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Quantification of Persistent Snow and Glacier melt Contribution in Hydrological Regime of Jhelum River basin using Spatial Processes in Hydrology (SPHY) model

By

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List of Abbreviations

Acronyms	Abbreviations
SPHY	Spatial Processes in Hydrology
IBIS	Indus Basin Irrigation System
HKKH	Hindu-Kush-Karakoram-Himalaya
UIB	Upper Indus Basin
WAPDA	Water and Power Development Authority
PMD	Pakistan Meteorological department
SRTM	Shuttle Radar Topography Mission
WFDEI	Watch Force ERA-Interim data
MODIS	Moderate Resolution Imaging Spectroradiometer
USGS	United States Geological Survey

ABSTRACT

Economy of Pakistan is largely based on agriculture activities which are strongly connected with water resources and a step ahead hydrological behaviour of rivers catchment in northern region of Pakistan. Jhelum River is the most significant western tributary of mighty Indus River which receives significant amount of glacier and snow melt. For current study Spatial Processes in Hydrology (SPHY) model is used to quantify hydrological components (base flow, rain fall, snow and glacier melt runoff) along with focus on changes in runoff sources, seasonal change in hydrological components and hydrological extremes. Due to trans-boundary nature of Mangla catchment, bias corrected WFDEI climate data was used. SPHY model was calibrated using actual evapotranspiration and discharge data to simulate discharge data and its hydrological components. It has been observed that runoff is underestimated due to low values of precipitation data for high altitude areas. Overall, peak runoff for the catchment is observed during snow melt season. A true representation of hydrological components all over the year and seasonal changes in rainfall, glacier snow melt runoff are observed. Analysis of hydrological components reveals that snow melt runoff peak occurs during summer and rainfall runoff peak occur during monsoon along with glacier melt runoff. Due to increase in precipitation and temperature over the time period (2001-2009), rainfall runoff, glacier and snow melt runoff are also increased. This model could be used to analyse climate change impacts on water sources and would help to improve reservoir operation for better water resources management.

Chapter 1

INTRODUCTION

1.1. Background

Water is a valuable resource on earth which plays a vital role in social and economic life. The amount of water is fixed on earth which is characterized by close hydrological system and its variation with respect to time and space may leads to extreme conditions i.e. drought and flood. These extreme conditions are further result in large scale agriculture losses ultimately affecting the world's economy (Zaidi & Afzaal, 2016).

Pakistan is an agricultural country and agricultural related activities are generally based on country's river and canal irrigation system. Indus Basin Irrigation System (IBIS) is world's largest agriculture irrigation system which receives large portion of water from glacier and snow melt along with rainfall. Pakistan's economy is largely dependent on hydrological resources for agriculture and hydropower plants. In summer, Upper Indus Basin (UIB) system receives large amount of water due to snow and glaciers melting in Northern areas of Pakistan (Azmat, 2015). This makes the overall Pakistan's water resources and irrigation canal system very unique. Therefore, it is essential to calculate the glacier and snow melt along with rainfall runoff and base flow to prevent any loss in agriculture due to flood or drought conditions.

In the high elevated areas of The Hindu-Kush-Karakoram-Himalaya (HKKH), snow and glacier cover area highly influence the contribution to water availability in summer and spring seasons. Climate change impact on snow and glacier melt contribution to river flow was studied for the better understanding of hydrological process for a river basin (Brown et al., 2010). Snow melt contribution to water resources of this region is more vulnerable to climate change i-e significant warming effects (Walter et al., 2010), (Immerzeel et al., 2013), (Tian et al., 2015).

Moreover, in high elevated regions of Himalaya, the rate of glacier retreat is increasing in response to climate change and global warming (Singh et al., 2011, Benn et al., 2012).

The main Indus River initiates from HKKH region. Its main eastern tributaries are Jhelum, Chenab, Sutlej and Ravi along with northern and western tributaries of Haro, Soan Kabul and Sawat. According to Indus Basin Treaty signed in 1960 by India and Pakistan, water rights of Jhelum, Chenab and Indus Rivers were given to Pakistan and of Ravi, Sutlej and Bias to India (Ahmad, 2001).

Pakistan's food security and sustainable economy is largely dependent on water resources and their efficient management. Due to socio-economic issues, climate change impact and international policies, it's a big challenge for Pakistan to maintain its water resources. Accordingly, for power generation and agricultural activities two main water storage structures Mangla and Tarbela Dams were constructed on main streams of Jhelum and Indus Rivers in 1974 and 1961 respectively (Azmat, 2015). It is very important to study hydrological regime of Pakistan and in this context, this study focuses on hydrological components of stream flow for the better management of Jhelum River basin.

During summer, the Indus River stream flow is contributed by glacier and snow melt from high and mid altitude areas respectively and rainfall contribute from foothill areas (Miller et al., 2012). Glacier and snow is melt is primary source for stream flow (Mukhopadhyay & Dutta, 2010). (Walte et al., 2010) found that discharge generated by glacier and snow melt is 151% greater than the discharge generated from downstream areas. Snow melt contribution is more sensitive to temperature changes and up to 50% of the total annual discharge is contributed by snow melt in Indus River basin. (Bookhagen & Burbank, 2010).As stream flow of UIB is strongly dependent on glacier and snow melt, it can cause of increase and decrease in stream flow in near and far future respectively.

Climate change impact on river discharge of UIB is more substantial because of high contribution of melt water (Rees & Collins, 2006). Hydrological modelling for this basin using snow melt runoff model (SRM) indicated that discharge is affected by warming because of increase in snow and glacier melt (Immerzeel et al., 2009). According to climate change impact study (Walter et al., 2010) under A2 scenario of Special Report on Emission Scenarios (SRES), 50% decrease in glaciated area and 53% increase in rainfall would cause decrease in glacier runoff by 22% and 7% increase in total runoff for 2071-2099 respectively. For 2050 and subsequent decades, significant decrease in summer and late spring flows were predicted. Climate change impact study using Providing REgional Climates for Impacts Studies (PRECIS) regional model under A2 scenario of SRES for 2071 – 2100 indicated that increase and decrease in discharge for 50% to 100% glacier cover area and 0% glaciers respectively (Akhtar et al., 2008).

During climate change Impact study of upper Indus hydrology, -15% to +60% changes were predicted in water availability at the end of 21st century compared to the time period from 1971 to 2000. According to climate change scenarios, in UIB, during summer minor increase and decrease in stream flow for 2021-2050 and 2071-2100 was observed respectively. During other seasons (winter, spring and fall) increase in stream flow was found for both time periods. Furthermore, increase in flooding events during 21st century and increase in frequency of extreme discharge for UIB were predicted (Lutz et al., 2016). According to climate change impact study on Jhelum River, annual temperature is predicted to increase by 2.37^{o}C and precipitation to reduce by 38.5% at the end of 21st century (Akhter & Ahanger, 2015).

Mainly hydrological model are categorized either as rainfall runoff or snowmelt runoff models based on the catchment characteristic (Azmat et al., 2016). In high elevated areas, rainfall runoff models are in efficient due to contribution of glacier and snow melt during simulation of daily stream flows (Martine et al., 2008).

Many studies have been conducted to simulate glacier and snow melt contribution to total discharge using different conceptual and distributed hydrological model. Different hydrological models vary from simple temperature index model to physically based energy balanced model for glacier and snow melt modules. Although, energy balance provides details about mass and energy exchange between atmosphere and snow/glacier, but an extensive input data are required to calibrate the model, which is mostly not available at regional scale. Instead, temperature index models require only air temperature data and are easier to setup compared to energy balanced model. Degree day (temperature index) modelling approach is most common to estimate both snow and glacier melt, mainly used in conceptual hydrological modelling (Braun et al., 1993), (Schaefli et al., 2005),(Konz et al., 2007), (Walter et al., 2010),(Bookhagen & Burbank, 2010),(Luo et al., 2013) Moreover, temperature index modelling approach is strengthen by incorporating other variables.

The distributed (Tracer Aided Catchment, Distributed) TAC^d catchment model based on HBV model was applied on Nepalese Himalayan headwater Langtang Khola (glacierized catchment) for daily time step. Temperature index method using daily sunshine duration was used to calculate glacier and snow melt contribution to main stream flow. Melting of snow, clean ice and debris cover ice was considered by using different melting conditions for each. This approach helped to determine the components of stream flows for scarce catchment using minimum input datasets (Konz et al., 2007)

In 2016, a study has been carried out by using HEC-HMS to analyses the flooding condition in Tarbela catchment of Pakistan. This study has shown satisfactory results in the storm event, and further concluded that HEC-HMS is suitable tool to estimate surface rainfall generated runoff, but poor to map runoff generated by snow and glacier melt (Zaidi & Afzaal, 2016).

The Snow melt Runoff Model (SRM) hydrological model incorporates snow melt contribution to main stream flow. By studying efficiency and performance of SRM and HEC-HMS for scarce snow-fed Jhelum River basin for daily simulation of stream flows, promising results were found by using SRM model compared to HEC-HMS as SRM includes both liquid and solid precipitation and provide spatio-temporal calibration(Azmat et al., 2016). Runoff for Gilgit Basin in Pakistan was computed by using SRM. It was found that this model was very effective to estimate seasonal snowmelt runoff with Moderate Resolution Imaging Spectroradiometer (MODIS) derived Snow Cover and articulate Digital Elevation Model (DEM) data. It was also observed that the model is efficient for un-gauged catchments (Bashir & Rasul., 2010). SRM also showed good results for both snow and glacierized regions of Hunza basin as it includes both solid known as snow and liquid precipitation known as rainfall. It is also efficient in use of remotely sensed data due to which it is less influenced by errors caused by gauging precipitation data for high elevated regions (Tahir et al., 2011). Although, this model shows the satisfactory results for snow fed regions, but it is unable to calculate glacier and snow melt contribution separately.

Estimation of snow melt runoff for hydropower generation and water resources management is very essential. SRM was used to estimate runoff from snow covered area and snow free area for Beas basin separately and found very good results with 0.854 value of coefficient of determination (Prasad & Roy, 2005).

Soil Water Assessment Tool (SWAT) physical based semi-distributed hydrologic model was developed to manage and study climate change impacts on water resources, sedimentation and pollutant load in a catchment over continues time scale. The said model is favourable for water resources management used in agricultural activities. Furthermore, climate change impacts on various hydrological processes can also be studied to manage water balance and agricultural activities. In 2017, the aforementioned model was used to establish the water balance and simulation of stream flow along with the estimation of monthly volume inflows for Khanpur dam and found good results. Likewise, a good relationship between simulated and observed values for both monthly and annually discharge was also being observed. This study also demonstrated that SWAT can be used for water resources management of semiarid regions (Hagras & Habib, 2017).

In 2013, a study conducted for glacier impact on stream flow for Manas River basin using SWAT model including glacier process and found that glacier melt is more sensitive due to temperature change as compared to precipitation change (Luo et al, 2013). Tian et al., 2015, studied snow and glacier melt contribution to total runoff for Hunza River basin by integrating simulation of snow and glacier melt within Water and Energy Balance-based Distributed Hydrological Model (WEB-DHM-S). A good relationship between observed and simulated discharge was found along with average accuracy of simulated snow cover area against MODIS snow cover area.

During early summer and spring seasons, snow melt is the primary source of discharge and cause flood condition over many areas, which eventually leads to water loss, essential for agricultural activities and power generation, so it is very important to study runoff along with its components (glacier and snow melt runoff). Variable Infiltration Capacity (VIC), semi-distributed hydrologic model which is used for glacier and snow melt studies. It incorporates snow as, ground snow pack, snow on top of lake and vegetation canopy. VIC integrated with Energy Balance Ice-Melt model was used to study a large mountainous and glaciated Aksu River basin and satisfactory results were found to simulate runoff components and climate change impact on each component (Zhao et al., 2013)

TOPographic Kinematic APproximation and Integration (TOPKAPI), physically base fully distributed hydrological model, was used to quantify hydrological response of climate change along with glacier movement simulations. Transient evolution of glaciers and hydrology process under climate change were studied using cryospheric hydrological model. Degree day factor for glacier and snow melt is used in this model. Climate change impacts on snow and glacier melt runoff along with total runoff for Hunza River basin was studied using TOPKAPI-ETH, glacio-hydrological model. Quantification of sources (model parameters, climate projection models and natural variability in climate data) for model uncertainty to simulate future runoff was also studied and it was found that model uncertainty for future prediction could be reduce by detailed recommendation on network design and considering space and time for field measurement (Ragettli et al, 2013).

Glacier and snow melt is a main contribution for water sources of glacierized catchments. Inconsistency in glacier and snow melt throughout the whole year makes hydrological modelling in these areas more challenging. Unavailability of data for ungauged catchment, make it more difficult to parameterize the model to simulate the discharge data. Spatial Processes in Hydrology (SPHY) model is fully spatially distributed model which can be used to simulate discharge data for poor data coverage or ungauged basins by using other remotely sensed data (MODIS snow cover, Actual Evapotranspiration). Water availability analysis along with climate change impact on water resources using Regional Climate Model (RCM) and Global Climate Model (GCM) data, for the Upper Indus, Brahmaputra, Ganges, Mekong and Salween River Basins were studied by using SPHY model. Glacier and snow melt run off, rain fall run off and base flow were calculated separately for given basins (Lutz & Immerzeel, 2013). Furthermore in year 2016, climate change impact was studied on upper Indus hydrology and focused on changes for hydrological extremes, seasonality and runoff sources. It was concluded that the UIB would face uncertainty in future water availability due to uncertain future projection of precipitation. Despite, the uncertainties in water availability and future climate, basin-wide runoff patterns and trends for intra-annual shifts of water availability was consistent for climate change scenarios (Lutz et al., 2016).

Comparison of SPHY model with other hydrological models is summarized in terms of spatial and temporal resolutions, process integrated in calculation of total runoff and its components (base flow, glacier, and snow-melt runoff) field of applications Table 1.

1.2. Rationale

Pakistan is an agricultural country and commonly related agricultural activities are based on country's river and canal system. Indus Basin Irrigation System (IBIS) is world's largest agriculture irrigation system which receives large portion of water from snow and glacier-melt along with rainfall. Therefore, it is important to calculate the glacier and snow melt along with rainfall runoff and base flow to prevent any loss in agriculture due to flood or drought conditions. Moreover, it would help to the policy makers for better decision making to control flood, drought, agricultural activities and dam sites management. This study will support to manage water resources in Pakistan in view of contribution of hydrological components to main stream flow.

1.3. Objective

The objective of the research work is the quantification of hydrological components i.e. base flow, rainfall runoff, snow and glacier melt runoff contributing in stream flow of Mangla catchment with special focus on sources of total runoff, seasonal changes of hydrological component and hydrological extremes to analyze the water balance of the catchment.

1.4. Scope of the study

In summer, a large portion of water is available to Pakistan due to glacier and snow melting in northern areas. Extensive work has already been carried out to calculate the total runoff for different catchments in Pakistan. Since Mangla catchment is a trans-boundary catchment, so the across border data acquisition for the part of catchment situated in India is quite impossible. This study emphasizes to calculate runoff, for sparsely gauged catchments of Pakistan using remotely sensed climate data. Snow and glacier melt runoff along with rainfall runoff and base flow, contributing in total runoff is also studied for agriculture and hydropower generation activities.

Table 1. [a]SPHY2.0 model comparison with other hydrological models.

Process and features	**SPHY**	**TOPKAPI-ETH**	**SWAT**	**VIC**	**LIS-FLOOD**	**SWIM**	**HYPE**
Rainfall-runoff	+	+	+	+	+	+	+
Evapotranspiration	+	+	+	+	+	+	+
Dynamic Vegetation growth	+	-	+	+	+	+	A
Unsaturated Zone	+	+	+	+	+	+	+
Ground Water	+	-	+	+	+	+	+
Glacier	+	+	-	-	-	+	+
Snow	+	+	+	+	+	+	+
Routing	+	+	+	+	+	+	+
Lake incorporated in to routing scheme	+	-	+	+	+	+	+
Reservoir management	-	-	+	-		+	+
Open Source	+	-	+	+	-	-	+
Fully Distributed	+	+	-	+	+	-	-
GIS Compatibility	+	+	+	-	+	+	+
Sub-Grid Variability	+	-	-	+	-	-	-
Sub daily Resolution	-	-	-	+	+	-	+
Daily Resolution	+	+	+	+	+	+	+
Flexible Output	+	+	-	+	+	+	+
GUI in GIS	A	-	+	-	-	+	-

Chapter 2

MATERIALS AND METHODS

2.1. Study Area

Major eastern tributary of Indus River is Jhelum River. In this river significant part of flow contributes from southern slopes of HKM region. At Muzaffarabad, Neelam River joins the Jhelum River, along with Kunhar River that falls in Jhelum River at 8 km downstream of Muzaffarabad. Pounch River from southern slop of Pir Panjal and Kanshi River also join the Jhelum River at Mangla reservoir. Mangla catchment is sub basin of Upper Indus Basin (UIB) region and includes Jhelum River along with its tributaries. The geographical location of catchment is 33.14 °N and 73.64 °E. The total catchment area is approximately 33,466 km^2. The study area with its geographical location is shown in Figure 1.

This is a trans-boundary catchment with 56% of its area situated in India, which makes data collection very difficult due to socio-political issues between the India and Pakistan. (Azmat, 2015). Approximately 2% (669 km^2) of the total catchment is covered with perennial glaciers and approximately 63% of the study area is covered with seasonal snow during the winter months (October–March). The mean elevation of catchment is approximately 2194 m with almost 23.5% of the area lying above 3000 m elevation from above mean sea level. Main sources of water for reservoir are Jhelum, Neelam, Kunhar, Kanchi and Poonch Rivers (Butt et al, 2010). About 56% and 12% of total Mangla catchment fall under the Jhelum and Poonch Rivers respectively.

