5	3501	4000	3766	486.8
6	4001	4500	4247	631.8
7	4501	9000	4735	368.5

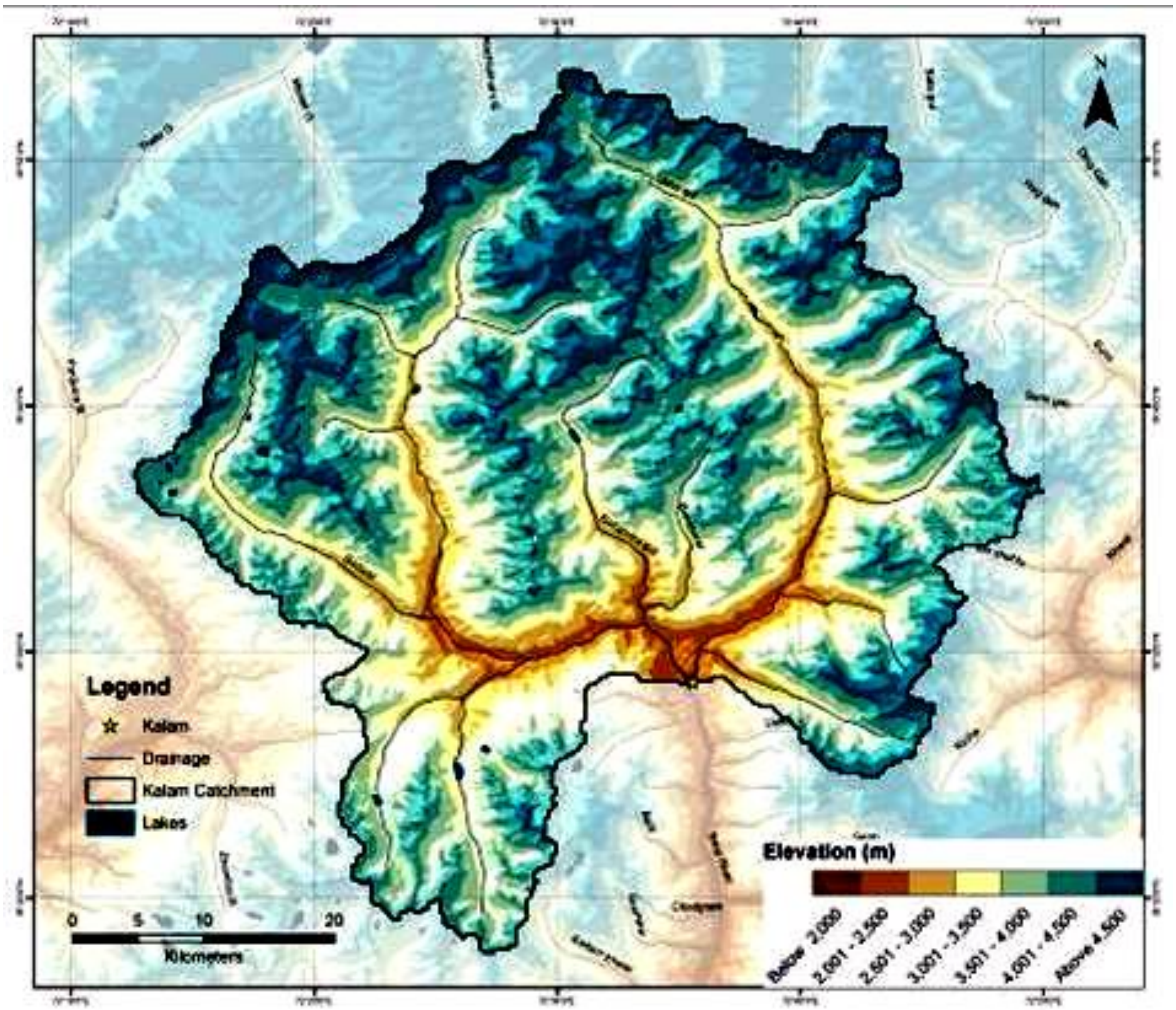


Fig. 4 Kalam Catchment elevation zones

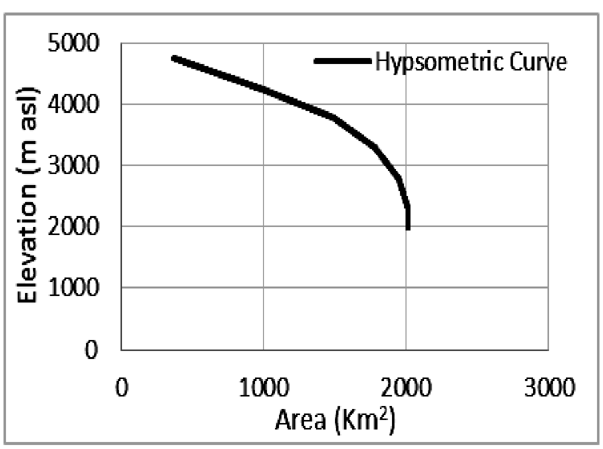


Fig. 5 Hypsometric mean elevation curve

4.2.2 MODIS

In the present study, Terra MODIS snow cover products has been downloaded and processed. The MOD10A1 snow product with 500m spatial was obtained for the study area for years 2000-2014 to be used in spatial investigation of snow cover area over Kalam and as a model input to snowmelt runoff model MODIS daily snow product MOD10A1 is 93-100% precise as a consequence of incessant improvement in algorithms [23]. This daily product has been designated as the source information to map snow cover area over the basin. Extent of MODIS has been shown in figure 6. It is very important to have the most recent data in hand, particularly in view of inevitable data gaps because of cloud coverage. Thus it is crucial to download the MODIS snow cover tiles on a daily basis. For the MODIS data, the following procedures were executed:

1. Daily MODIS tile is downloaded from server for Kalam area.
2. Temporal interpolation procedures are adopted to eliminate cloud cover and correct the raster cells with no data information.
3. Snow and no-snow statistics has been obtained after correction of MODIS data.
4. Linear interpolation is done in case of missing data and snow curves are calculated by applying smoothening techniques.

