Rainfall Runoff Modeling using Geo-spatial Techniques in Tarbela Sub-catchment

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Abstract

This paper presents flood analysis of Tarbela sub-catchment using remote sensing (RS) data and geographical information system (GIS) techniques. Tarbela catchment is largely supplemented by glacier and snow melt as well as rain, which are considered as the most critical flood-producing factors in the basin. Among various flood control measures, dams are considered as flood controlling structures. The world's largest earth filled dam, Tarbela Dam, is located in Pakistan. This study focused on rainfall-runoff modeling and estimated surface runoff in the Tarbela catchment with the help of hydrologic simulation model (HEC-HMS with HEC-GeoHMS). Drainage area, stream network and slope of the catchment were generated using Arc Hydro extension of ArcGIS and ASTER DEM of 30m resolution. Soil type and land cover/use characteristics play an important role in the amount of surface runoff reaching the nearby streams. Land use/cover details were derived from LANDSAT satellite imagery. Soil maps and land use/cover were used to develop curve numbers of the Tarbela sub-catchments. In-situ data comprising precipitation, temperature, humidity and wind speed were acquired from manual and automatic weather stations (AWS) of Pakistan Meteorological Department. ERA-Interim data set of precipitation, temperature, evaporation and snowmelt was used for un-gauged area of the catchment. The temperature and precipitation data set of CRU was used for historical climatic background of study area from 1900-2014. The Natural Resources Conservation Services (NRCS) runoff curve number method was selected to estimate precipitation excess and applied for estimation of flood hydrograph. The output of HEC-HMS simulation model was a runoff hydrograph that was validated with the available discharge data at the catchment outlet. The study area is a complex one because the inflow at Tarbela consists of contribution from rain, surface runoff, snow and glacier melt as well as base flow. The contribution of the lower part of a basin comes from rainfall-runoff and snow melt whereas the high altitude region, the runoff derives from snow and glacial melt. The synthetically developed sequence of hydrological data can be used for flood forecasting.

Key Words: Hydrological Modeling, Hydrograph, Curve Number, LULC, HSG.

Introduction

Water, a precious resource on earth, forms the foundation of life and plays a vital economic and social role. The water cycle is characterized by the hydrological cycle, which is a closed system as the water amount is fixed. However, its circulation varies with space and time. These variations lead towards two extreme situations of water i.e. droughts and floods which may result in issues like agricultural losses that affect the livelihoods as well as the economy of the world. That is why; these extreme situations are actually a big challenge for the public and specifically for the government. Globally, floods are considered as a great natural hazard (Seyedeh et al, 2008). Floods have caused about 40% of the total deaths, with most of the extreme floods happening in the developing tropical regions (OhlandTapsell, 2000). There are many reasons of flooding including the rise in the ground water level (Burt et al., 2002), breakage or opening of a reservoir or a dam (Forkuo, 2011), coastal flooding (Nicholls, 2002) and also due to the excessive rainfall. Flooding due to extreme rainfall that occurs for a short time period may damage crops, as well as, the economic and social infrastructure (Sanyal and Lu, 2004).

Hindukush-Karakoram-Himalaya (HKH) region is actually a global asset. HKH area is the biggest reserve of ice and snow other than the Polar Regions. This area comprises about 54,000 glaciers having 6,000 km^3 ice volume; 60,000 km^2 area, while the cover of snow in this area is about 0.76 million km^2. There are 10

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river basins, out of which 6 are trans-boundary. This area facilitates 1.3 billion people and it is known as the Water Tower of the South Asia. Two weather systems, summer monsoon and westerly are dominant in the region (B. Bookhagen et. al., 2010). It has been observed in the HKH region, during past few decades that over the Himalayan high mountain belt, in the east specifically, there is an increase in the monsoon precipitation. The seasonal variation has also been experienced. While the number of extreme rainfall events is decreasing, the intensity is increasing, especially towards the western parts of the HKH. Generally, within HKH region, increase in the minimum temperatures during three months of winter has been observed with higher extreme seasons. In general, regarding climate change in the Indus basin, rainfall in summer has been reduced while in winter the rainfall has been increased. The intensity of extreme events of rainfall has intensified in the major mountainous area. In the eastern region; winters are getting warmer and summers are getting cooler.