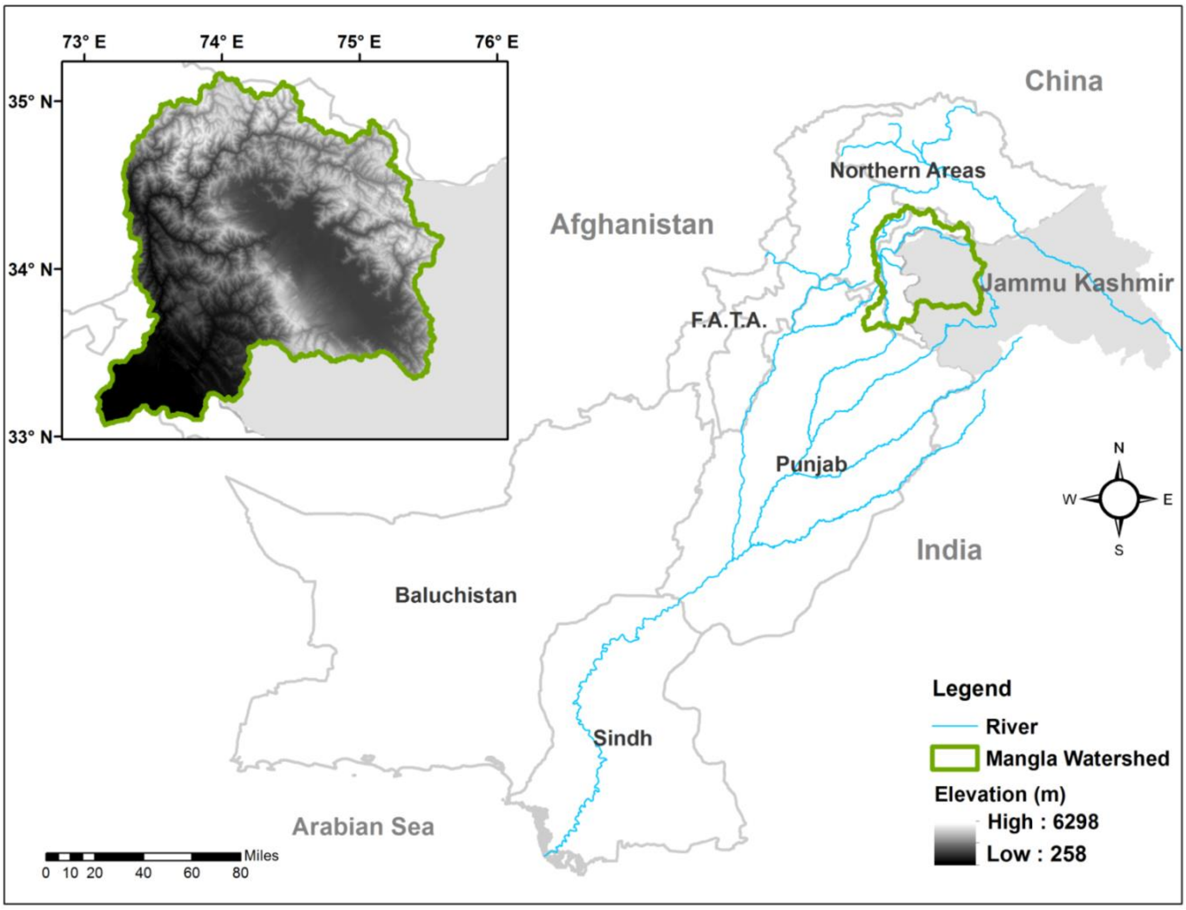

Figure 1.Study area map of Mangla catchment.

This area receives heavy rainfall during summer, and snowfall & light shower during winters. According to observed climate data from Water and Power Development Authority (WAPDA) and Pakistan Meteorological Department (PMD) climate stations, the average annual precipitation varies from 786 mm at Burzil to 1679 mm at Pirchinasi and decline again moving southward to1413 mm at Gharri Dopatta. High values of mean temperature from 13^{o}c to 29^{o}c are observed at Muzaffarabad and low values from -13^{o}c to 8^{o}c are observed at Burzil.

This catchment has two peaks in runoff, one in June due to snow-melt and other in July-September due to combination of rainfall and snow-melt (Yaseen et al, 2015). High altitude catchment area generates runoff due to melting of snow and glacier along with rainfall runoff. While low subarea of the catchment generates runoff from rainfall. High values of Mangla stream flow are observed during summer as compare to other seasons (Archer & Fowler, 2008). At Mangla reservoir, mean annual discharge from 2001-2009 was 759 m^3/S. Monthly mean discharge calculated with the help of daily discharge data from WAPDA for 2001-2009 is shown in Figure 2.

The main purpose of reservoir was to manage water resources for agricultural activities and hydroelectric power generation in Pakistan. The stored water in reservoir is supplied for wheat and rice growing areas during winters and summers respectively. It was constructed with the live storage capacity of 6.5 billion m^3 which has been decrease due to sedimentation. Recently WAPDA estimated that about 17% live storage of Mangla reservoir has been lost (Ahmad, 2001). The main characteristics of catchment are shown in Table 2.

2.2. Description of datasets

To calculate the total runoff at Mangla, different types of ancillary data are used to prepare input parameters for SPHY model.

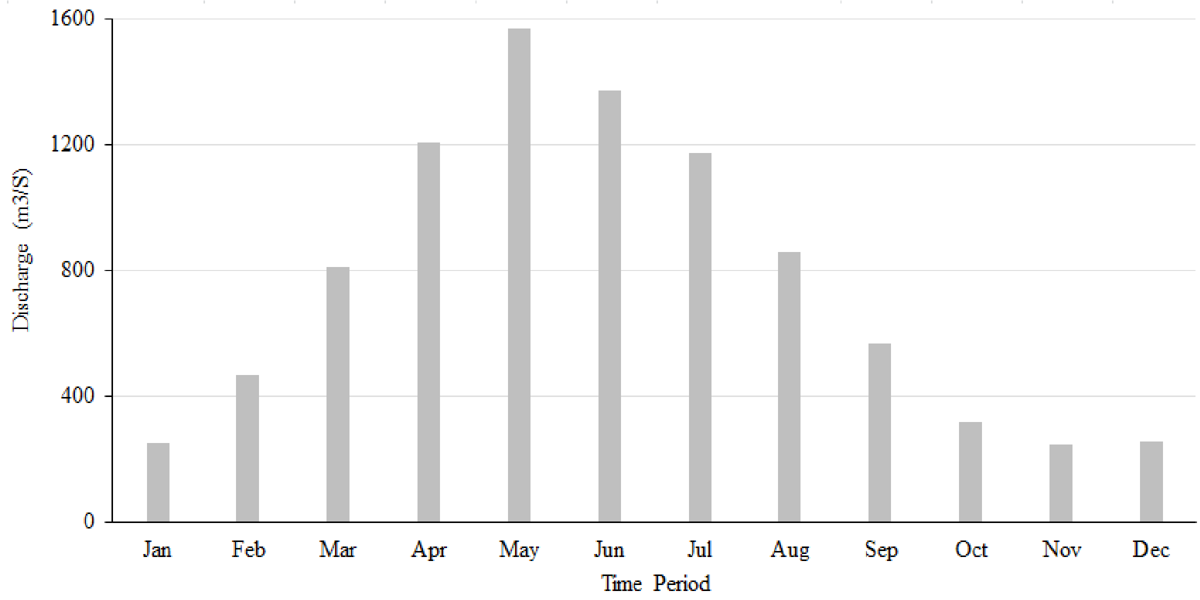

Figure 2.Mean monthly discharge from 2001-2009 at Mangla reservoir.

Table 2.Major Physical characteristics of Mangla catchment.

Physical Characteristics	**Description**
Catchment Area	33466 km^2
Glacier Cover Area	669 km^2
Elevation range	258 m – 6298 m
Latitude Location	33.14°N
Longitude Location	73.64 °E
Dominant LU/LC type	Forest, irrigated and grass land
Outlet gauging station	Mangla
Mean Annual runoff	759 m^3/S
WAPDA Stations	Burzil, Saif ul Maluk, Pirchinasi
PMD Stations	Muzaffarabad, Murree, Gharri Dopatta

2.2.1. Elevation dataset

Hydrological information for Mangla catchment is extracted from void fill HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivative). It is derived from the Shuttle Radar Topography Mission (SRTM) DEM at 3 arc-sec by averaging of 1 arc-sec and applying various procedures including void filling, filtering, stream burning and upscale burning.

2.2.2. Hydrological and Climate datasets

Climate data of precipitation and temperature data are collected from PMD and WAPDA. The data ranges from year 2000-2009 and include average, maximum and minimum temperature and precipitation values for different meteorological stations. Figure 3 shows the geographical location of WAPDA and PMD climate stations along with Mangla gauge station. Statistics related to these stations are mentioned in Table 3. WAPDA stations, Burzil, Saif ul Malook and Pirchinas, ranges from elevation of 2875m to 4325m and PMD stations (Muzaffarabad, Murree and Gharri Dopatta) ranges from 685m to 1629m PMD stations ranges from in Mangla catchment. Daily climate data from 2001-2009 for Burzil, Saif ul Malook, Muzaffarabad, Murree and Gharri Dopatta and 2004-2009 for Pirchinasi is obtained. High and low temperature values are observed at low and high altitude areas respectively.

As discussed above, due to socio-political issues between Pakistan and India, climate data is obtained from Watch Force ERA-Interim data (WFDEI) database for the same time period as WAPDA and PMD. WFDEI is WATCH Forcing Data methodology applied to ERA-Interim data at 3-hourly time steps, and as daily averages, for the global land surface at 0.5^o x 0.5^o resolution. Daily temperature (average, maximum and minimum) and precipitation data from 2001-2009 is used for hydrological process of the catchment.

Table 3.WAPDA and PMD climate stations in Mangla catchment.

Stations	Record Period (year)	Elevation (m)	Annual Rainfall (mm)
Muzaffarabad	2001-2009	685	1511
Murree	2001-2009	1629	1481
Ghari Dopatta	2001-2009	828	1413
Burzil	2001-2009	4325	786
Saif ul Malook	2001-2009	3241	1390
Pirchinasi	2004-2009	2875	1679

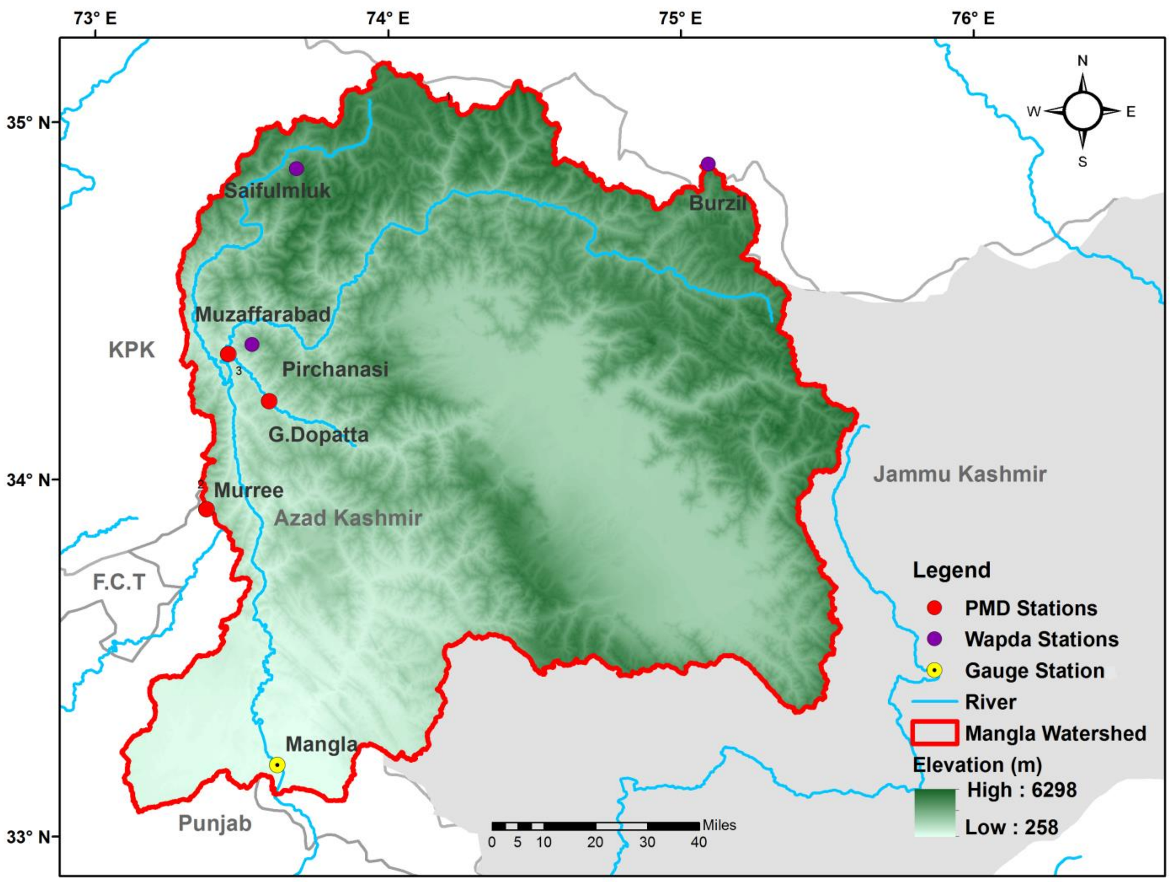

Figure 3.WAPDA and PMD climate stations and Mangla gauge station.

2.2.3. Land use and Land cover

Land use land cover characteristics are derived from GlobCover 2009 land cover map, used in different scientific researches. It is prepared by automatic and regionally-tuned classification of time series of 300 m MEdium Resolution Imaging Spectrometer (MERIS) sensor dataset deployed on the ENVISAT satellite mission for the year of 2009. Under United Nations (UN) Land Cover Classification System, land cover classes are defined for GlobCover 2009 (Defourny et al., 2011). Crop factor (Kc) for each Land use /Land cover, to calculate actual evapotranspiration, is defined according to literature (Allen et al., 1998; FAO 2013).

2.2.4. Glacier Cover

To calculate glacier runoff, glacier out lines are extracted from Randolph Glacier Inventor. It is global glaciers inventory representing outline of glaciers. It is proposed for the assessment of glacier mass changes and total ice volumes at regional and global scales. Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) is the basic of Randolph glacier inventory. Randolph glacier V6 was used for this study. In Mangla catchment approximately 2% (669 km^2) of the total study area is covered by perennial glaciers Figure 4. Debris cover glacier area (169 km^2) and clean glacier area (669 km^2) maps are generated for SPHY model to calculate glacier melt runoff using RGI shown in Figure 5 and Figure 6.

2.2.5. Soil Data

Soil maps of hydraulic properties were obtained from HiHydroSoil database, which is derived from "SoilGrids1km" soil data of high resolution. Harmonized World Soil database is used to fill missing data values of "SoilGrid1km" and add accuracy to soil data. Input variables from SoilGrid1km to derive soil hydraulic properties maps are shown in Table 4. SoilGrid1km gives soil properties for 6 soil depth layers, including soil depth layer 1 (0 - 5cm), soil depth layer 2 (5 - 15cm), soil depth layer 3 (15 - 30cm), soil depth layer 4 (30 - 60cm), soil depth layer 5(60 - 100cm) and soil depth layer 6 (100 - 200cm). Soil hydraulic maps used for SPHY model are prepared using above mentioned soil layers.

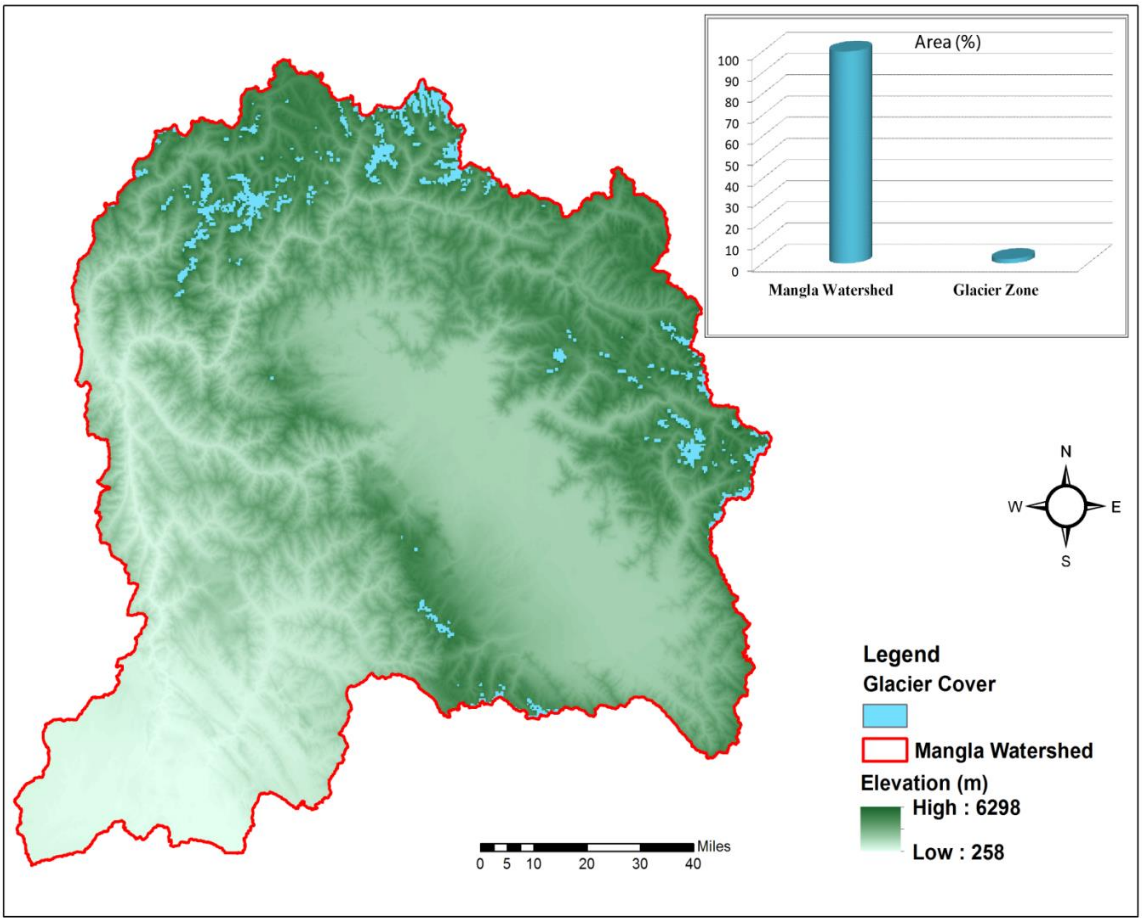

Figure 4.Glacier cover area of Mangla catchment.