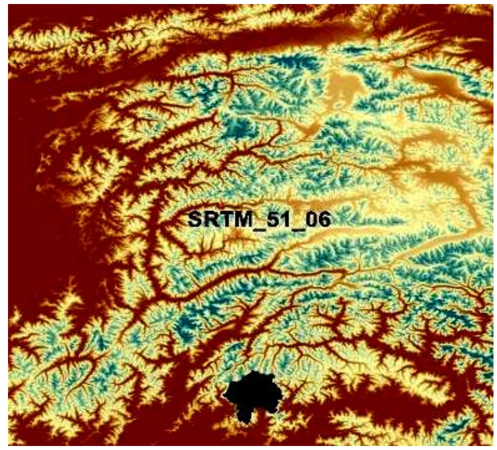
4.2.3 RFE

Rainfall Estimates (RFE) version 2.0 was executed by the NOAA Climate Prediction Center (CPC). This algorithm replaced the dekadal (or 10-day) version 1.0 that was functioning from 1995 through 2000 [24]. A detailed description of the NOAA CPC daily RFE 2.0 data can be found at the Website of Colombia University. All data are in geographic coordinates at 0.10 degree resolution. The individual daily RFE tiles are ~65-80 KB per file. The daily data are provided for download in three formats: daily, monthly daily data (~2MB per month), and annual daily data (~25 MB per year). Extent of RFE has been shown in Figure 6. Historic precipitation data was downloaded in raster formats from 2002-2014. For RFE information, following procedures were performed:

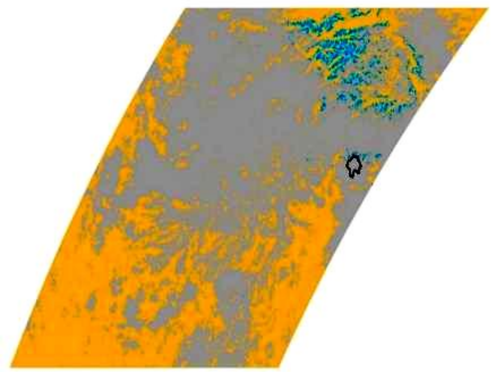
1. Daily RFE tile is downloaded from server for Kalam area and converted into workable format.
2. Daily precipitation value is extracted for each pixel in terms of min, max and mean. This distributed values of mean has been applied over the entire catchment.
3. Extraction of RFE pixel information over Kalam station for comparison purposes.

4.2.4 Landcover data

According to Anderson, the lowest level of analysis accurateness in the identification of land cover and landuse classes from remote sensed data is at least 85% [25]. Land cover statistics for estimating curve number has been taken from Forest cover change assessment using satellite images in Swat and Shangla districts, NWFP, Pakistan. WWF – Pakistan, Lahore [26].



Extent of DEM



Extent of MODIS

Extent of RFE

Fig. 6 Extents of Three Satellite Data of DEM, MODIS & RFE covering Kalam

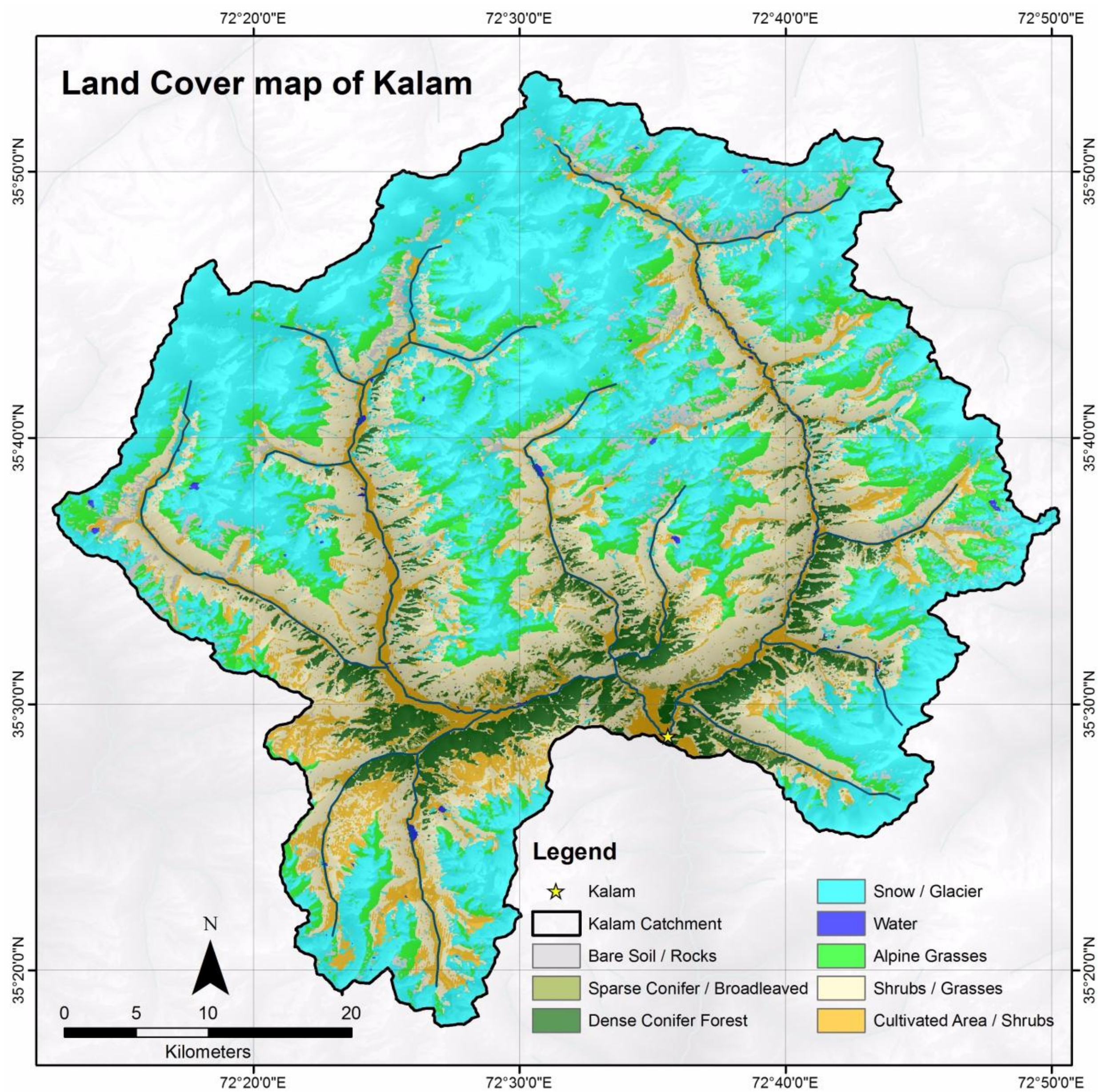


Fig. 7 Landcover Map of Kalam Catchment

5. Methodology

In order to attain the intended objectives, following schematic steps are followed:

1 Downloading and extraction of snow data from MODIS and masking of tiles for Kalam catchment for the extraction of snow cover area is processed and investigation of spatial distributions of snow cover area over catchment is conducted through mapping which gives an idea of areal depletion of snow over the year.

2 Downloading and extraction of rainfall data from satellite RFE for Kalam is processed and daily rainfall of RFE over Kalam is then compared with ground station for its validity and to be use in SRM model.

3 After acquisition and extraction of all data for the model, calibration of the model is done and total snow melt runoff for the Kalam catchment is estimated. Snowmelt from SRM is estimated by separating rainfall days on basis of critical

temperature. Critical temperature will help in order to differentiate between precipitation falling as snow and as rain; the snow precipitation will then be incorporated in the model to obtain the total snowmelt component from the catchment.

4 Use of conventional approach and snowmelt model for estimating snow melt flows is carried out and results from conventional approach is compared with SRM model. In conventional approach, a water balance method is incorporated in which various components like rainfall volume and ground water volume is estimated to get snow melt flows by using simple relation (Snowmelt flow = observed flows – Rainfall runoff – groundwater flows). A represent able value of rainfall and groundwater volume is estimated then there respective share are subtracted from observed volumes to estimate snow melt contribution for the catchment.

6. Results and Discussions

6.1 Spatial Distributions of Snow Cover over the Catchment

The fourteen years snowcover investigation with remote sensing shows that the snow area may encompass about 99 % (almost covered) of the entire part of the catchment in January-March to as low as 5% in September. Figure 8 shows the graphical variation of mean monthly snow cover for the year 2013 in the Kalam catchment with blue and brown color showing snow cover and snow free area respectively. Figure 9 gives us an idea how snow

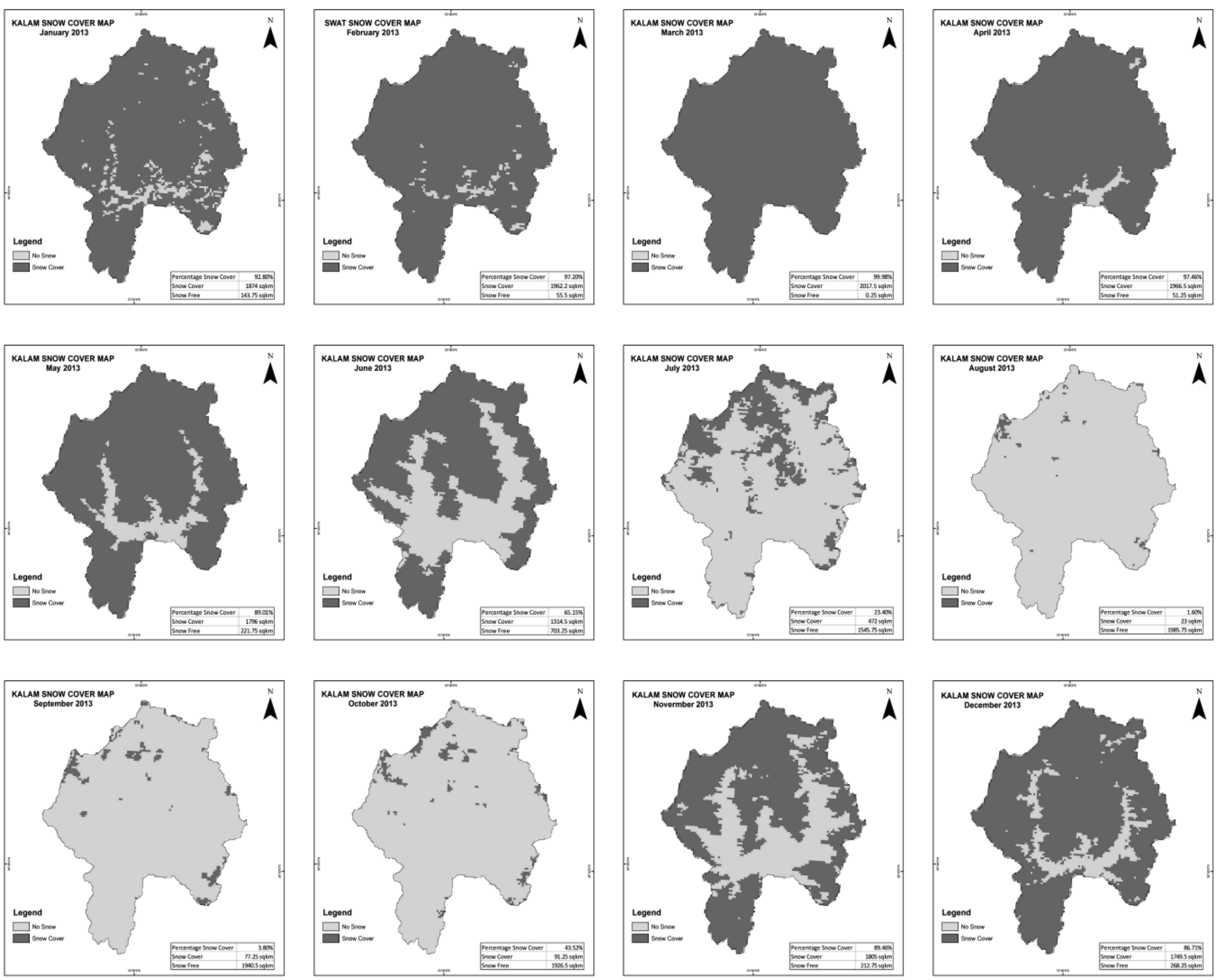


Fig.8 Snow cover variation in Kalam catchment (Year 2013)