The Indus flood 2010 has influenced about 20million people that resulted in the destruction of infrastructure including livelihood and property (Ali. et. al., 2011). This flood caused deaths of about two thousand people. Those floods were attributed to an anomalous pattern of air circulation through Asia as well as Europe resulting extreme rains in northern part of Pakistan. Along with the flooding event in Pakistan, an extreme and record breaking heat wave was observed in the western part of Russia and resulted in the hottest summer in Europe in the year of 2010. It has been noted that, since 1994, rainfall of monsoon in 2010 was the highest in the entire country. In the second half of July, amongst the causes of floods in 2010, there was a blocking incident that froze the meanders of the Jet stream over Asia and Europe. The pattern took towards extreme weather over the continent. In order to assess the rainfall runoff, many hydrological simulation techniques can be used (Smith and Bedient, 1981). HEC-HMS, Hydrologic Engineering Center's Hydrologic Modeling System, developed in 1992, is used in this study to analyze the rainfall-runoff flood. The output of the model is further compared with the field collected observation.

General Study Area

This study particularly focuses on the sub-catchment of up-stream Tarbela as shown in Figure 1. The study area located in the Upper Indus Basin (UIB), lies between the Himalaya and the Karakoram (Ali and De Boer, 2007; Khan et al., 2009; Tate et al., 2000).Indus basin is defined as a control structure of reservoir, barrages and most of the runoff comes from snow and ice melt (Khan, 2001). The catchment receives the western disturbance and summer monsoon rainfall in addition to seasonal snow and ice. Snow and ice are among major sources of water supply to Indus Basin Irrigation System.