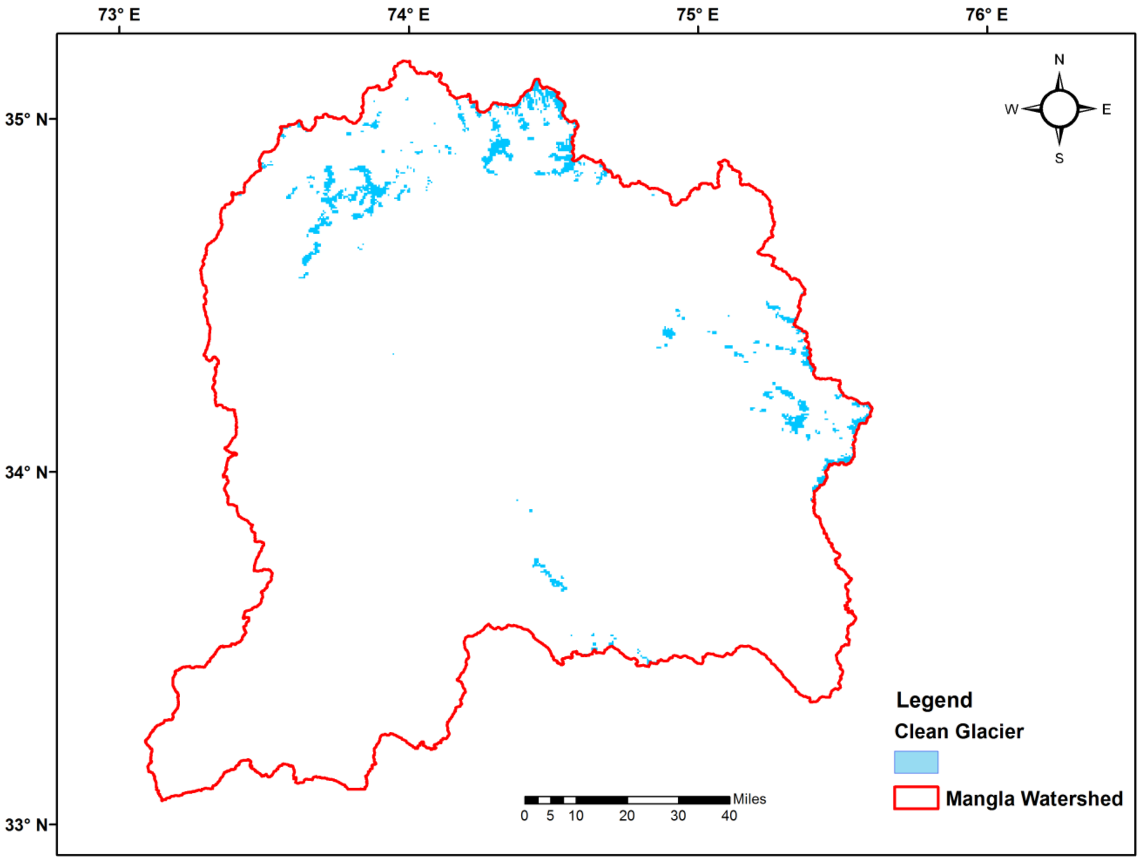

Figure 5.Clean cover glacier area map of the catchment

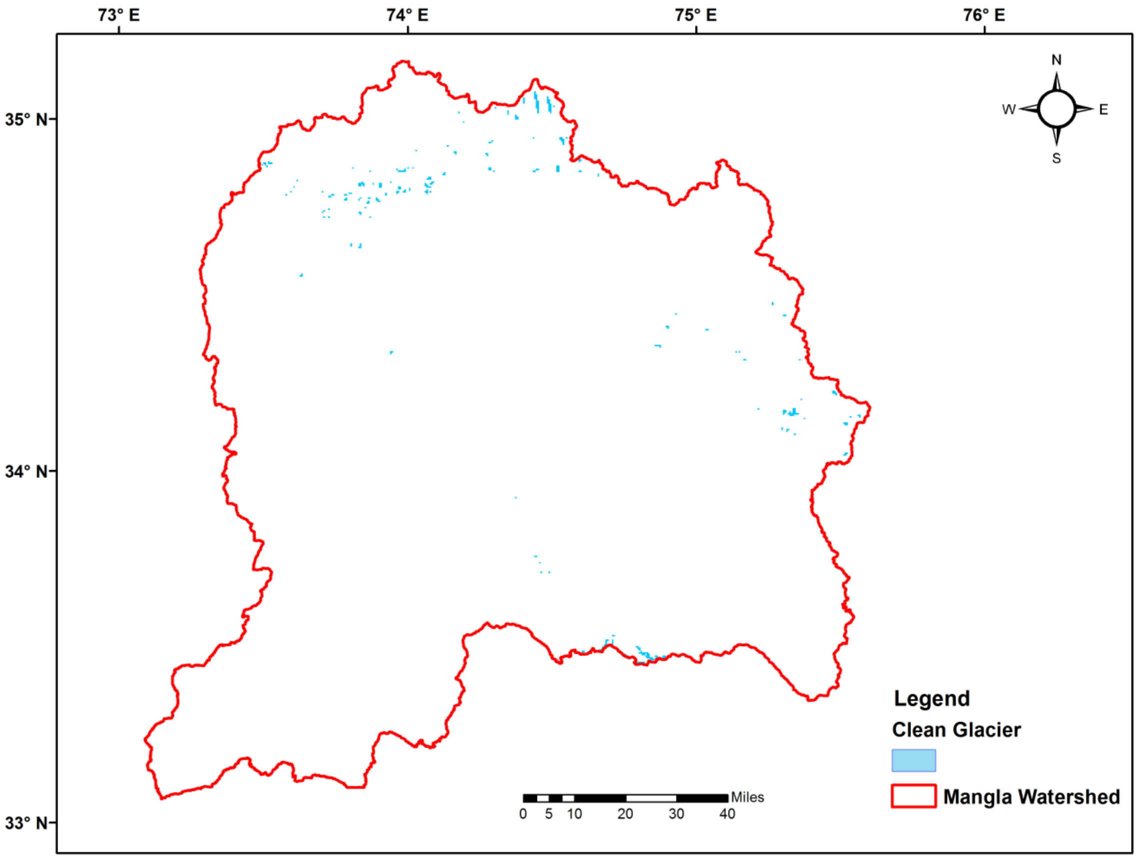

Figure 6.Debris cover glacier area map of the catchment.

For top soil layer, averaging of soil depth layers 1, 2 and 3 (0 - 30cm) and second sub surface soil layer, averaging of soil layers 4 and 5 (30 - 100cm) are used. Field capacity (mm/mm), saturated water content (mm/mm), saturated Hydraulic conductivity (mm/d) maps are prepared for both top and sub-surface soil layers. Permanent wilting point (mm/mm), wilting point (mm/mm) maps only for top soil layer are prepared. Soil maps are shown below from Figure 7 to Figure 14.

2.2.6. Actual Evapotranspiration (ETa)

Evapotranspiration combination of evaporation from soil and transpiration from vegetation is produced with the help of energy balance approach called Simplified Surface Energy Balance (SSEBop) model with unique parameterization. It combines evapotranspiration generated by using thermal imagery of MODIS, with reference evapotranspiration.

SSEBop uses predefined, seasonally dynamic, boundary conditions unique to each pixel according to cold/wet and hot/dry reference points. For the current study Eta from 4^{th} version of SSEBop is used which incorporates dynamic and scene specific crop factor parameterization and improve the accuracy of evapotranspiration spatially by modelling and subdividing each MODIS tile into 25 units. The unit of actual evapotranspiration is mm. To calibrate SPHY model monthly Eta for 2003-2005 is used. Monthly average of ETa from 2003-2005 is shown in Figure 15.

2.2.7. Discharge Data

WAPDA daily discharge data at Mangla from 2001 to 2005 is used to calibrate the SPHY model whereas model is validated using Mangla discharge data from 2006-2009. To simulate discharge data, input datasets, used in SPHY model are described in Table 5.

2.3. Hydrological Model

SPHY is a grid based fully spatially distributed model which uses a degree day factor method to simulate snow and glacier melt in total run off. Figure 16 shows the conceptual representation of SPHY model. In SPHY model each cell represent a single average value, sub grid variability is taken in account for glaciers. A cell can be completely or partially covered by glacier or it could be glacier free. However the grid which is not covered with snow or glacier may contain of vegetation, forest, bare soil, or open water.

In SPHY, precipitation is pretended as rain or snow depending upon temperature. Precipitation can be intercepted by vegetation. A part of precipitation is transformed as surface runoff, whereas the remaining part is infiltrated by soil. Some part is evapo-transpirated depending on soil properties or vegetation cover and remaining part is contributed as base flow to main stream. Snow and glacier melt also contribute to the main river.

Table 4. Variables for different depths of soil.

Name	Variable	Units
BLD	Bulk Density	Kg/m^3
CEC	Cation Exchange Capacity	Cmol+/kg
ORCDR	Dry Organic Carbon	g/kg
PHIHOX	PH*10 in H_2O	-
CLYPPT	Clay Percentage	%
SLTPPT	Silt Percentage	%
SNDPPT	Sand Percentage	%
BDRICM	Depth to bedrock	Cm

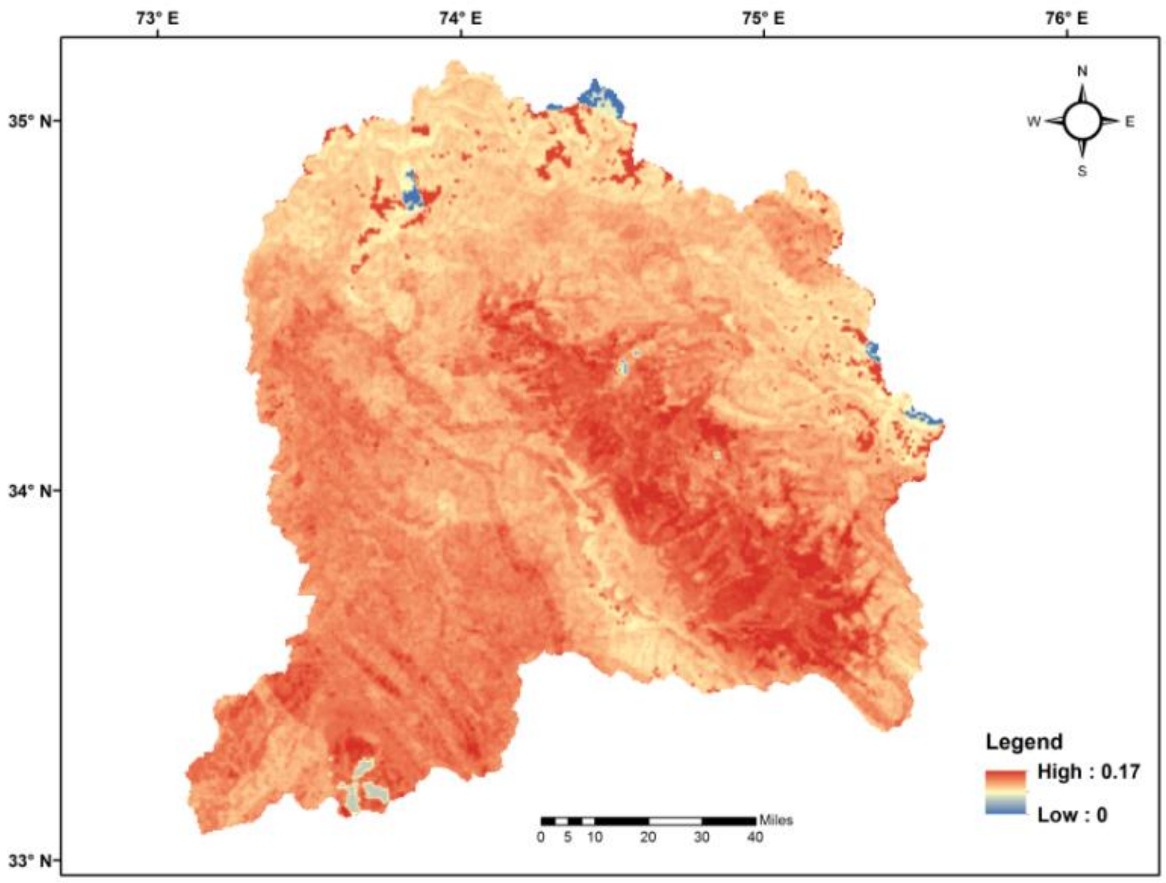

Figure 7.Permanent wilting point map of top soil layer.

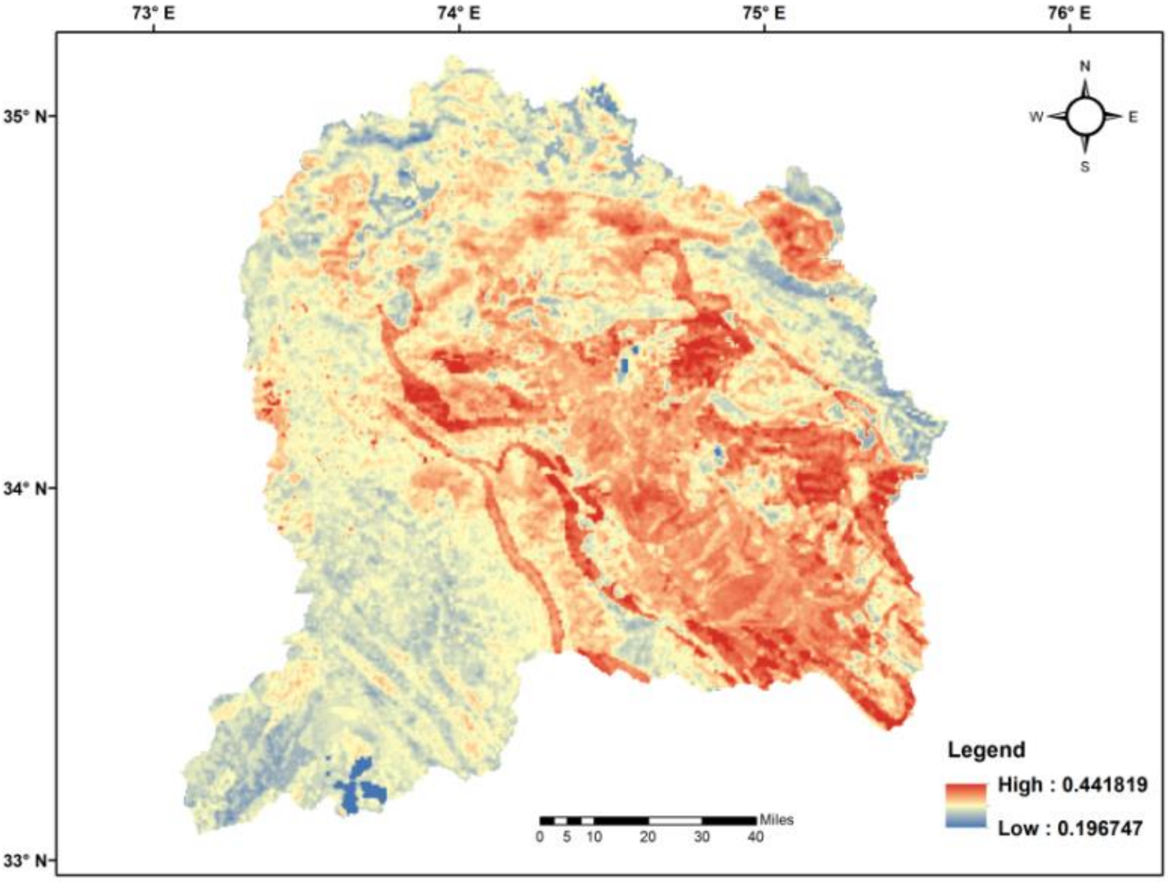

Figure 8.Field capacity map of top soil layer.

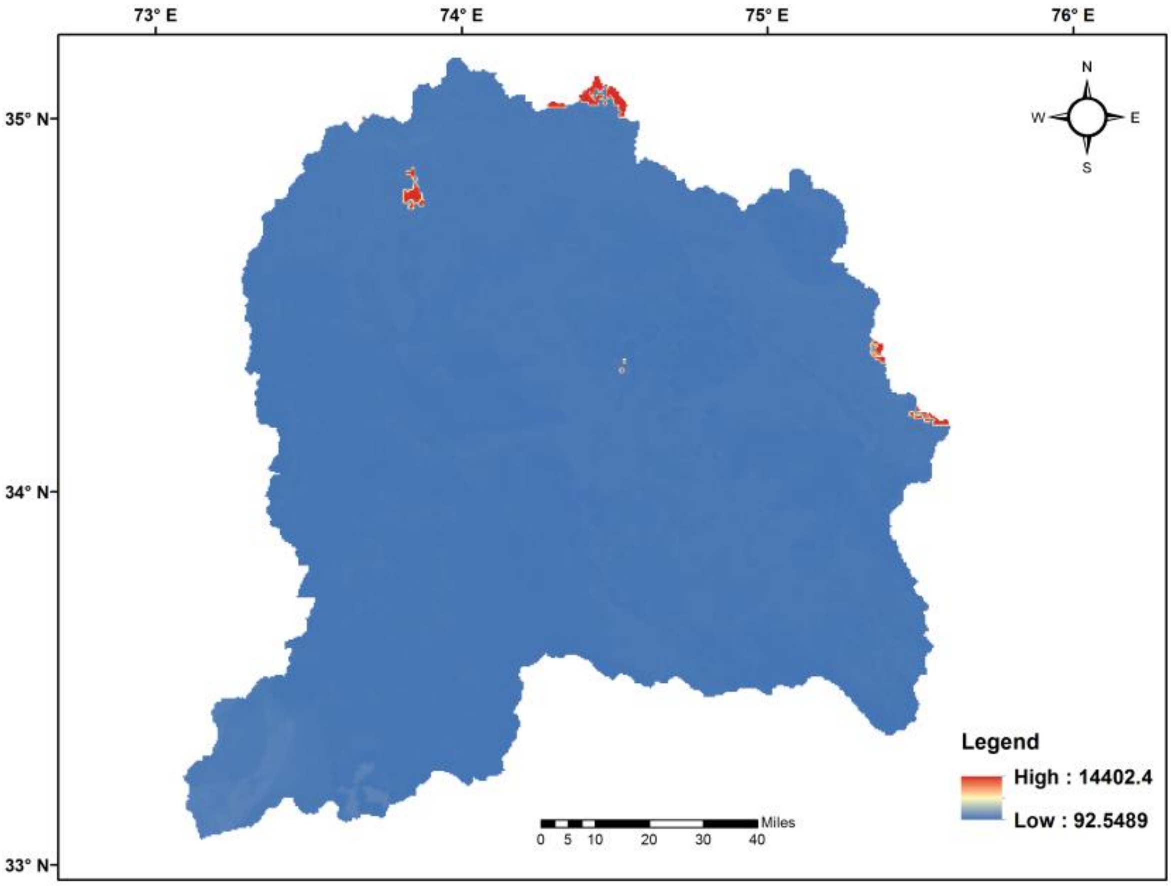

Figure 9. Saturated hydraulic conductivity map of top soil layer.