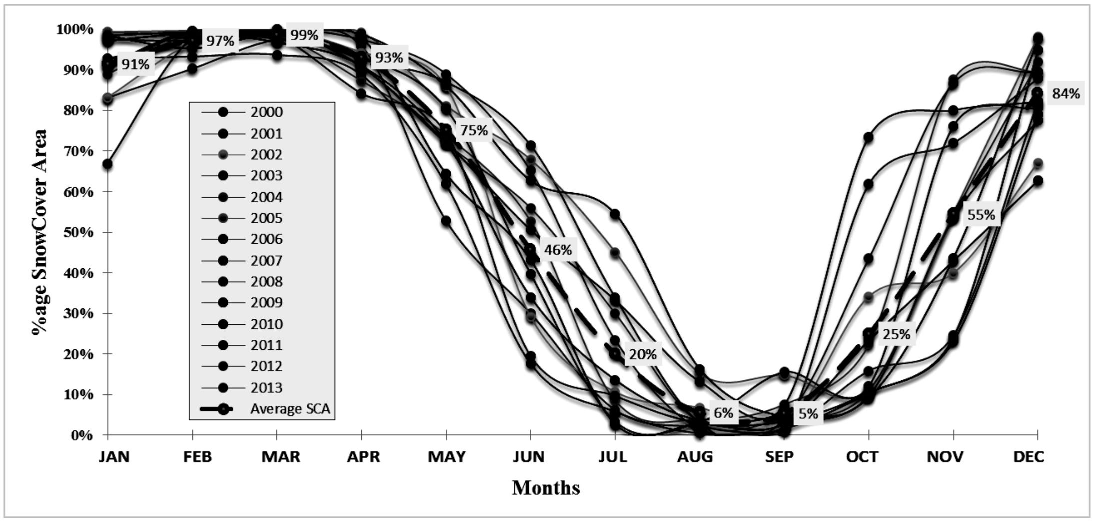
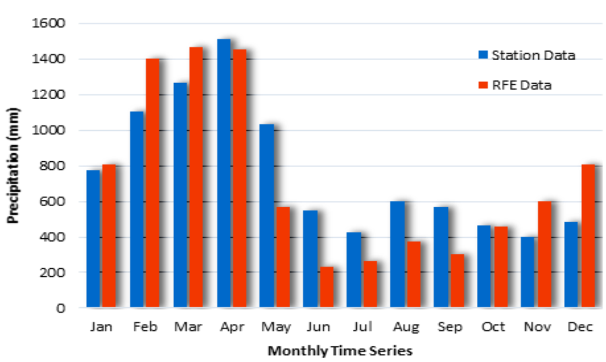


Fig. 9 Graphical representation of monthly percentage variation of snow cover over Kalam

varied over Kalam catchment with the increase and decrease of temperatures. It means that the whole watershed principally accommodates periodic snowcover, which is an essential element of hydrological cycle and major contributor to the watershed's fresh water resources. The investigation clearly shows that Kalam receives highest amount of snowfall in September with an increase in area of snow cover upto March then melting begins and catchment is almost cleared with only snowcover left on mountain tops.

6.2 Comparison of RFE Precipitation with Kalam Station Data

After extracting the information from RFE satellite data, a comparison is made between station rainfall and RFE on monthly and yearly data for 11 years (2002-2012) showing good correlation coefficient of 0.702 and 0.77 respectively. Following figures shows the comparison of RFE with Kalam station data. However, it has been seen that there is no relation exists on daily basis.



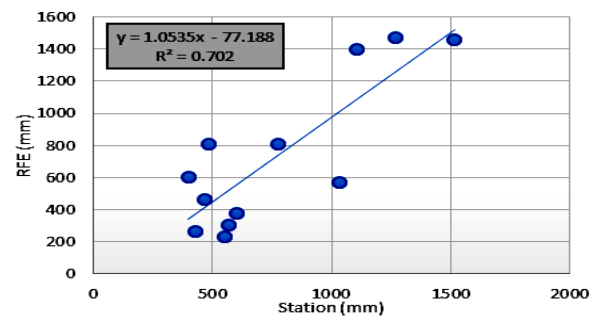
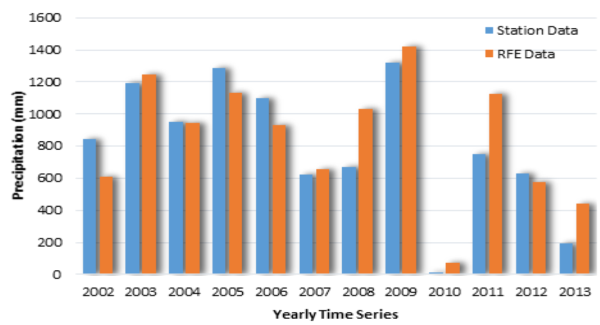


Fig. 10 Monthly comparison of RFE with Kalam station data



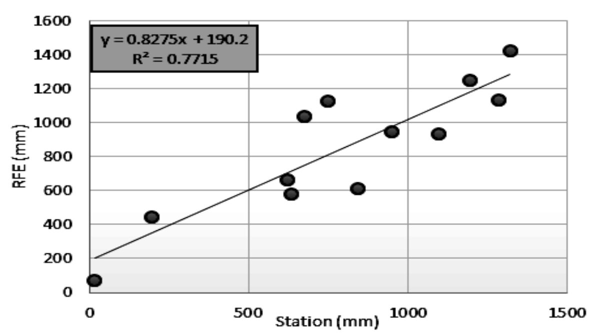


Fig. 11 Yearly comparison of RFE with Kalam station data

6.3 Assessment Of Total Snowmelt Runoff Contribution For The Catchment

6.3.1 Snowmelt contribution from conventional method

Two methods for the estimation of rainfall runoff volumes and three hydrograph separation method for the ground water are used owing to unavailability of any ground related data and an average of these methods are presented in graphical format in Figure 12. For rainfall runoff analysis, CN was based on ISRIC data and the soil for the catchment is considered to have 46% sand, and 25% silt. It is converted to soil textural classification of USDA as Sandy Clay Loam. Sandy Clay loam corresponds to HSG of category C. Curve number for each land cover is selected from table of curve numbers proposed by Soil Conservation Service and reported in TR55 of USDA. A weighted area CN is calculated for diverse land classes under AMC-II conditions i.e 87 as given in Table 4 and calculated as 74 and 94 for AMC-I and AMC-III respectively and rainfall runoff volume is estimated. For Volumetric rainfall coefficient, loamy clay conditions has been adopted and against rainfall depths different values of C_v is considered. Results of snowmelt contribution estimated from the equation as discussed in Methodology section (no.3) are follows are given in Table 5 and graphically shown in Figure 15. For groundwater estimation, three methods as described above are averaged to have a good estimate of contribution.