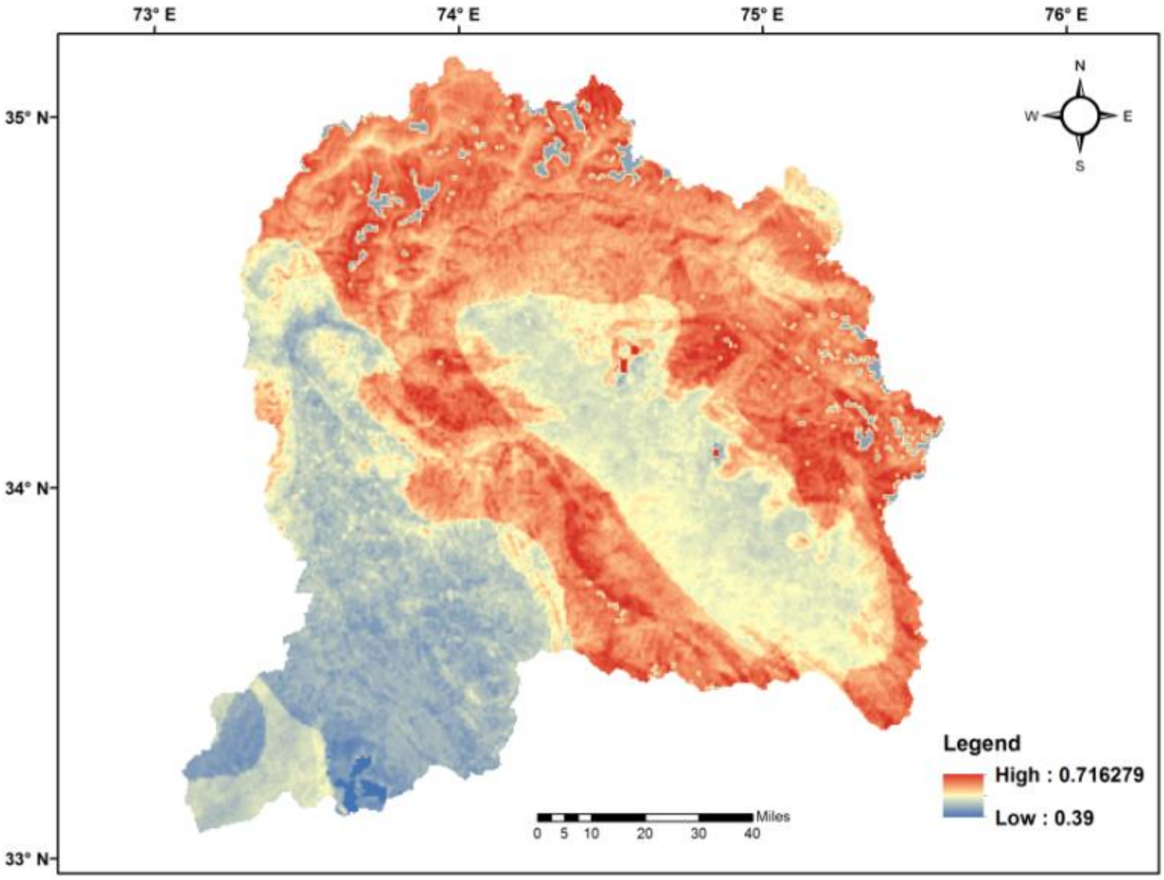

Figure 10. Saturated water content map of top soil layer.

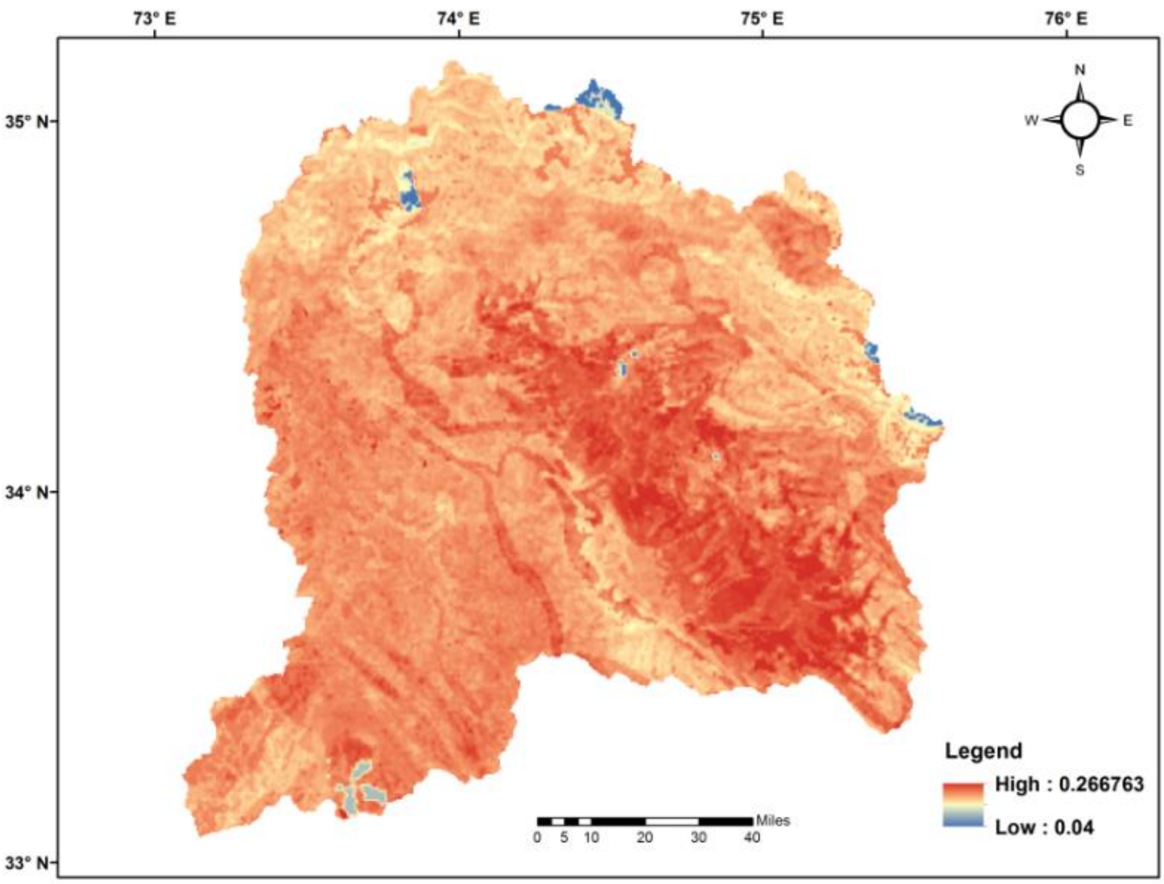

Figure 11. Wilting point map of top soil layer.

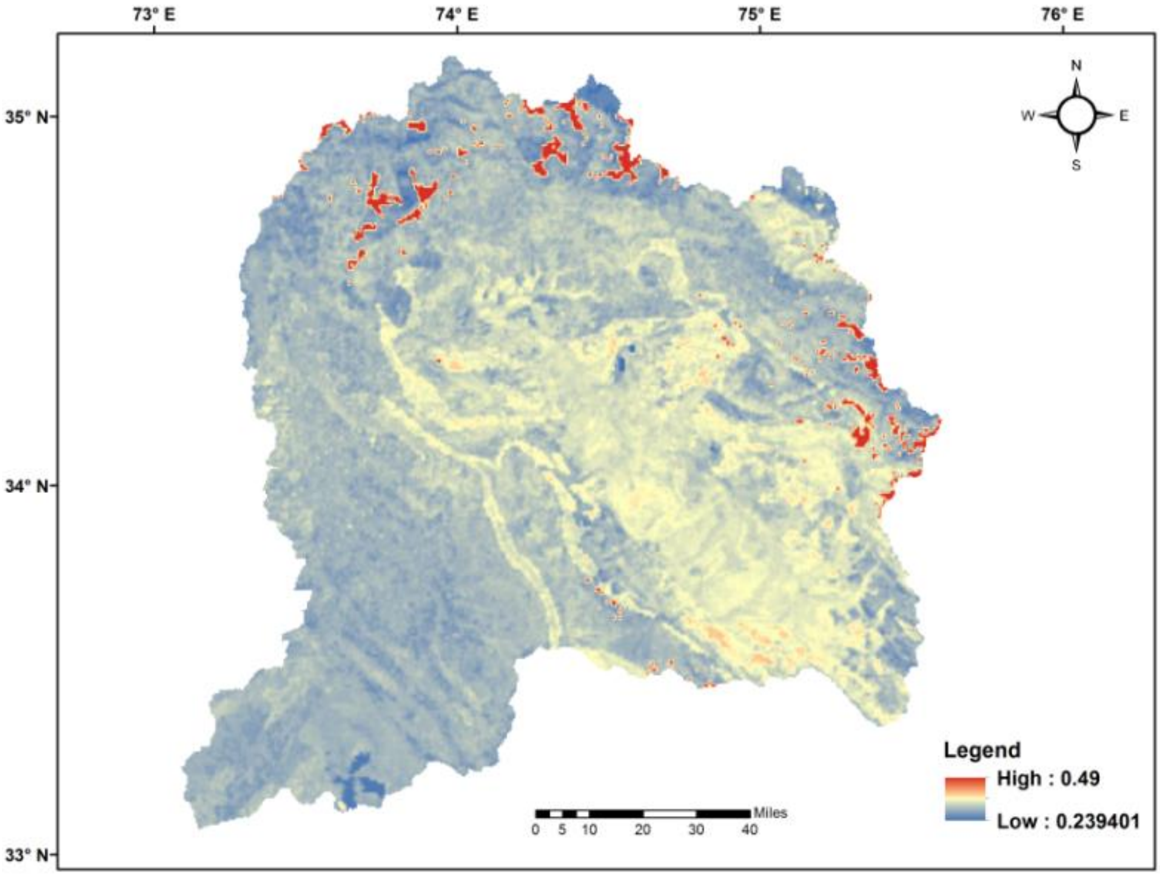

Figure 12. Field capacity map of sub surface soil layer.

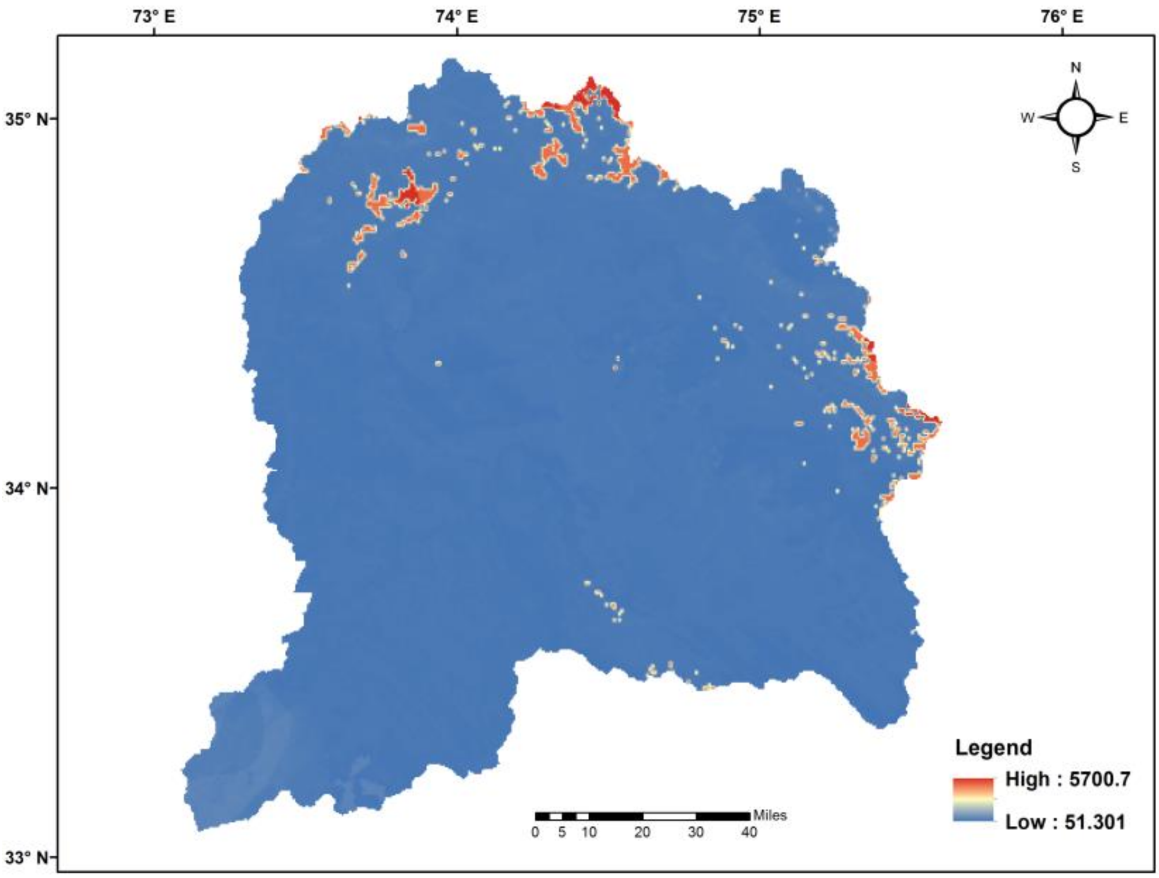

Figure 13. Saturated hydraulic conductivity map of subsurface soil layer.

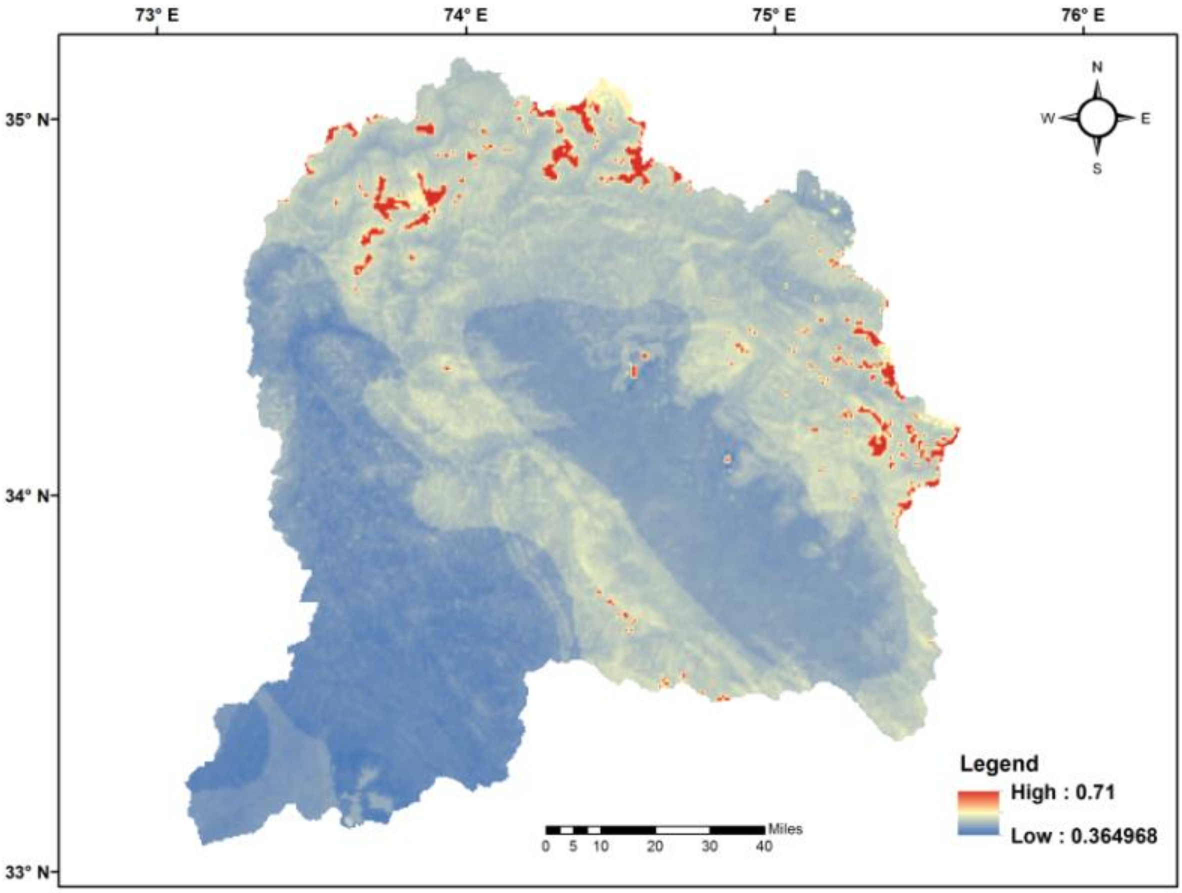

Figure 14. Saturated water content map of subsurface soil layer.

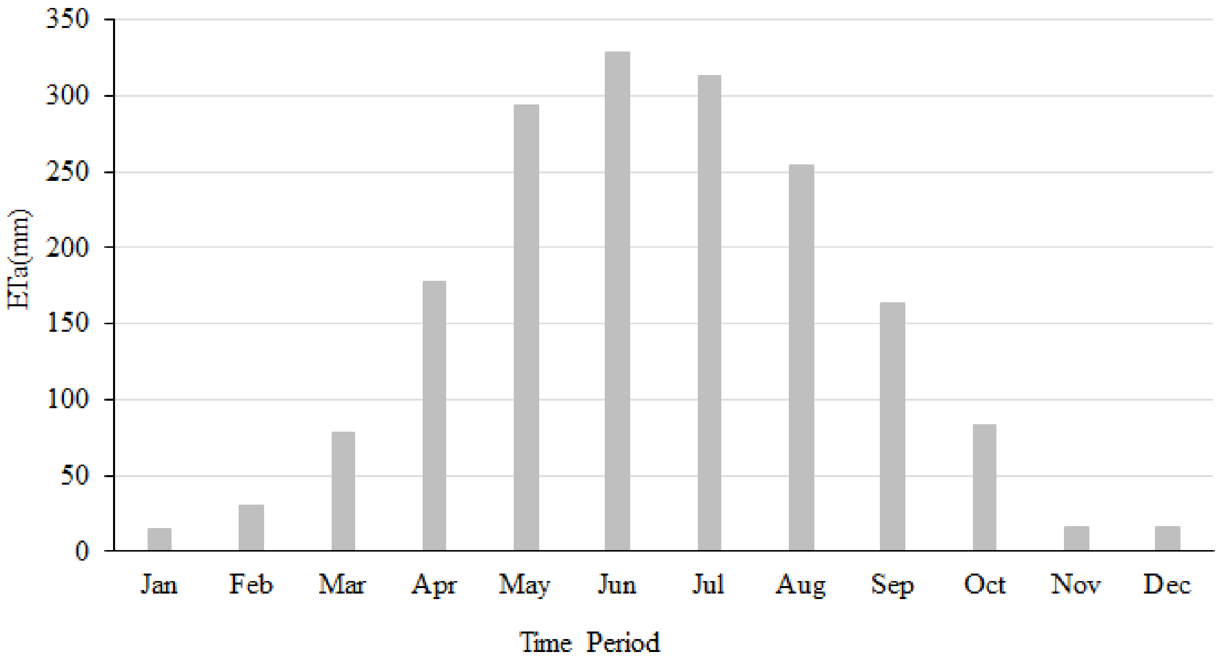

Figure 15. Mean monthly Actual evapotranspiration (2003-2005) for Mangla Catchment.