All these components of water balance approach are given in Table 4 and by using water balance equation snowmelt runoff contribution is calculated.

Table 4 Weighted CN for Kalam catchment for various land cover data

Type	Area (km^2)	CN-Weighted
Dense Forest	113.53	4
Open Forest	33.34	1
Grasses/Shrubs	512.67	19
Cultivated Areas/Shrubs	199.6	9

Type	Area (km^2)	CN-Weighted
Bare Soil/Soil	64.31	3
Lake/River	6.11	0
Aphine Grasse	233.57	9
Snow Glacier	854.63	42
Total:	**2018**	**87**

Table 5 Water balance approach results

Year	Observed Flow Volume	Rainfall Runoff Flow Volume		Groundwater Flow Volume			Rainfall Runoff Flow Volume	Groundwater Flow Volume	Snowmelt Flow Volume”
		SCS-CN	Volumetric Analysis	Constant Discharge	Constant Slope	Concave Method	(AVG)	(AVG)	
	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(%)
1	2	3	4	5	6	7	8	9	10=(1-8-9)/(1)
2000	23659	3623	2366	4210	5253	4731	2995	4731	67%
2001	22209	3329	2221	5191	4717	4954	2775	4954	65%
2002	28613	5997	3434	5484	5253	5368	4715	5368	65%
2003	33443	6211	4682	5535	5509	5522	5447	5522	67%
2004	31342	6418	3448	7749	6645	7197	4933	7197	61%
2005	39544	7822	3559	6063	6851	6457	5690	6457	69%
2006	28031	6526	3924	3933	5011	4472	5225	4472	65%
2007	28104	4939	3935	4584	4801	4693	4437	4693	68%
2008	23276	3449	3026	4049	4655	4352	3237	4352	67%
2009	30795	4363	3695	3854	4745	4299	4029	4299	73%
2010	29794	6790	4469	6990	5991	6491	5630	6491	59%
2011	27584	5186	4138	5435	5516	5476	4662	5476	63%
2012	29551	6107	5910	6296	5802	6049	6009	6049	59%

Note: MCM is Million cubic meters

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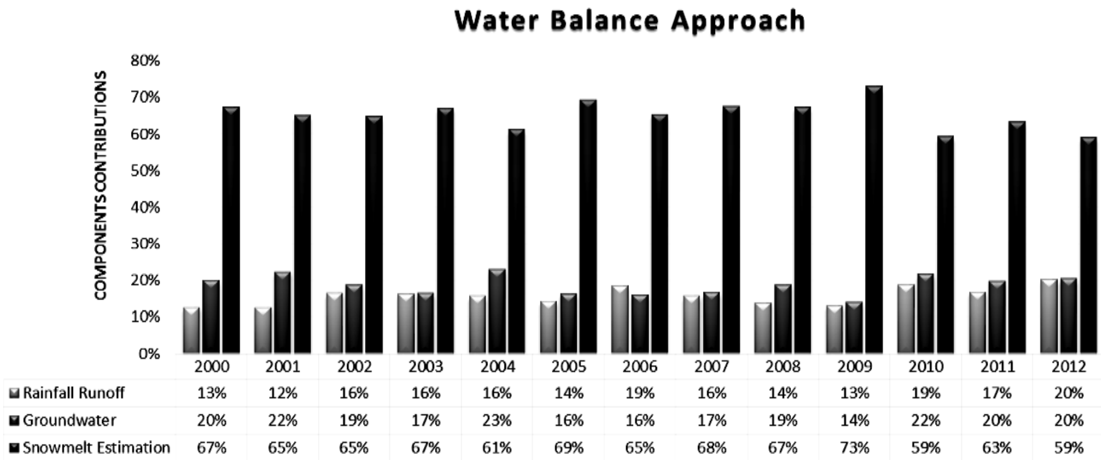

Fig. 12 Results of conventional method for estimation of snow melt contribution

6.3.2 Snowmelt contribution from SRM

a) Calibrated Model Parameters

Following parameters are needed for carrying out the snowmelt modeling:

1. Degree day factor (A_n)
2. Runoff coefficient for rain (C_r)
3. Runoff coefficient for snow (C_s)
4. Critical temperature (T_{cric})
5. Rainfall contributing area (RCA)
6. Recession coefficient (k)
7. Temperature lapse rate (λ)
8. Time lag (L)

Various studies carried out in different basins of Pakistan as presented in Table 6 which was used as a baseline for development of parameters for Kalam catchment. Degree day factors and time constant parameters are shown in Table 7 and Table 8.

Table 6 Variation in parameters on various basins

Researchers	**Basins**	**An**	**Λ**	**Cs**	**Cr**	**L**
Adnan	Hunza	0.5-0.7	0.48-0.76	0-0.5	0-0.5	6-18
	Gilgit	0.55-0.8	0.43	0.03-0.35	0.03-0.35	18
	Astore	0.65-0.9	0.61	0.03-0.45	0.03-0.45	12
	Shyok	0.35	0.75	0.03-0.25	0.05-0.15	18
Nabi et al	Astore	0.3-0.75	0.6	0.6-0.85	0.6-0.95	18
Farrukh	Gilgit	0.001-0.6	0.6-0.9	-	-	-
Bilal et al	Astore	0.1-0.99	0.2-0.9	0.1-0.99	0.1-0.99	4-24
Tahir et al	Hunza	0.5	0.64	0.15-0.3	0.1-0.2	18
Qamar	Kunhar	0.15-0.8	0.2-	0.8	0.4-0.8	18

Table 7 Degree-Day Factor Functions for Kalam

10-Daily	**Period 1**	**Period 2**	**Period 3**	**Period 4**
An	0.15	0.2	0.25	0.3
10-Daily	**Period 5**	**Period 6**	**Period 7**	**Period 8**
An	0.35	0.4	0.5	0.6

Table 8 Calibrated Values of Time-constant Parameters

Parameter	**Value**	**Units**	**Remarks**
L	18	hrs	= 1 day
Pcrit	0.1	cm	Fixed
C_s	0.8	–	Fixed
C_R	0.5-0.8	–	Varies
kx ky	0.994 0.003	– –	K= 0.981 (Basin wide)
T_{cric}	3-0.75	°C	Fixed
ΔT	5.5	°C/km	Calibrated

Recession coefficient was calculated from the recession analysis of observed flows at Kalam and by using the equations as described in SRM manual (Chapter 5.3.6) and graph is shown in figure 13.

b) Calibration of the model

The two (2) error standards commonly used to describe the precision of model results associated to observed hydro-graphs, sometimes also stated as "model performance". Absolute value of the total volume difference ranges from 1.6 – 17.2%, an good assessment of total yearly discharge. The coefficient of determination R^2, that symbolizes the goodness of fit amongst the simulated & observed hydro-graphs ranges from 0.83 – 0.96 which also shows a close fit of the graphs.

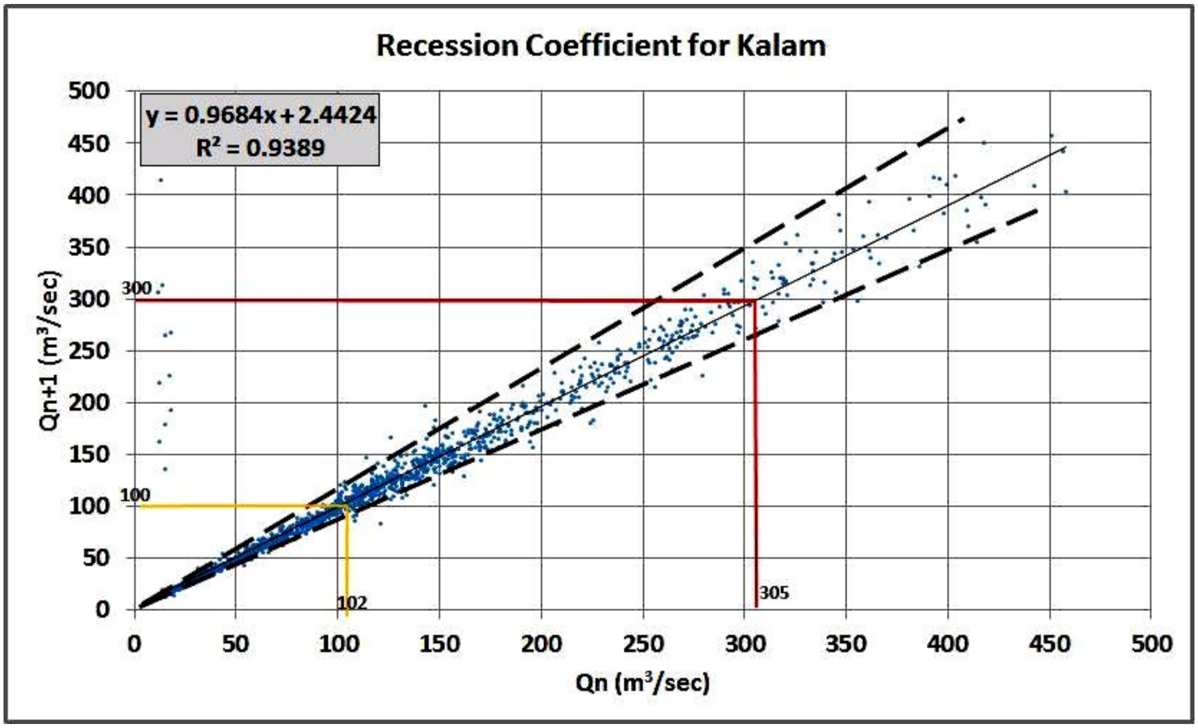

Fig. 13 Recession analysis of basin

c) Validation of the model

The model is calibrated well for two (4) years 2000-2003. Parameters as presented in Table 8 was fixed and applied on rest of the years for validation. After assessment and descent of all the model input variables, SRM is calibrated well with observed discharges during 2000-2003. Few factors were faintly attuned and calibrated model is validated for years 2004-2012. The coefficient of determination and the volume differences are shown in Table 9 while two comparison hydrogrphs, one for calibration and other for validation is also shown in Figure 14.

d) Comparison study of RFE and Kalam station data in SRM

A comparison study has also been conducted by incorporating RFE rainfall data instead of rainfall observed at Kalam which shows almost similar results by making all the variables and parameters fixed, results are tabulated in Table 10. On average basis, coefficient of determination for RFE data is 90% while station rainfall data shows 89% by the analysis of seven years (2003-2009).

Snowmelt flows into river discharge as a response of snowcover and precipitation that occurs as a snowfall which has been obtained by mean of critical temperature has been incorporated in the model in order to have the contribution of pure snowmelt. The results clearly shows the dominancy of snowmelt flows as the catchment is primarily a snow-fed. Kalam receives very less amount of rainfall which can be seen from the rainfall analysis and from the model as well. Rainfall contribution estimated to about 17% on average basis with an variation of 7% – 25%. The study utilizes daily record of snowcover which indicates that snowfall took place during seven months (September – March)

Table 9 SRM Calibration and Validation Table

Years	SRM Calibration				Validation Table								
	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
D_v	-1.6	-7.6	-7.1	-5.9	-5.0	-11.4	-11.6	-6.7	-2.6	22.3	-14.5	-14.5	-15.5
R^2	0.91	0.92	0.94	0.96	0.91	0.93	0.91	0.94	0.95	0.7	0.81	0.92	0.90