Table 5. Summary of dataset used for SPHY model.

Data	**Temporal Resolution**	**Specifications**	**Data Sources**
DEM	Fixed	30 m	Shutter Radar Topographic Mission (SRTM)
Soil Data	Fixed	Clay, Silt, Sand, Bulk Density	Soil grid
Climate Data	Daily	Min, Max & Avg Temperature (^{o}C) Precipitation (mm) (2000-2009)	Pakistan Meteorological Department (PMD), Water and Power Development Authority (WAPDA) & Watch Force Data ERA Interim (WFDEI)
Land Use / Land Cover	Fixed	300 m	Envisat
Glacier Cover	Fixed	Glacier Outline (Version 6)	Randolph Glacier
Actual Evapotranspiration Data	Monthly	(mm) (2003-2005)	USGS
Mangla Discharge Data	Daily	(m3/s) (2001-2009)	Water and Power Development Authority (WAPDA)

Total runoff including surface runoff, lateral flow, base flow, and snow and/or glacier melt of a specific cell is used for routing of runoff to catchment end point (Terink et al, 2015).

SPHY model use different modules, to calculate total runoff from precipitation, snow and glacier melt, including base flow and surface runoff. In SPHY model, there are 6 modules available including snow, groundwater, dynamic vegetation module simple routing and lake/ reservoir. The SPHY model provides flexibility to choose a particular module by considering catchment characteristics such as a catchment is lacking with glacier part but a fraction of snow is present during winter season. Therefore, snow module can be used according to the specific characteristics of catchment and irrelevant modules (e.g. glacier) can be turned off. Switching off these irrelevant modules not only reduces processing time but also decreases number of input datasets to run the model.

Furthermore, it is also noted that the snow module is relevant, if glacier module is used. Ground water module is also turned on with glacier module as glacier melt percolates to ground water well (Verbunt et al, 2003; Singh and Kumar 1997). Two modules are available for routing runoff, first, simple flow routing module, second, fractional flow routing module in case of lake/ reservoir presence. In this study, we adopted snow, glacier and ground water modules along with simple flow routing.

Dynamic snow storage is simulated according to the model represented by Kokkonen et al. (2006) at daily time step and for each grid cell. Snow melt refreezing along with rain fall within snow pack is also simulated. Precipitation is defined as solid or liquid form according to temperature threshold value. It is calculated using Eq.1.

$$P_e,d \;=\; \begin{matrix} P_s,t & if\ Tavg,d \leq Tcrit \\ P_l,t & if\ Tavg,d > Tcrit \end{matrix} \qquad \text{Eq.1}$$

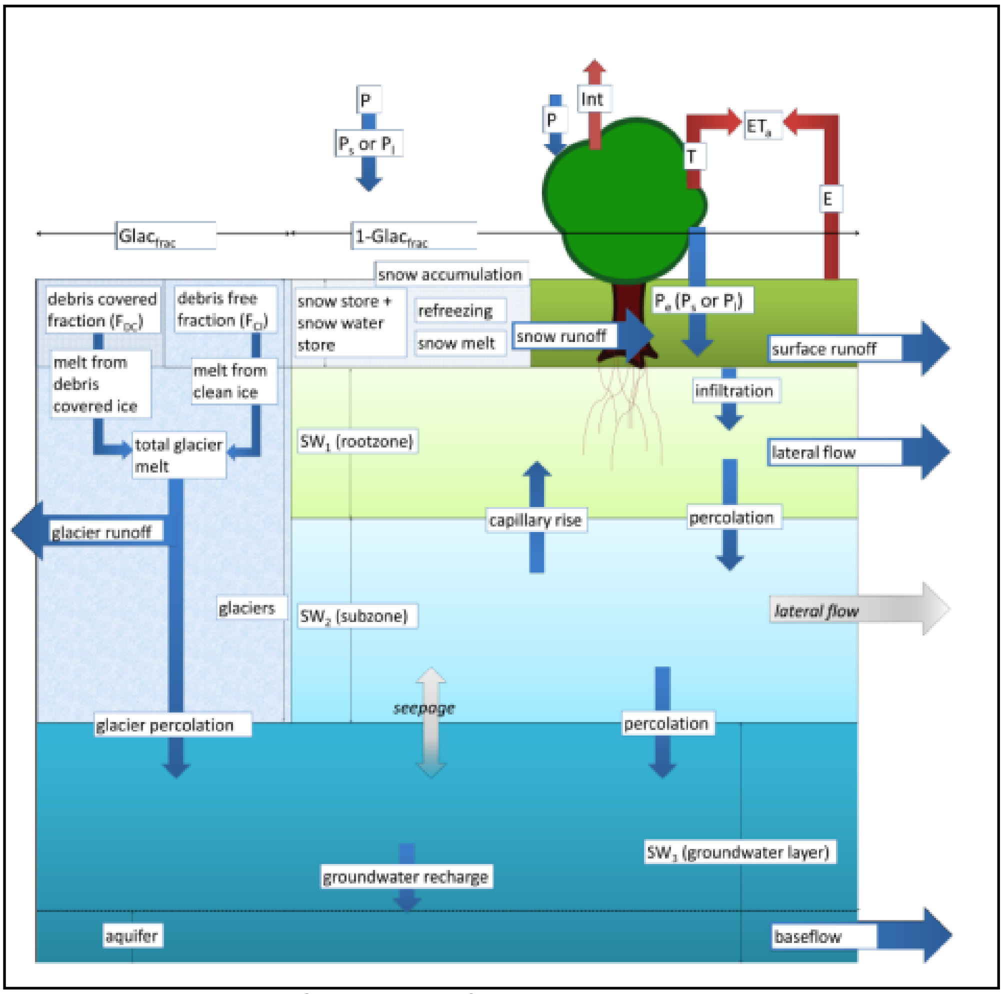

Figure 16. Conceptual framework of SPHY model (Source: Terink et al, 2015).

Where P_e (mm) is effective precipitation at day d. P_s (mm) and P_l (mm) represent precipitation as snow fall and rain fall on day depending upon the daily average temperature (Tavg) less than or greater than Tcrit.

Degree day temperature model is used to calculate snow melt (Hock 2003). The empirical relationship between temperature and snow melt is defined according to Eq.2.

$$S_{pot},d \;=\; \begin{cases} Tavg,d.DDFS & if\ Tavg,d > 0 \\ 0 & if\ Tavg,d \leq 0 \end{cases} \qquad \text{Eq.2}$$

Where S_{pot} (mm) represent potential snow melt on day d and DDFS (mm ∘C −1d −1) is calibrated degree day factor value for snow. The actual snow melt (S_{act} (mm)) is dependent on snow storage (SS) at previous day d and is calculated using Eq.3.

$$Sact, d \;=\; min(Spot, d\ , SS, d - 1) \qquad \text{Eq.3}$$

Snow storage at current day (d) is updated with the help of solid precipitation (Ps) and actual snowmelt (S_{act}). In snow pack, a portion of actual snowmelt freezes when average temperature is less then melting point and doesn't create runoff. Capacity of snow to freeze snowmelt is defined as snow storage capacity SSC ($mm.mm^{-1}$).

When no more snowmelt is present to be frozen in snowpack and average air temperature is greater melting point, snow runoff (mm) is generated.

In SPHY model dynamic of glacier (ice flow) is not resolved, therefore in SPHY model glaciers are melting surfaces and glacier melt is calculate using degree day factor approach. As glaciers melt from debris cover glaciers and debris free glaciers is different from each other so both debris cover glaciers and debris free glaciers are handle separately with different degree day factors in SPHY model. The daily glacier melt from debris free glaciers (G_{CL} (mm)) is calculated using Eq.4.

$$G_{CL},d \;=\; \begin{cases} Tavg,d\ .\ DDF_{CL}\ .\ FC_{CL} & if\ Tavg,d > 0 \\ 0 & if\ Tavg,d \leq 0 \end{cases} \qquad \text{Eq.4}$$

DDF_{cl} is degree day factor for debris free glaciers and FC_{cl} fraction of debris free glaciers. Similarly daily glacier melt from debris cover glaciers (G_{DC} (mm)) is calculated using Eq.5, where DDF_{DC} is degree day factor for debris cover glaciers and FC_{DC} is fraction of debris cover glaciers

$$G_{DC},d = \begin{cases} Tavg,d \; . \; DDF_{DC} \; . \; FC_{DC} & if\; Tavg,d > 0 \\ 0 & if\; Tavg,d \le 0 \end{cases} \qquad \text{Eq.5}$$

Glacier melt generate glacier runoff after percolation, a fraction of glacier melt to groundwater.

Soil water processes are simulated for a top soil layer, sub surface soil layer and third (ground water) layer. Soil water content for upper soil layer is calculated using Eq.6.

$$SW1,d = SW1,d-1 + Pe,d - ETa,d - RO,d - LF1,d - Perc1,d + Cap,d \qquad \text{Eq.6}$$

$SW_{1,}$ d and $SW_{1,}$ d−1 represent soil water content for top soil layer on day d and d-1 respectively. Soil water content involved, effective presentation (P_e), actual evapotranspiration (ET_a), surface runoff (RO), lateral flow from upper soil layer (LF_1), percolation ($Perc_1$) from top soil layer to sub surface soil layer and capillary rise from (Cap) from sub surface soil layer to top soil layer on day d. Soil water content for sub surface soil layer is calculated using Eq.7.

$$SW2,d = SW2,d-1 + Perc1,d - Perc2,d - Cap,d \qquad \text{Eq.7}$$

$SW_{2,}$ d and $SW_{2,}$ d−1 represent soil water content for sub surface soil layer on day d and d-1 respectively. It includes percolation from top soil to sub surface soil layer and percolation from sub surface soil to ground water layer along with capillary rise from sub surface layer to top soil layer. For third layer soil water content is calculated using below Eq.8.

$$SW3,d = SW3,d-1 + Gchrg\; d - BF,d \qquad \text{Eq.8}$$

$SW_{3,}$ d and $SW_{3,}$ d−1 represent soil water content for third (ground water) soil layer on day d and d-1 respectively. Ground water recharge (G_{chrg}) from sub surface soil layer to third soil layer and base flow on day d is used to calculate soil water content for third soil layer.

Rainfall-runoff consists of the surface runoff from rainfall, lateral flow is released from the soil water storage and base flow is released from the groundwater storage.

Total runoff and its components are routed downstream using a digital elevation model (DEM). SPHY model, accumulate water of each grid cell to its nearby downstream cell. This is done by using flow accumulation function, which involves accumulation of runoff from upstream cell and runoff generated within cell itself along with recession coefficient (kx (–)) that is used to account for flow delay, which due to channel friction. In SPHY model routed runoff is calculated by using three equation mentioned below from Eq.9 to Eq.11.

$$Q_{Tott*} = \frac{\mathrm{QTott} \cdot 0.001 \cdot \mathrm{A}}{24 \cdot 3600} \qquad \text{Eq.9}$$

The specific runoff ($Q_{Tott}*$ (m3 s $^{-1}$)), consider specific run off (Q_{Tott}) in mm on day d along with area of grid cell (A (m^2)) the grid-cell area. Accumulated runoff (Q_{accu}, d (m3 s $^{-1}$)) is calculated as

$$Qaccu,d = (Fdir, QTott\ *)\ d \qquad \text{Eq.10}$$

It is function of flow direction network (F_{dir}) and specific runoff ($Q_{Tott}*$ (m3 s $^{-1}$)).

$$Qrout,d = (1 - kx) \cdot Qaccu,d + kx \cdot Qrout,d-1\ d \qquad \text{Eq.11}$$

Q_{rout}, d (m3 s $^{-1}$) and Q_{rout}, d−1 (m3 s $^{-1}$) represent routed runoff on day d and d − 1, flow recession coefficient (kx (–)) varies between 0 and 1. 0 signifies quick response to catchment whereas 1 corresponds to slow response to catchment. (Terink et al, 2015).

SPHY model incorporates static and dynamic data. Static data involved DEM, Land use land cover, glacier cover, soil and lake or reservoir characteristics. The dynamic data include climate data. For setting up the model stream flow data is not necessary however for model calibration and validation, flow data is required. The model can also be calibrated with other datasets including Actual evapotranspiration, soil moisture or snow cover area. SPHY model provides a wealth of output variables including actual evapotranspiration, total runoff and ground water recharge based on user requirements. With maps output, time series for each cell can be generated in study area.

For each grid cell the total runoff (Q_{TOT}) is calculated using Eq.12.

$$QTOT = QGM + QSM + QRR + QBF \qquad \text{Eq.12}$$

Where Q_{GM} is glacier melt runoff, Q_{SM} is snow melt runoff, Q_{RR} is rainfall runoff and Q_{BF} is base flow (Lutz et al., 2016).

2.4. Efficiency of Model

For Mangla catchment stream flow simulation was carried out on daily bases using SPHY model. The model was calibrated using daily stream flow at Mangla and monthly actual evapotranspiration. Model efficiency for the catchment was calculated by using different statistical methods by considering trade-off between residual variance and long term bias. Residual variance measures the difference between simulated and measured data and bias measures the tendency of simulated data to be larger and smaller than measured data. Correlation between predicted and observed stream flows was evaluated by Nash-Sutcliffe Coefficient (NSE), Percent Bias, Pearson correlation coefficient and as well as R^2 (Coefficient of determination).

2.4.1. Pearson's correlation coefficient (r) and Coefficient of determination (R^2)

Degree of collinearity between simulated and observed data is measured with Pearson's correlation coefficient and coefficient of determination. The Pearson's correlation coefficient represents degree of linear relationship between simulated and observed data. It is calculated as

$$\text{Pearson's Coefficient} = \frac{\sum_{i=1}^{n}(X_i-\overline{X})(Y_i-\overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\overline{Y})^2}}$$

In above formula $\overline{X}$ and $\overline{Y}$ represent the mean values of observed and simulated data, whereas X_i and Y_i represent the i^{th} values of observed and simulated data from model respectively and n is the total number of entities. It ranges from -1 to1.

The Pearson's correlation coefficient of value 1 indicates the perfect positive relation between observed and simulated data values, means if simulated data values are increasing observed data values also increased. Whereas Pearson's correlation coefficient of value -1 indicates the perfect negative relationship between observed and simulated data values, it means increase in simulated data values and decrease in observed data values and vice versa. While if r = 0, it shows no relationship between simulated and observed data values.

Similarly coefficient of determination R^2 represents the proportion of total variance in observed data explained by model. It is calculated as square of r. Its value ranges from 0 to 1, higher value indicating less error in variance. R^2 and r coefficients are sensitive for high extreme values and insensitive to additive & proportional differences between simulated and observed data (Legates & McCabe, 1999),(R. D. Harmel et al., 2007)

2.4.2. Percentage bias (PBIAS)

Average tendency of simulated data to be larger and smaller than observed data is measured as percentage bias (PBIAS).It is calculated as

$$\text{PBIAS} = \frac{\sum_{i=1}^{n}(Y_i - X_i) * 100}{\sum_{i=1}^{n} X_i}$$

Where n represent total number of observations, X_i represents the i^{th} value of observed data and Y_i represents the i^{th} value of simulated data.

Deviation of simulated data from observed data is being calculated in percentage. The ideal PBIAS value is 0.0, and model simulation results are satisfactory with low values of PBIAS. Positive and negative values indicate overestimation and underestimation from model respectively. If PBIAS is less than ± 25% for stream flows at monthly time step, results are satisfactory for model performance and PBIAS less than ± 10% indicates very good calibration of model (R. D. Harmel et al., 2007). This test is suggested due to its ability to explain poor performance of the model.

2.4.3. Nash-Sutcliffe efficiency coefficient (NSE)

According to Sevat and Dezetter (1991) Nash-Sutcliffe efficiency Coefficient is best objective function to represent overall fit of hydrograph. It is calculated as

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - \overline{X})^2}$$

Where n represents number of total observations $\overline{X}$represent the mean value of observed data, X_i and Y_i represent the i^{th} values of observed and simulated data from model simultaneously. E value lies between 1 and $-\infty$. Generally values between 0 and 1 gives satisfactory level of performance. E value less than 0 represents observed mean value as better predictor than simulated data which is not acceptable. According to different hydrological studies in literature, if NSE > 0.50 model performance results are satisfactory and for very good performance of model NSE should be greater than 0.75(R. D. Harmel et al., 2007). Unlike R2 and r, NSE is sensitive for differences in means and variances of observed and simulated data. However as for NSE, differences between observed and simulated values are calculated as squared values, which is largest drawback of NSE and it results as overestimated of larger values and underestimated of lower values (Legates & McCabe, 1999)(R. D. Harmel et al., 2007), (Koua et al., 2014).

2.5. Application of Model

In this study SPHY model (version 2.0) is used to calculate the total runoff for Mangla catchment. The model runs at 500 m spatial resolution and all datasets are resampled at 500*500 m resolution. Dynamic climate data (min, max, avg temperature and precipitation data) along with static remotely sensed soil data, glacier boundary and land use land cover data are used to prepare input datasets of SPHY model using SPHY preprocess, Figure 17. The output of SPHY preprocess (climate data forcing files, debris cover and debris free glacier cover data, top soil layer and sub-surface soil layer properties) along with gauge stations point data are used to run SPHY model, Figure 18.

Different parameters of SPHY model are optimized for better simulation of discharge data with respect to observed. The most important parameters include degree day factor of clean and debris cover glacier, degree day factor of snow, water storage capacity of snow pack, base flow recession constant and routing recession coefficient. The objective function of optimizing parameters is to achieve minimum error in simulated discharge data through the use of Pearson's correlation coefficient (r), coefficient of determination (R^2), PBIAS and Nash-Sutcliffe efficiency (NSE) after comparing observed discharge data of Mangla with simulated discharge data. After preparing input datasets for SPHY model daily discharge data is simulated and results are compared with observed daily discharge data. SPHY model run many iteration until there is minimum difference between simulated and observed discharge data and model efficiency is acceptable.

2.6. Model calibration and validation

In hydrological modelling proper model calibration is necessary to reduce uncertainty in model simulation. SPHY model was calibrated manually using monthly actual evapotranspiration data (2003-2005) from United States Geological Survey (USGS) and discharge data collected from WAPDA for (2001-2005). After calibration the model was validated using discharge data for from 2006- 2009. Calibration and validation results were compared with observed data. Hydrological components (rainfall runoff, base flow, snow and glacier melt runoff) analysis was done to find out the contribution to main stream flow over the complete calibration and validation time period.

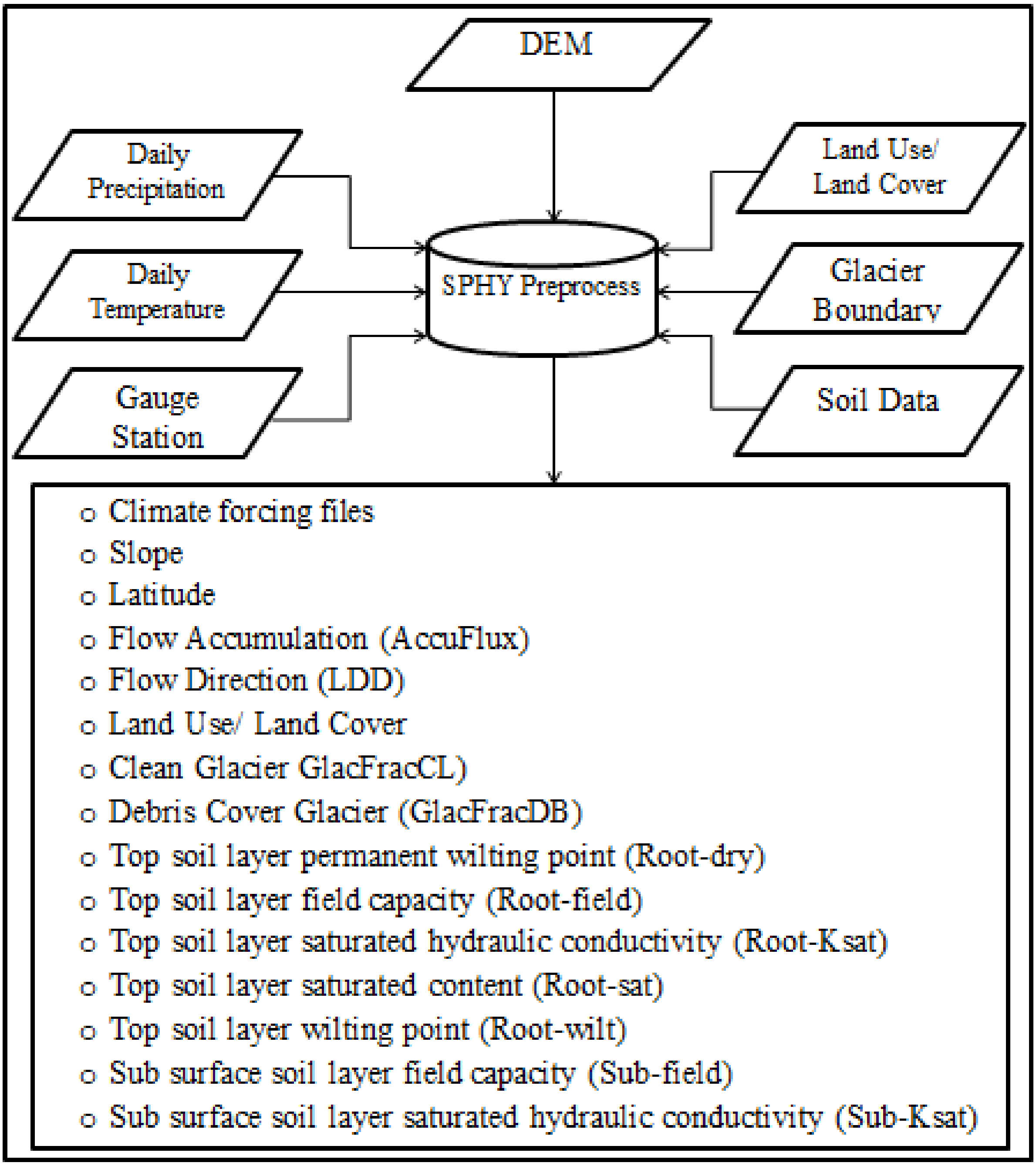

Figure 17.SPHY Preprocess to generate input files for SPHY model.

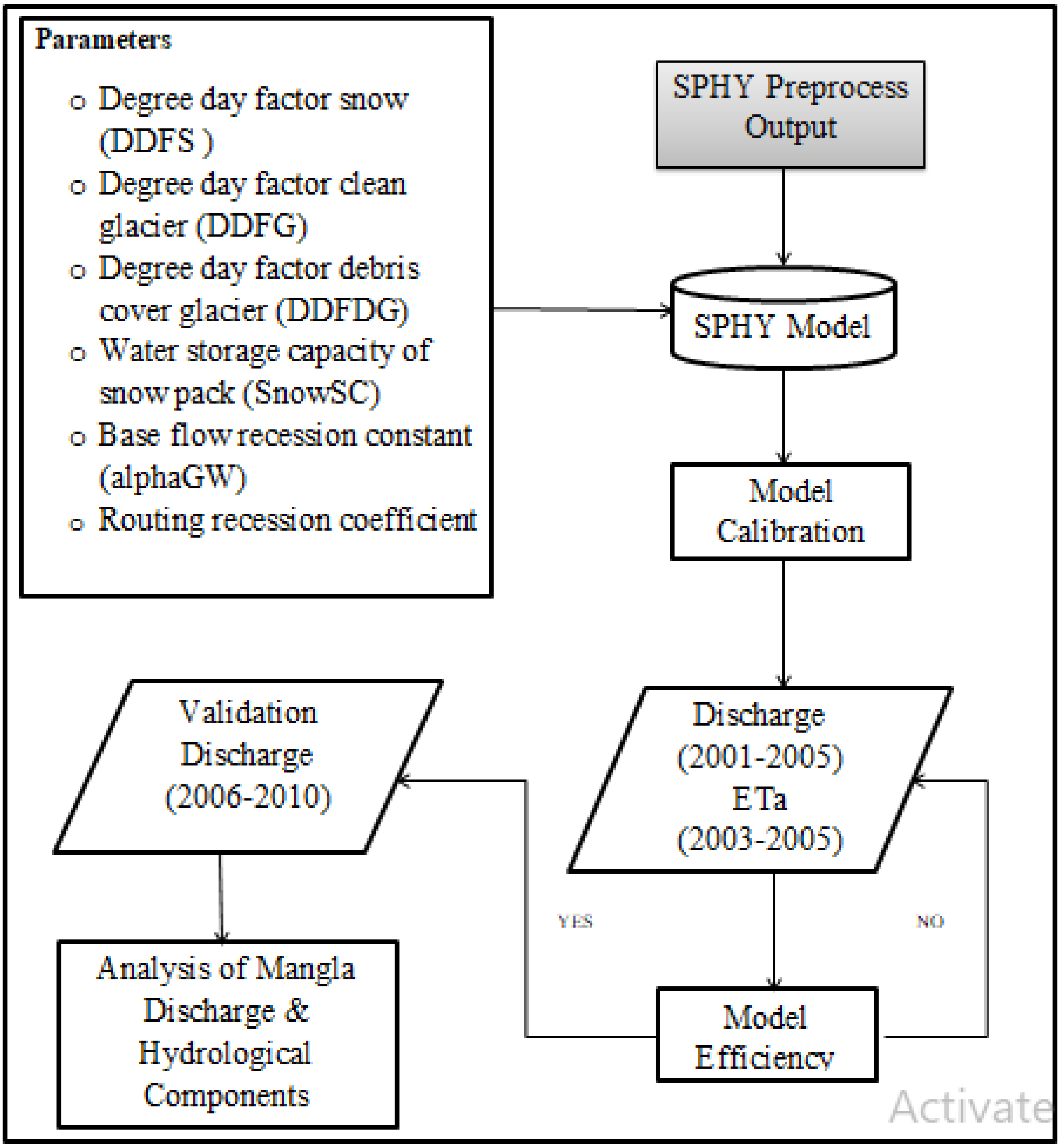

Figure 18. Methodology of SPHY model for calibration and validation.

Chapter 3

RESULTS AND DISCUSSIONS

3.1. Analysis of Temperature

Monthly average temperature data for WAPDA and PMD climate stations from 2001-2009, is shown in Figure 19. Overall for climate stations, there is increase in temperature except at Gharidopatta where is slightly decrease in temperature from 2001-2009. For high elevated stations, Burzil and Saif ul Malook, slightly increase in temperature values strongly influence to the snow and glacier melt runoff.

3.2. Analysis of Precipitation

Most important climate data is precipitation for distributed hydrological modelling, as it strongly affects the hydrological simulations.

Daily precipitation at climate stations were used to calculate total annual precipitation (mm) from 2001-2009, shown in Figure 20. There was an overall increase in precipitation from 2001 to 2009.The maximum precipitation values were noticed during 2006 and the lowest for the year 2001. Highest total annual precipitation approximately 2154 mm was observed at Muzaffarabad for year 2006, highest increase in precipitation trend was also observed at this station. At Pirchinasi, decrease in precipitation trend was observed with passage of time. An overall low precipitation values were observed for Burzil, a high-altitude station, which receives precipitation mostly during winter season in the form of solid precipitation.

Due to extensive missing or shortfall of the observed data at climate stations for whole Mangla catchment makes such datasets limited for use. Therefore, the use of only 6 climate stations data could not represent a true picture of the spatial distribution of precipitation occurrence in this catchment. Additionally, a trans-boundary nature of the catchment is further contributing in gap of the available climate data. Therefore, to overcome the issue of climate data for the hydrological model, a bias corrected gridded daily precipitation data offered by WFDEI were an alternative and used. Prior to the use of WFDEI data for hydrological modelling, it was compared with the available observed data at climate stations located within the boundary of catchment. Monthly total precipitation averaged over 2001-2009 for observed climate stations compared with WFDEI data is shown in Figure 21. For climate stations, overall precipitation is on the lower side with WFDEI as compare to observed data except Burzil and Saif ul Malook stations, which could be due to gap in observed data. Over all the reliability of WFDEI for the catchment was very poor so a scale factor was calculated to improve the reliability of WFDEI daily precipitation data by comparing observed precipitation and WFDEI data at climate stations, shown in Figure 22. For high altitude stations, Pinchinasi, Saif ul Malook and Burzil, least R square values 0.31, 0.03, 0.27 respectively, were observed. WFDEI precipitation data was corrected by multiplying with the 1.153 correction factor.

3.3. SPHY model calibration and validation

In SPHY model, multiple optimization trials were carried out to calibrate better suited parameters (mentioned in Table 6) for the catchment. The model was calibrated using discharge data at Mangla reservoir from 2001-2005 and monthly average actual evapotranspiration from 2003-2005.

For snow and glacier melt, degree day factor was optimized by comparing observed and simulated discharge data as for summer (May, Jun, July) main contribution to stream flow is due to snow and glacier melt runoff. Water storage capacity of snow pack was also calibrated as refreezing of snow melted water is also included in SPHY model. Other than these, two most important parameters are base recession coefficient (αGW) which represents base flow respond to ground water recharge and routing recession coefficient (kx). Areas with low and high values of αGW indicate slow and rapid response of base flow to ground water recharge respectively. Whereas, kx effects downstream movement of water to Mangla reservoir. These parameters values are adjusted to achieve better simulated discharge data at Mangla.

Observed discharge data and ETa data were used to calibrate, base flow, routing, snow and glacier related parameters and crop factor ((kc) values. These parameters were set to minimize the difference between simulated and observed discharge data (2001-2005) and simulated actual evapotranspiration and actual evapotranspiration (2003-2005). The selection of time period depends upon the availability of observed discharge data, climate (temperature and precipitation) data and actual evapotranspiration. Insignificant parameters values for model, add the uncertainty in simulation of discharge. However, best parameters values were found during model calibration. After setting the parameters for the whole catchment, SPHY model is validated by using discharge data from 2006-2009.

ETa is affected by crop factor (kc) and its best values are set to calculate actual evapotranspiration for catchment. Monthly averaged ETa from USGS and simulated from SPHY model was compared (Figure 23) and good agreement was found between observed and simulated actual evapotranspiration, with Nash-Sutcliffe efficiency coefficient **(**NSE) = 0.66, Pearson's correlation coefficient (r) = 0.83, coefficient of determination (R^2) 0.83 = and Percentage bias (PBIAS %) = -11 for the time period of 2003-2005. During summer (May to July) simulated actual evapotranspiration was underestimated whereas during winter (Nov to Feb) it was slightly overestimated. It could be due to static land use land cover and could be improved by using dynamic vegetation cover.

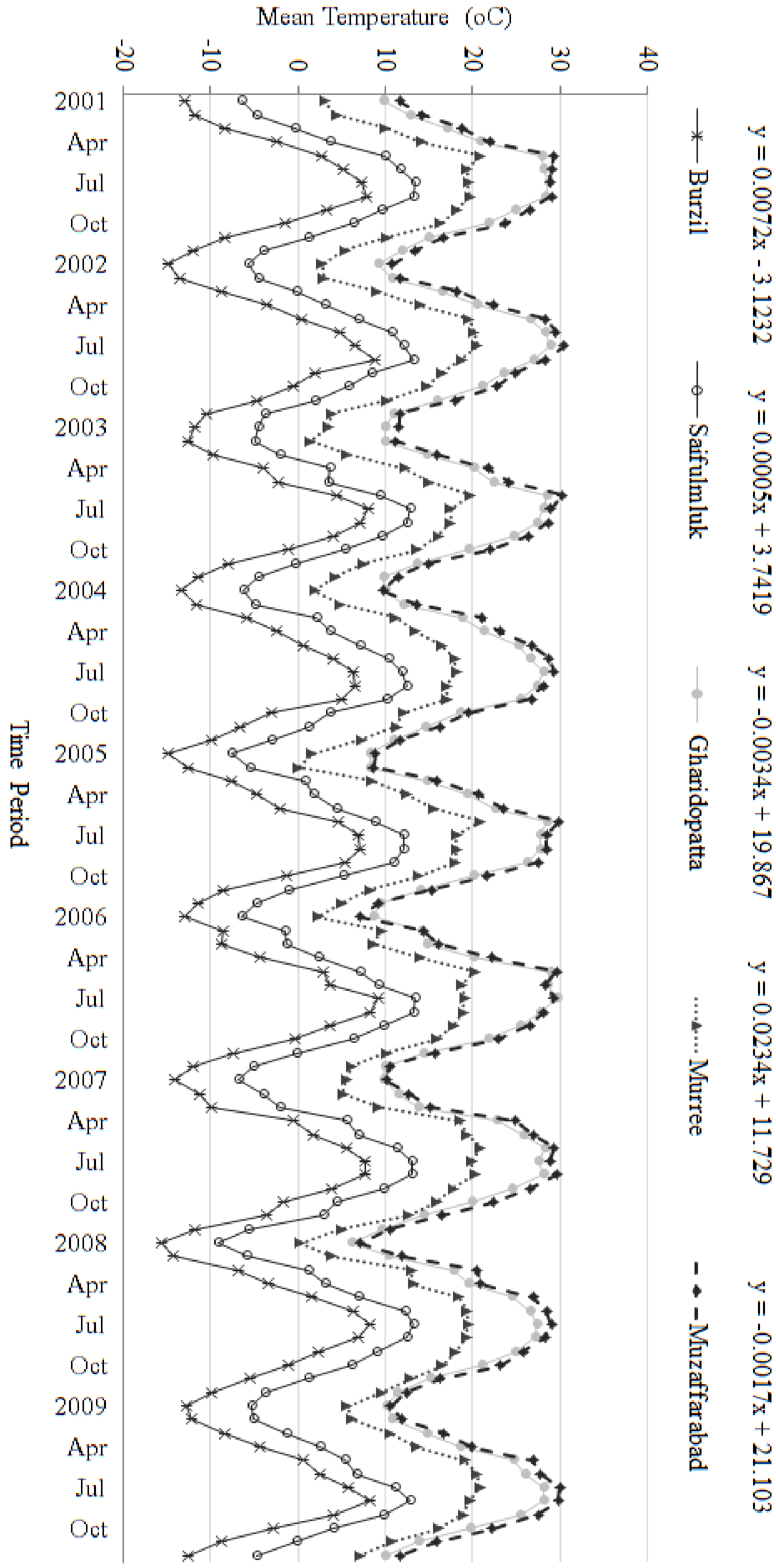

Figure 19. Monthly mean temperature (oC) of WAPDA and PMD climate stations for2001-2009.