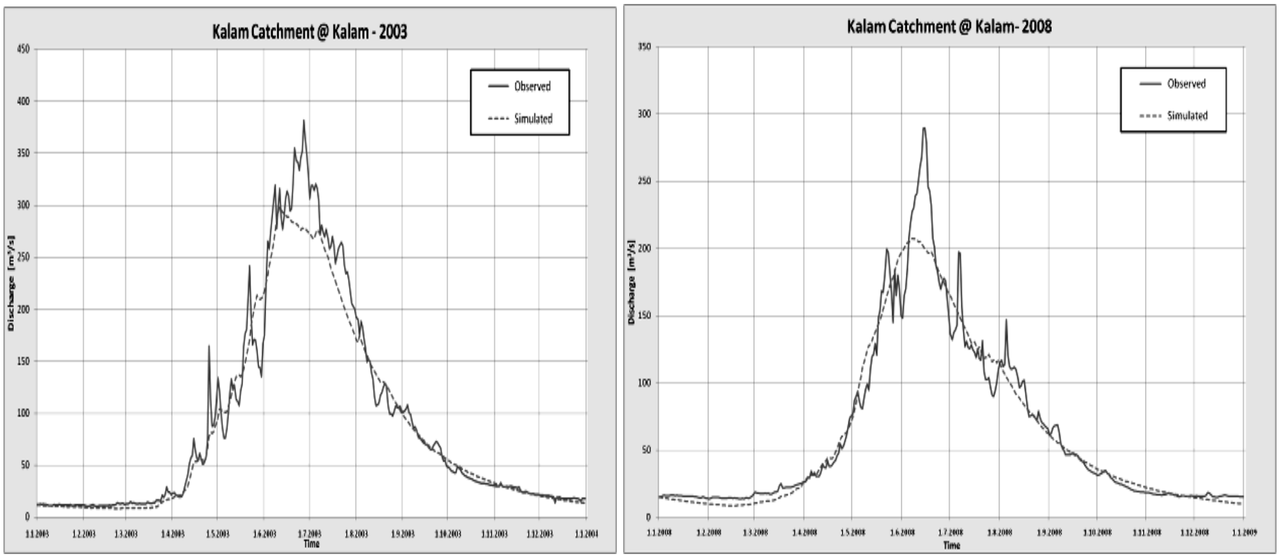

Fig.14 Kalam one calibrating year 2003 and validating year 2008 (observed vs simulated) hydrograph

and even little amounts can be detected during the remaining five summer months. Monthly averages of snowmelt as well as observed discharges for the years 2000-2012 has been shown in graphical form in Figure 15. A polynomial relation has also been developed during the snowmelt months to have the average monthly discharges in Kalam catchment. Relationship as in Figure 16 ($Y=2*10^{-6}X^3-0.0019X^2+0.9838X-11.104$) where Y = Snowmelt discharges and X= Observed/measured discharges in m^3/sec is developed for estimating snowmelt flows in snow period (April – September).

Table 10 RFE and Kalam rainfall station comparison in SRM model

Years	Station Rainfall Data		RFE Data	
	D_v	R^2	D_v	R^2
2003	0.1	96%	4.4	96%
2004	-4.4	92%	-3.2	92%
2005	6.6	90%	6.4	90%
2006	1.6	86%	4.4	87%
2007	5.3	85%	6.1	84%
2008	7.7	89%	12.9	86%
2009	10.3	88%	-1.8	92%

Table 11 shows an average yearly discharge volumes that has been observed at Kalam gauging station and snowmelt flows estimated by the SRM model. Analysis of 13 years of data shows a snowmelt contribution of 72% in Kalam catchment with an variation 59% to 80% in year 2011 and 2009 respectively. Average snow variation of all the years is presented in figure 17 that shows the variation in snow contribution.

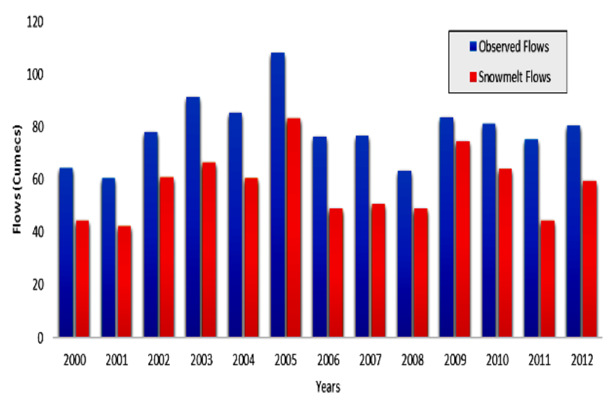

Fig.15 Monthly averages of observed vs snowmelt flows (2000-2012)

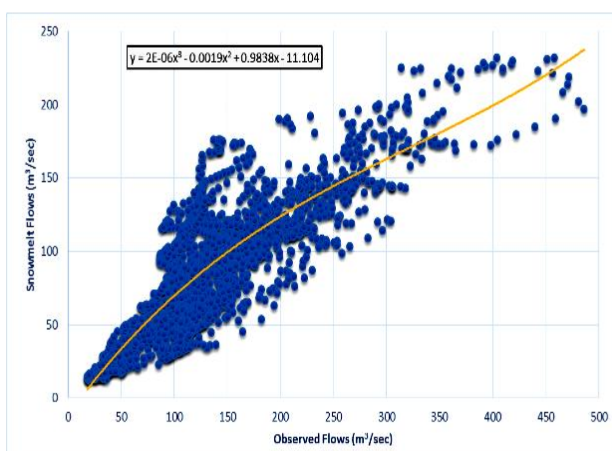

Fig.16 Relationship between observed and snowmelt discharges

Table 11 Snowmelt contribution in Kalam (2000-2012)

Years	Observed Flows (MCM)	Snowmelt Flows (MCM)	Snow melt Contribution (%)
2000	23659	16385	69%
2001	22209	15499	70%
2002	28613	22382	78%
2003	33443	24391	73%
2004	31342	22131	71%
2005	39544	30420	77%
2006	28031	17934	64%
2007	28104	18632	66%
2008	23276	17848	77%
2009	30795	24636	80%
2010	29794	23561	79%
2011	27584	16147	59%
2012	29551	22000	74%

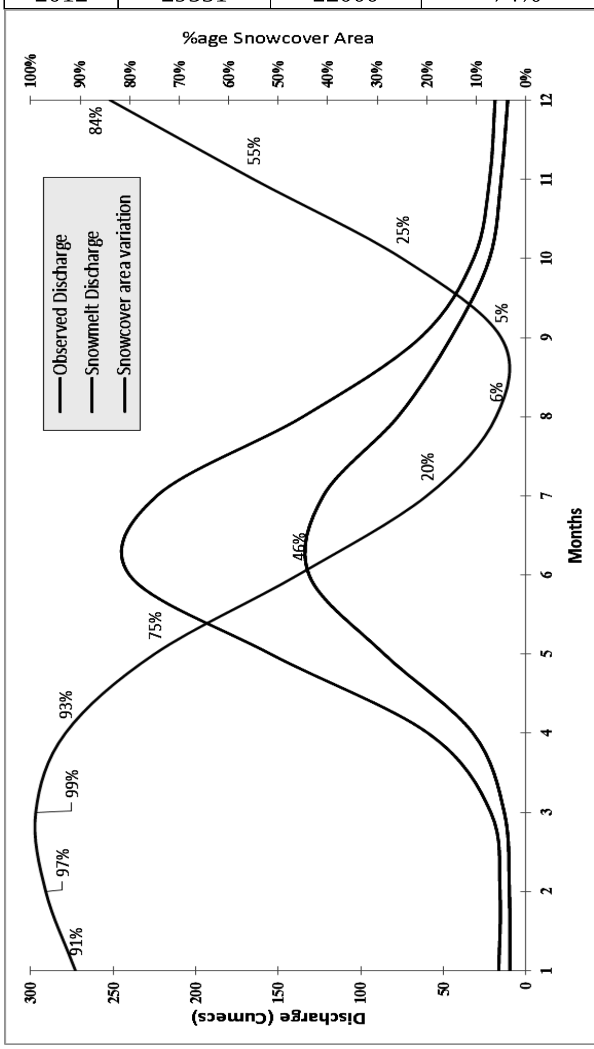

Fig.17 Average observed vs snowmelt discharge with a depletion of snow cover area

Relationship between average snowcover, average snowmelt and river discharge (2000-2012) has also been presented in figure 17 which shows the snowcover depletion starts from mid-march with maximum snowcover area and a little snowmelt flows and as season progresses it begins to gain momentum and on average reaches to its peak flow in mid-June or in July when snowcover area almost disappeared or snowline retreats to mountain tops and glaciated surfaces appears. Temperature begins to drop and due to snowfalling, snowcover area increases.

6.3.3 Comparison of conventional method with SRM

The result obtained from water balance approach and SRM shows an overall snowmelt contribution in kalam catchment as 65% and 72% respectively. Variation of snowmelt discharges ranges from 59-80% and 59-73% for SRM and conventional method from the analysis of 13 years of past record in Kalam as presented in Table 12.

Table 12 Overall Comparison of snowmelt runoffs using conventional approach and SRM results

Year	Snowmelt Runoff Model	Water Balance Approach
2000	69%	67%
2001	70%	65%
2002	78%	65%
2003	73%	67%
2004	71%	61%
2005	77%	69%
2006	64%	65%
2007	66%	68%
2008	77%	67%
2009	80%	73%
2010	79%	59%
2011	59%	63%
2012	74%	59%
Average	**72%**	**65%**

7. Conclusion

Due to readily avalibility of MODIS and RFE satellite data, it is now possible to estimate the snow and rainfall related activities more accurately. Snowcover mapping using the satellite data is very resourceful method for watershed having tough topography and large extents with the scarcity of snow related data. Snowcover mapping of Kalam catchment has been done by using the MODIS snow data, average snow cover in Kalam ranges from 5% to 99% in September & March, respectively.

RFE rainfall data shows a good relation with monthly and yearly with correlation coefficient of 0.702 and 0.77 respectively while it has also been seen that there is no relation exists on daily comparison.

Snowmelt Runoff Model (SRM) was applied to Kalam catchment and the model is calibrated and validated using daily stream flow from 2000 to 2012 with fairly high correlation coefficient (average Calibration ~0.95 & validation ~0.89, annual volume bias<6.5%). Thirteen (13) years of simulation results show that Kalam is predominantly a snow-fed catchment as snowmelt flow to the river flows ranges from 59% in Year 2011 and 80% in Year 2009 and provide sustainable supply of fresh water for domestic, irrigation as well as hydropower purposes.

Comparison of conventional approach with snowmelt runoff model shows an snowmelt contribution of 65% and 72% respectively in relation with Kalam flows. The snowmelt typically starts in early April and increases progressively from around 12–15 m^3/sec to 100 m^3/sec and reaches it maximum contribution as 185 m^3/sec in early July.

A comparison study has also been conducted by incorporating RFE rainfall data instead of rainfall observed at Kalam in SRM which shows almost similar results. On average basis, coefficient of determination for RFE data is 90% while station rainfall data shows 89% by the analysis of seven years (2003-2009).

8. Recommendations

- SRM model is recommended for simulating the hydrology of snow-fed catchments like Kalam using remotely sensed information.
- Snowcover mapping can be effectively carried out using MODIS satellite data while using MODIS for the assessment of snowcover area, a temporal interpolation technique can be adopted to correct raster cells with clouds or undefined data.
- RFE rainfall product can be used in data scarce catchments for snowmelt modelling as it shows good correlation with the ground station and in simulated model results.
- Tropical Rainfall Measuring Mission (TRMM) is a high spatial and temporal resolution rainfall product that may be compared with RFE and ground station data to check its accuracy and improvements in model results.
- MODIS LST temperature data can be compared with ground station data for zonal temperature input and for calculating the lapse rate.

9. Acknowledgement

The University of Engineering & Technology authors are thankful to Prof. Dr.-Ing. Wolfgang Bogacki, Vice President, Hochschule Koblenz, Germany and Rashid Saleem, Remote Sensing Specialist for his assistance during the study and SWHP, WAPDA for sharing the desired data.

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