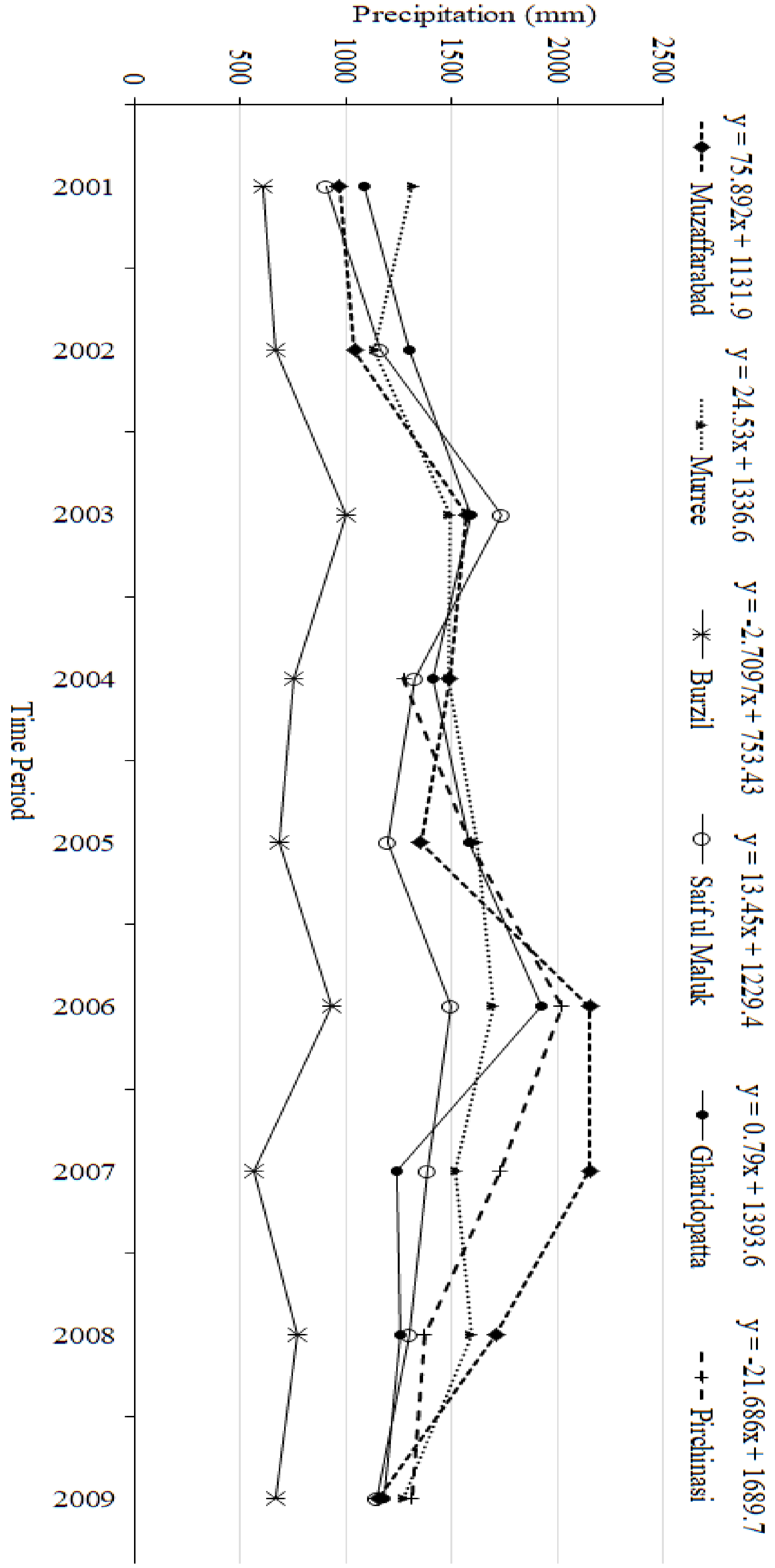

Figure 20. Total annual precipitation (mm) of WAPDA and PMD climate stations for 2001-2009.

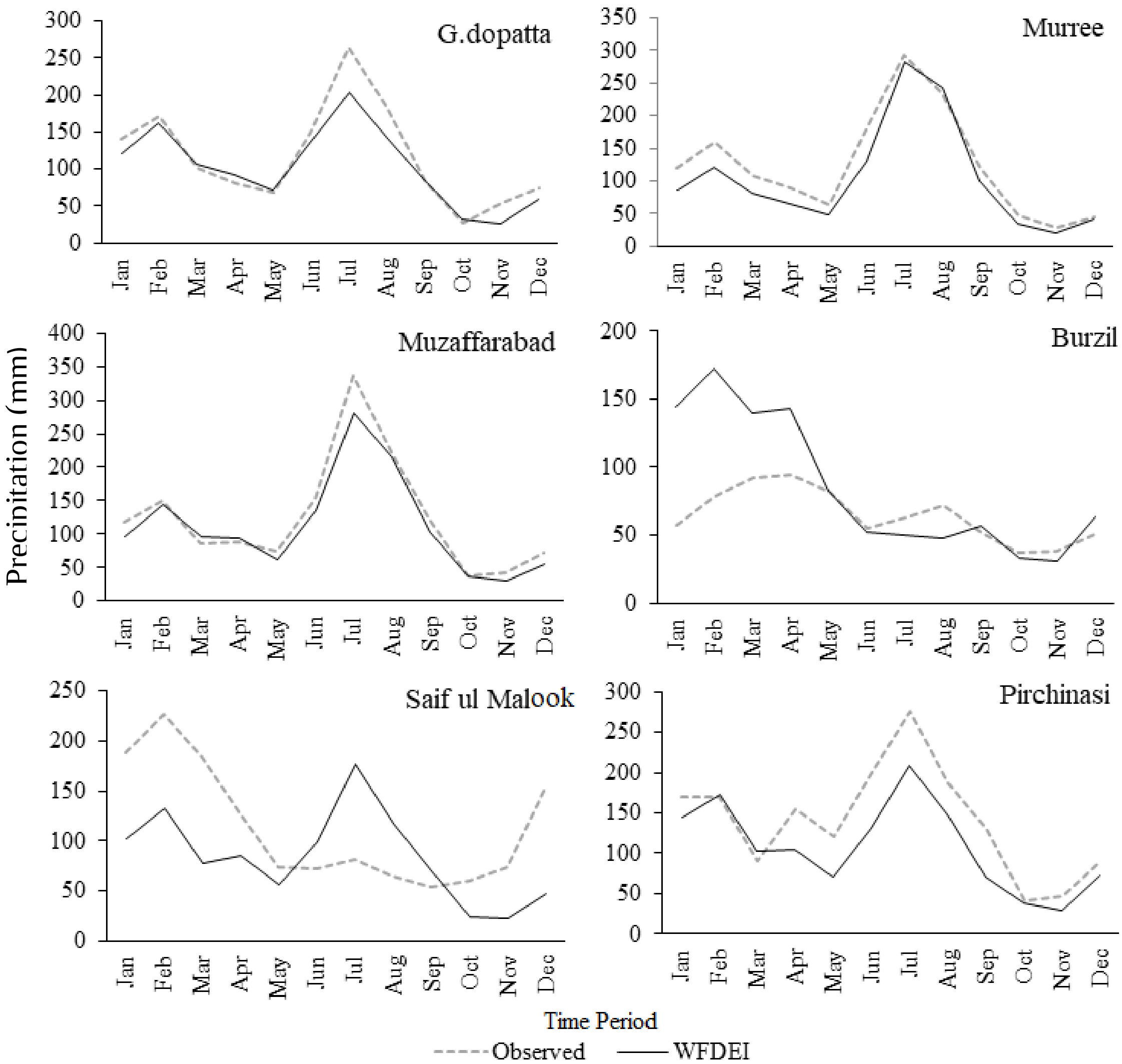

Figure 21. Comparison of total monthly values of Observed and WFDEI data at climate stations averaged over years 2001 to 2009.

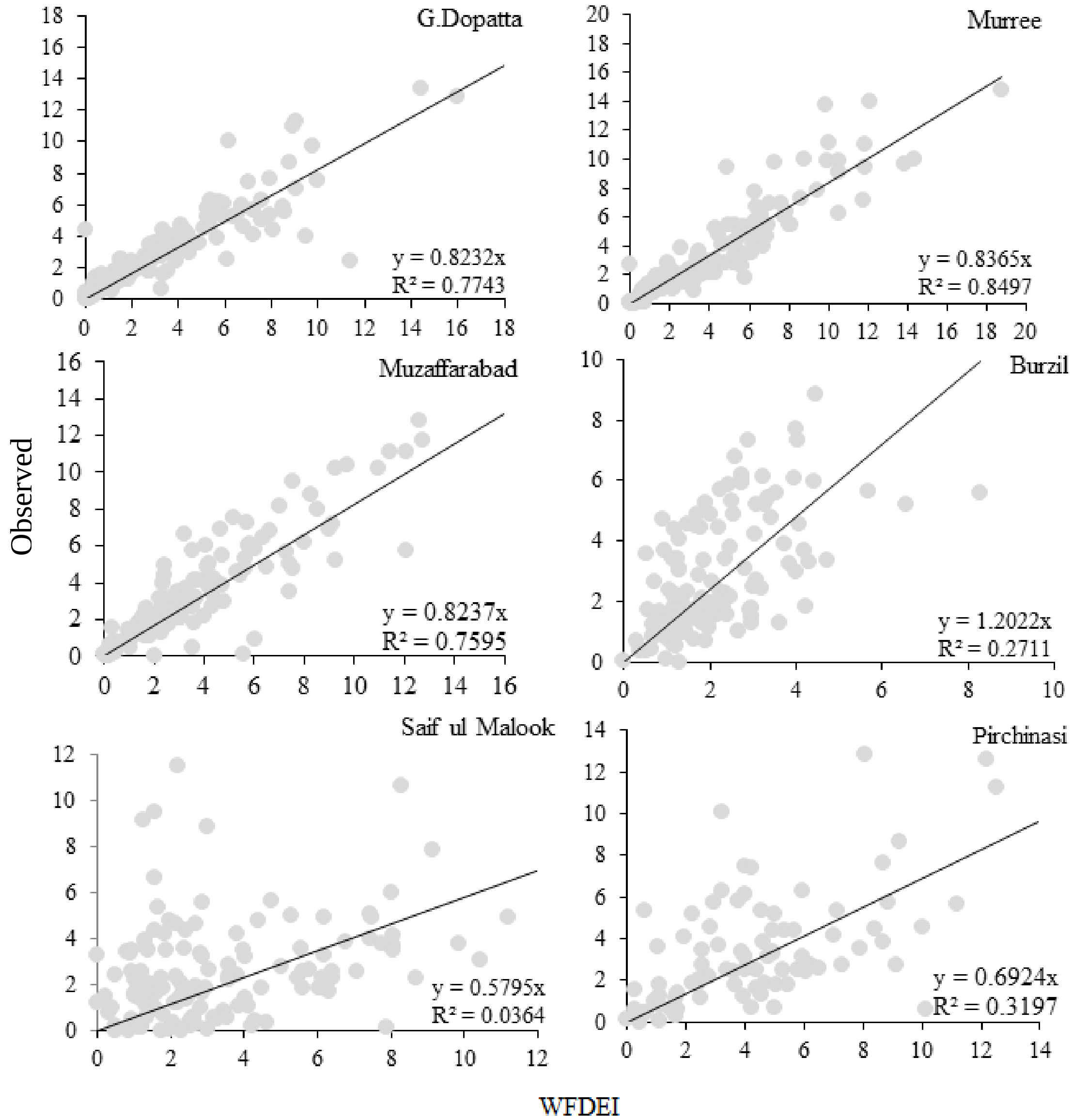

Figure 22. R2 values repressing comparison of Observed and WFDEI data at climate stations.

During calibration, using observed daily discharge data for the time period of 2001-2005 (Figure 24), NSE = 0.73, r = 0.87, R^2 = 0.87 and PBIAS = -11 was found. During winter season discharge is low compared to summer season. Discharge slowly increased from April and the peak value was observed during May, June and July due to snow and glacier melt from high elevated areas along with summer monsoon rainfall. During summer season after melting of fresh snow, glacier melts starts. Snow and glacier melt runoff are main contributions to discharge. Simulated discharge was underestimated during Apr, May, Jun and Jul which could be due to inaccuracy in WFDEI temperature data, affecting snow and glacier melt. During validation, using daily discharge data from 2006-2009, NSE = 0.65, r = 0.83, R^2 = 0.83 and PBIAS = -14 was calculated, shown in Figure 25. Peak values during snow melt and monsoon rainfall are not captured with SPHY model. As model is calibrated by using dry season years, so during validation it shows more compromising results due to presence of wet years.

Scatter plots (Figure 26-28) between observed and simulated discharge data for both calibration and validation time periods, show simulated discharge was underestimated compared to observed discharge. During calibration using monthly average discharge data, over all NSE = 0.81 was observed with PBias -11%.Whereas during validation, the highest NSE (0.87) calculated for 2007 along with PBias -7 whereas lowest NSE (0.62) for 2006 along with PBias -11 was found. In 2006, large abnormality during May, Jun, July and Aug, was observed. During these months discharge data is dominated by snow and glacier melt derived by air temperature. Overall NSE= 0.75, R2 = 0.89, r = 0.89 and PBias = -13 for validation period (2006-2009) was observed and large variation between observed and simulated discharge data was found during snow and glacier melt season in response of daily temperature variations. Over all model efficiency comparison between different years is mentioned in Table 7.

Table 6. Calibrated Parameters values for SPHY model.

Parameters (acronym)	**Units**	**Calibrated values**
Degree day factor clean glacier (DDFci)	$mm^{o} C^{-1} day^{-1}$	6
Degree day factor debris cover Glacier (DDFdc)	$mm^{o} C^{-1} day^{-1}$	6.5
Degree day factor snow (DDFs)	$mm^{o} C^{-1} day^{-1}$	4
Water storage capacity of snow pack (SnowSC)	$mm\ mm^{-1}$	0.4
Base flow recession constant (αGW)	-	0.005
Routing recession coefficient (Kx)	-	0.97

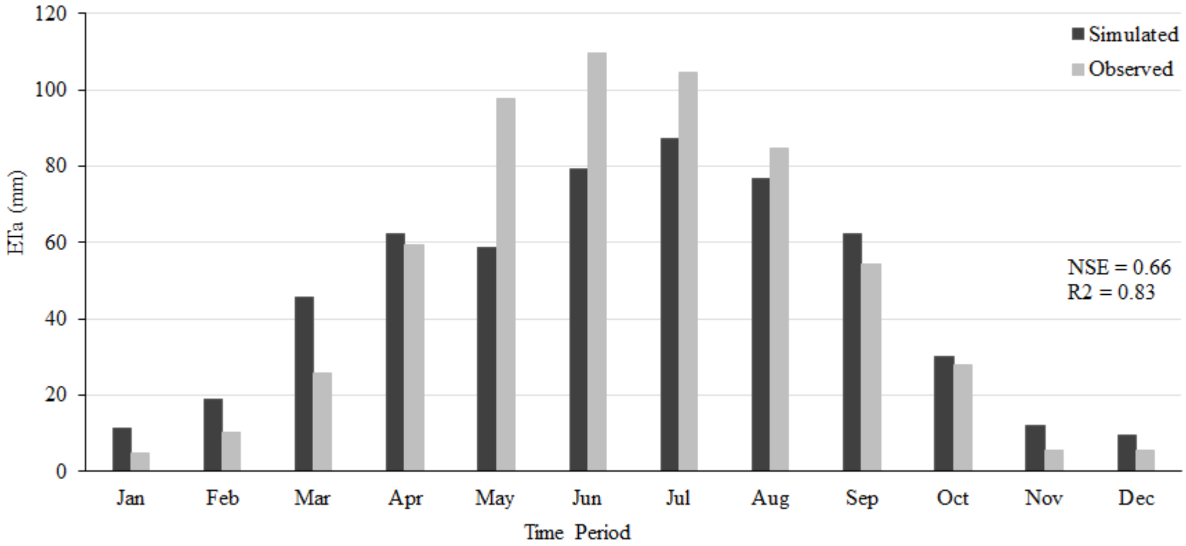

Figure 23. Monyhly average actual evapotranspiration for Mangla catchment from 2003-2005.

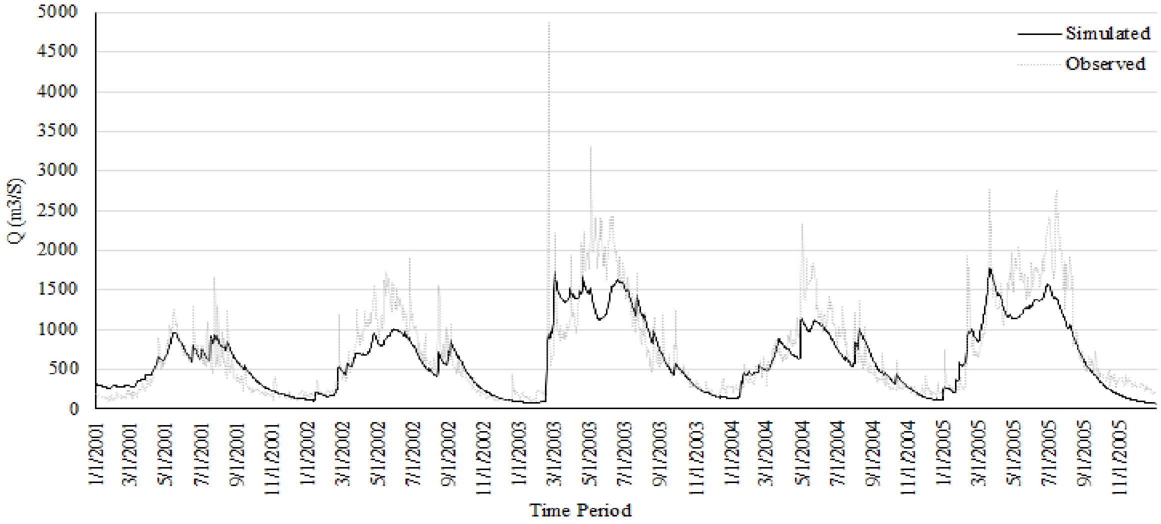

Figure 24. Time series analysis of daily discharge data for calibration time period (2001-2005).

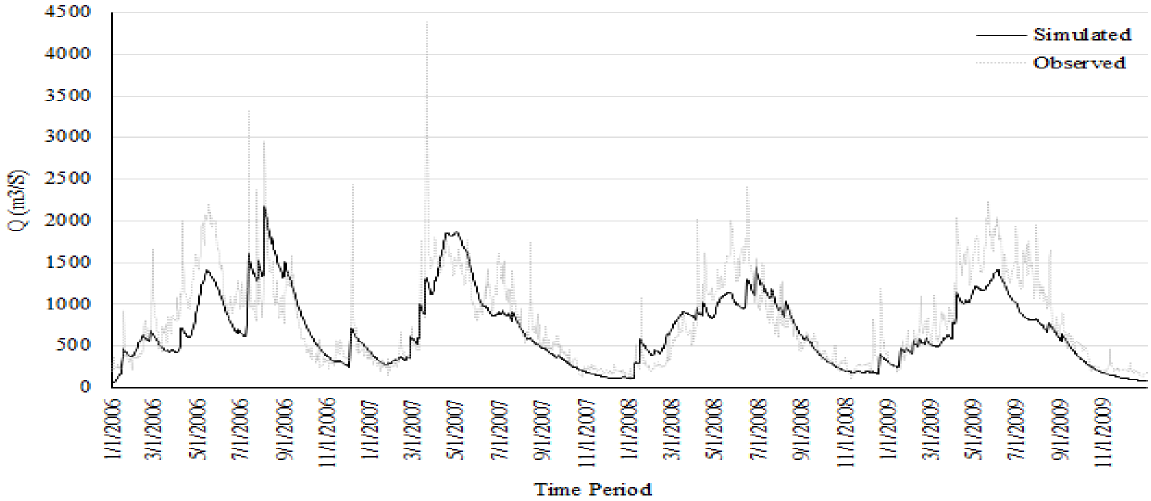

Figure 25. Time series analysis of daily discharge data for validation time period (2006-2009).

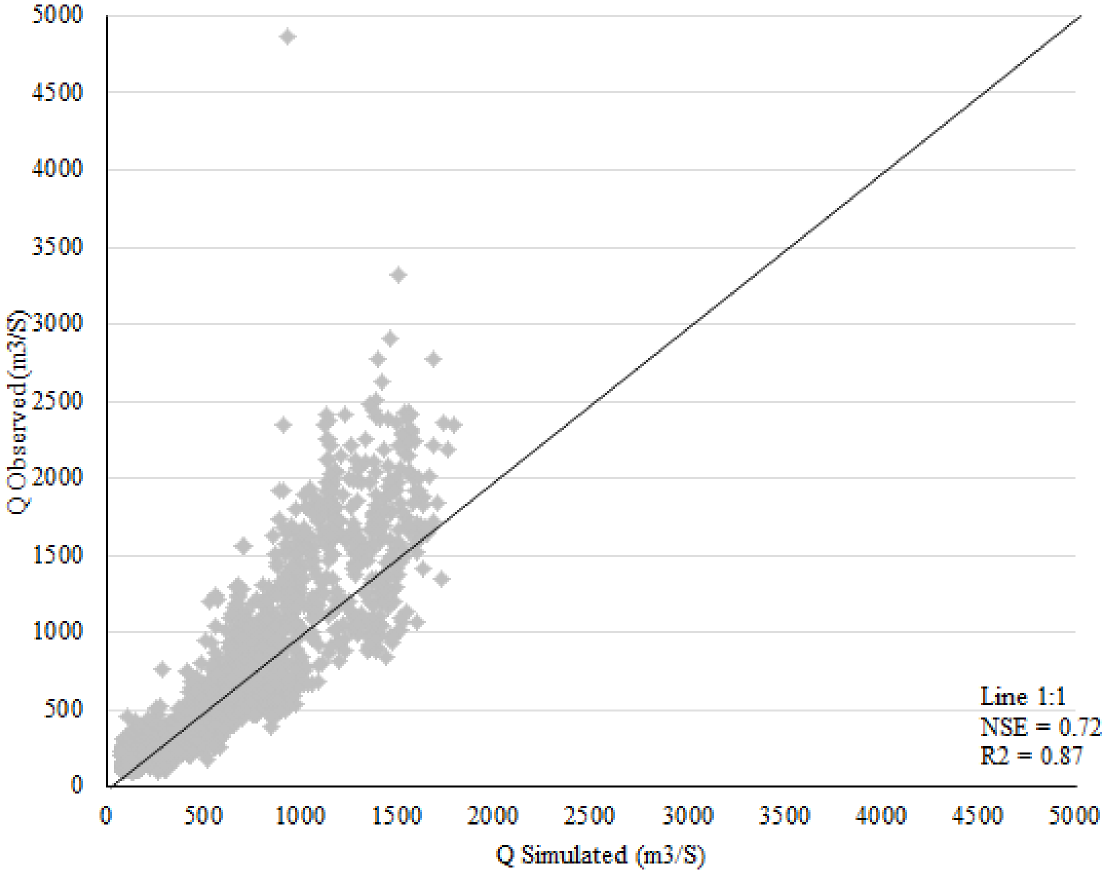

Figure 26. Scatter plot showing efficacy of SPHY model for calibration time period.

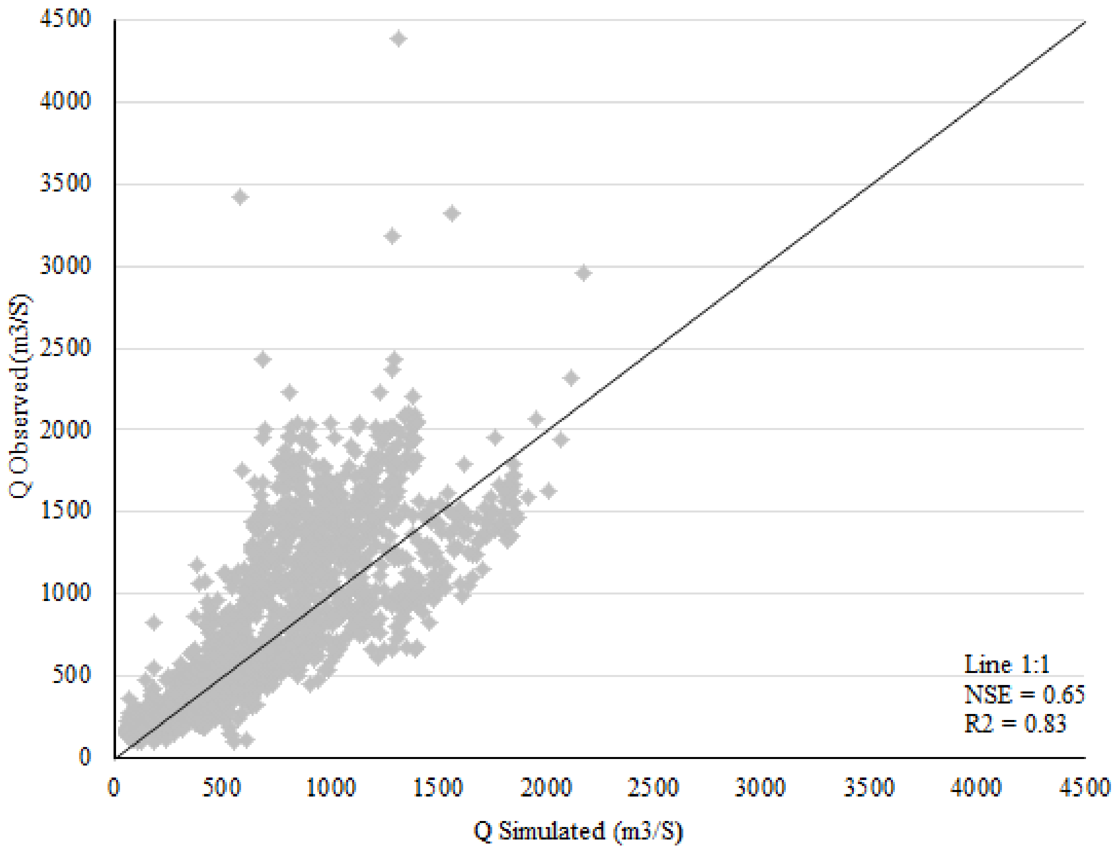

Figure 27. Scatter plot showing efficacy of SPHY model for validation time period.

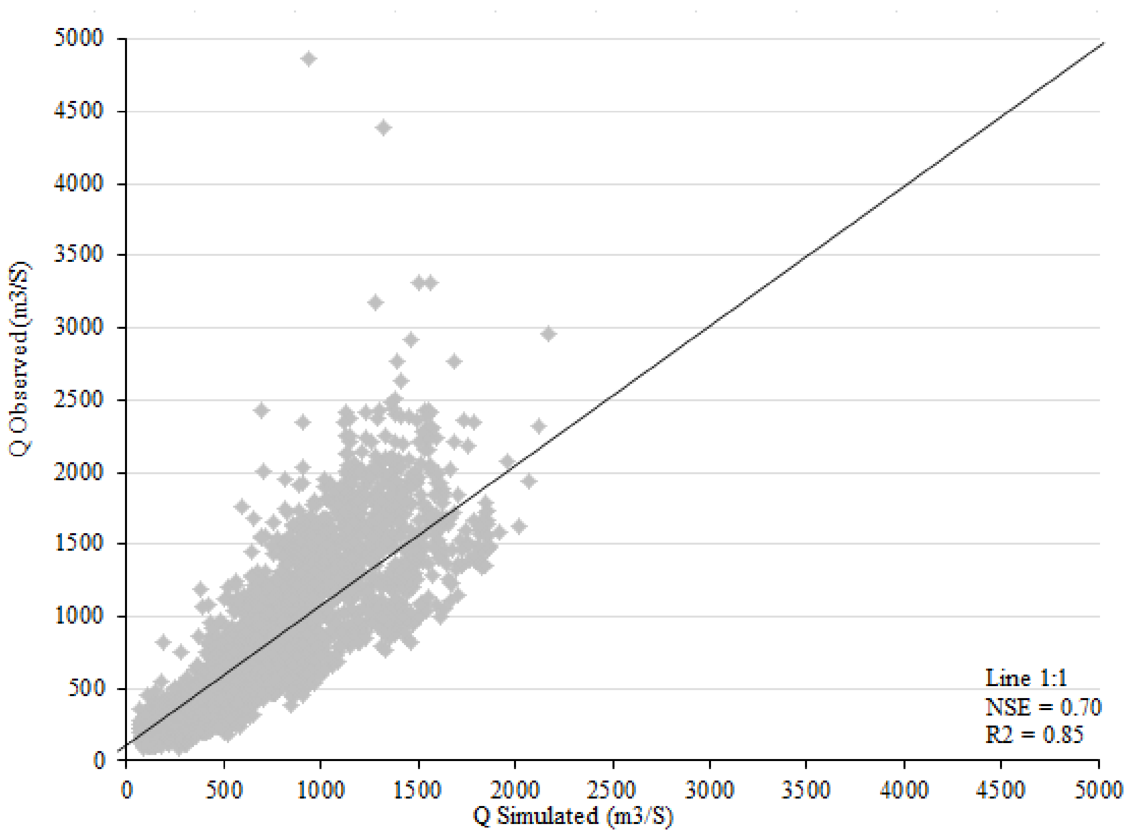

Figure 28. Scatter plot showing efficacy of SPHY model for calibration and validation time period.

Table 7. Model efficiency during monthly and daily time period.

Calibration (C) / Validation (V)	**Duration**	**Nash-Sutcliffe efficiency**	**Pearson's coefficient of correlation**	**BIAS (%)**
C	2001-2005 (Daily)	0.72	0.87	-11
V	2006-2009 (Daily)	0.65	0.79	-14
C	2001-2005 (Monthly)	0.81	0.92	-11
V	2006-2009 (Monthly)	0.75	0.89	-13
C	2001 (Monthly)	0.84	0.95	15
C	2002 (Monthly)	0.76	0.95	-18
C	2003 (Monthly)	0.77	0.88	19
C	2004 (Monthly)	0.77	0.91	-10
C	2005 (Monthly)	0.78	0.94	-19
V	2006 (Monthly)	0.62	0.82	-11
V	2007 (Monthly)	0.87	0.95	-7
V	2008 (Monthly)	0.77	0.88	-6
V	2009 (Monthly)	0.71	0.98	-27

3.4. HYDROLOGICAL COMPONENTS

Total discharge and its composition (rain runoff, base flow runoff, snow and glacier melt runoff) are necessary for understanding the integrated hydrological process of a catchment. Snow melt runoff is generated due to melting of snow. Glacier melt runoff is due to melting glacier cover area. Liquid precipitation contributes to rainfall runoff. Monthly average values (from 2001-2009) of hydrological components from model simulation are presented in Figure 29. Main contribution to total discharge during (May, Jun and Jul) is due to snow melting. After completion of snow melt, glacier melting starts and its large contribution during Aug and Sep is observed along with moon soon rain fall. It was found that about 55% of total runoff is generated due to snow melting which is main contribution to total discharge during summer season, whereas during winter snow melt runoff contribution is negligible as solid precipitation is stored as snow. Other main contribution (32%) of total runoff is rainfall during Jul, Aug and Sep. Glacier melt runoff has the least contribution to discharge as 2% of total catchment area is covered with glacier. Snow accumulation, during spring and winter, cause snow melt runoff in Apr to Jun. The peak value of discharge varied from May to Aug depending on air temperature and precipitation. Figure 30 shows rainfall, base flow, snow and glacier melt contribution for each month. It shows highest contribution of snow melt (80%) during summer month June due to highest temperature and highest contribution of glacier melts during Sep and Aug along with rain fall contribution. During winter season highest contribution to main stream is base flow after accumulation of rainfall and snow and glacier melt to ground depth layer.

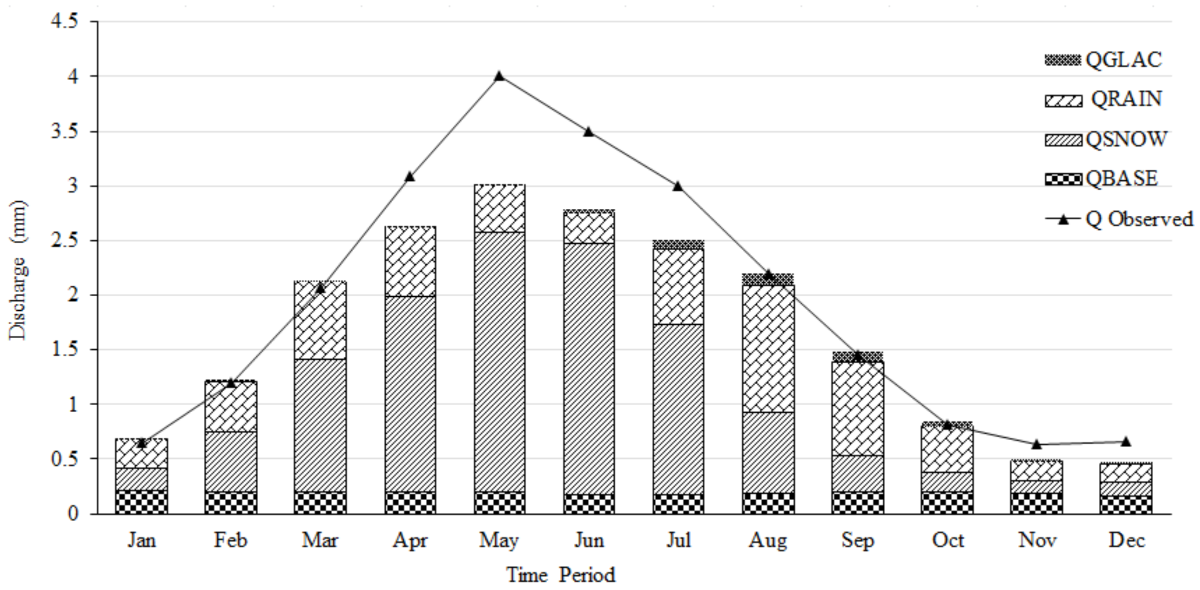

Figure 29. Average monthly discharge from snow glacier, rainfall and base flow with observed total discharge.

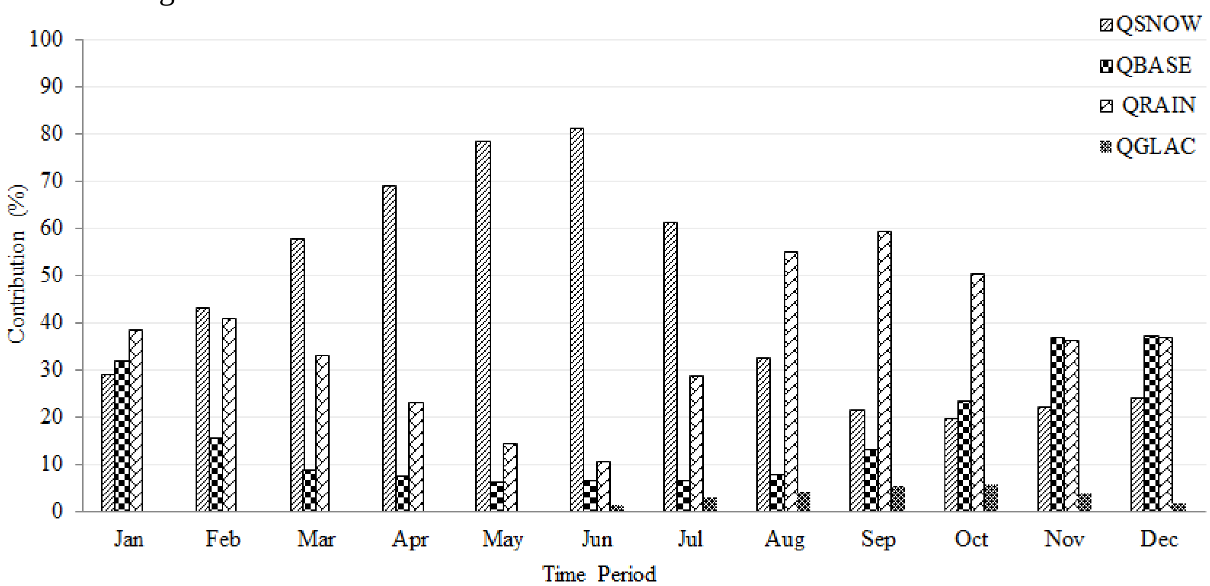

Figure 30. Discharge component distribution in % over the year for Mangla Catchment.

Chapter 4

CONCLUSION AND RECOMMENDATIONS

4.1. Conclusion

This study was carried out to find out the contribution of discharge components to main stream flow over scarcely gauged, high altitude snow and glacier- fed Jhelum River basin. Overall increase in average temperature (^{o}C) and total annual precipitation (mm) from 2001 to 2009 was observed for Mangla catchment. Gridded daily precipitation and temperature data from WFDEI was used due to trans-boundary nature of catchment and spatially & temporally limitations of observed datasets. For true representation of hydrological process, WFDEI precipitation data was bias corrected with the help of observed climatic datasets.

Total discharge and its components were simulated by using SPHY model to simulate water availability for catchment. SPHY grid based spatially distributed model use degree day factor approach to find out snow and glacier melt contribution to main stream flow. SPHY model is more sensitive to precipitation, therefore during wet years it gave more bias results as compare to dry years. It underestimated overall discharge during snow melt and rainfall season. It is more likely due to underestimation of WFDEI precipitation data for high altitude areas. SPHY model gives output for each hydrological component separately. It represents a true contribution of discharge component to main stream flow over the whole time period and seasonal changes of rainfall runoff, snow and glacier melt runoff. For Mangla catchment, during summer season more contribution to main stream flow, due to snow melt runoff and during monsoon season more contribution, due to rainfall runoff along with glacier melt runoff was observed. Overall there was slightly increase in temperature and precipitation from 2001-2009, so increase in rainfall runoff and snow & glacier melt runoff was also observed. As SPHY model provides the discharge components separately along with total discharge, it would help to understand the hydrological process and to improve reservoir operation seasonally for better water resources management. Management of water availability from the Jhelum River basin, impacts to agriculture activities, domestic use of water, hydroelectric power generation and ecosystem.

4.2. Recommendations

There are number of limitations for current study in terms of input datasets that could be addressed for future study. In current study dynamic glacier is not included due to limitations of data availability. Consequently, limitation of input datasets affects the total runoff and its components. In current study snow depth for the whole basin is considered constant which effect the stream flow, as most of the runoff is generated due to melting of snow in this region. Inclusion of glacier dynamics improves the biasness between simulated and observed discharge data as compare to static glacier. Moreover dynamic vegetation cover will also improve the output of SPHY model as crop factor depending upon vegetation type, effect the evapotranspiration which ultimately conclude the total runoff. For the future work spatially distributed and dynamic input datasets should be considered using remotely sensed data sets and in situ measurements for the more accurate results.

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