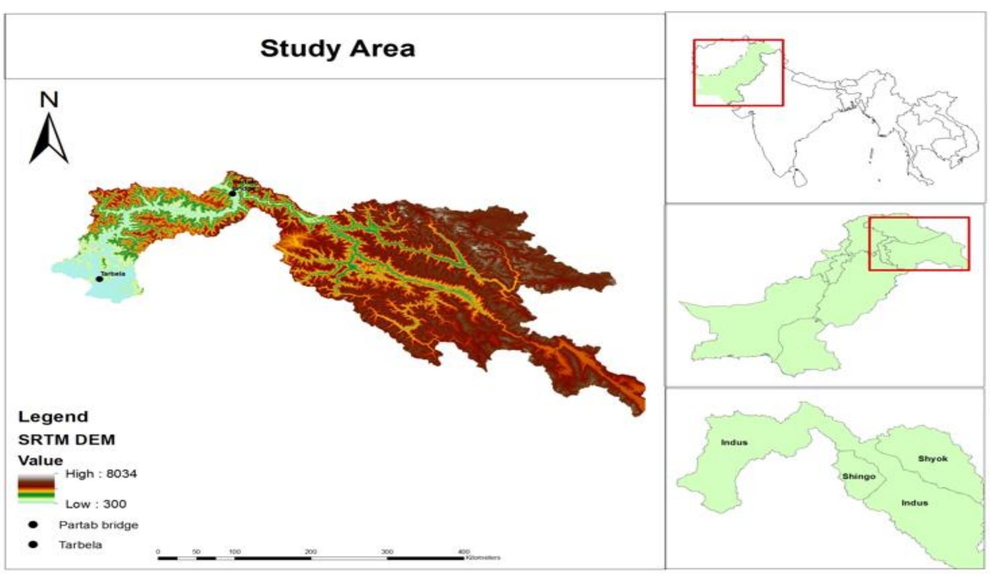


Figure 1: Tarbela Sub-catchment

The drainage area of Upper Indus Basin above Besham Qila consists of Indus, Gilgit, Hunza, Shigar, Astore, Shoyk and Kharmong basins. In this study the hydrological model run only on Indus, Shoyk and Kharmong basins. HEC-HMS does not account snow accumulation and melting process (J.M. Cunderllk and S. P. simonovlc, 2004). One of the major drawbacks of HEC-HMS model is that it only takes rainfall runoff into account; it does not include snow melt and glacier melt. Here question arises why we select only Indus, Shoyk and Kharmong basins. This is because we only compute the surface runoff resulting from rainfall-runoff. Mukhopadhyay and Khan (2015) concluded that in all of these stations, snowmelt begins to contribute to river discharge in April and reaches maximum in June except in Kharmong where the maximum snowmelt peak occurs in July. This study focuses on extreme event in July in which Indus basin received extreme rainfall according to Pakistan Meteorological Department data. We Selected Indus, Kharmong and Shoyk because seasonal snow melting of other basins ceases before July, although Kharmong snow melting still contributes to river flows.

The global warming directly influences the temperature and indirectly impacts the hydrological cycle. Local temperature increase is directly correlated with evaporation and snow melting. Precipitation is a primary source of water either in the form of rainfall or snow and ice. This study focuses on rainfall-runoff modeling of sub-catchment Tarbela. The catchment is shared with China, India and Pakistan. The river of this catchment is called Indus River Figure 2. The Indus River originates at an elevation of about 5,166 meters in the remote region of western Tibet (Mukhopadhyay and Khan 2015).

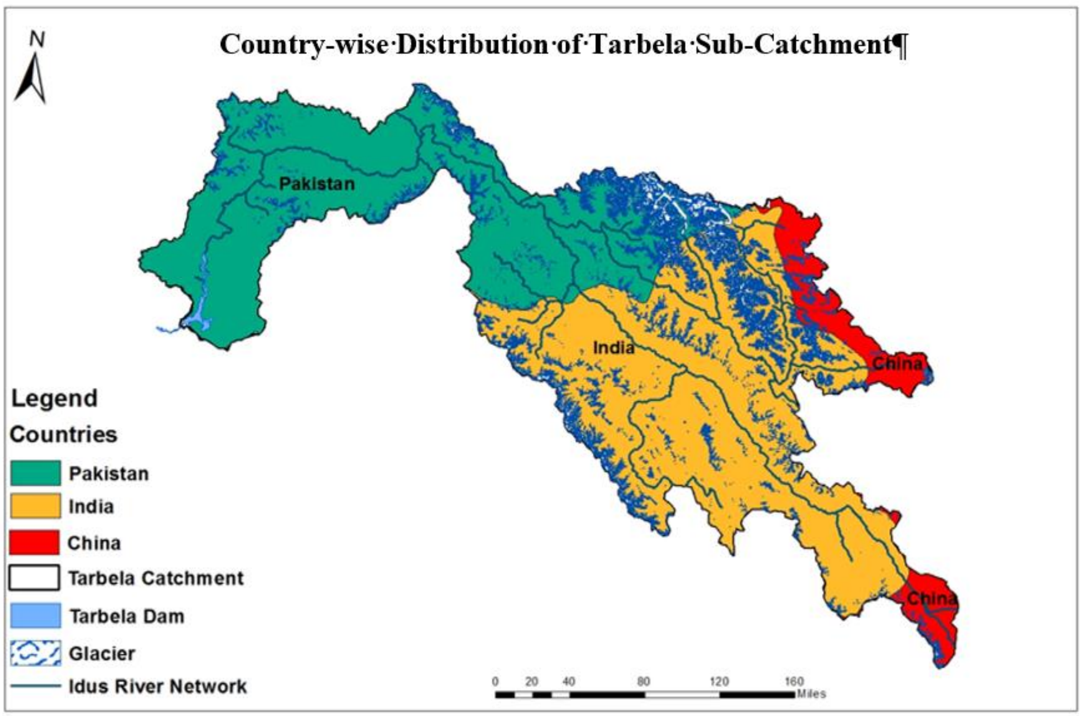


Figure 2: Country wise distribution of Tarbela Sub-catchment.

Climatic Background

Meteorological parameters such as air temperature and precipitation are the most important factors in hydrometeorology. The climate conditions of the study area in terms of spatial and temporal distribution of temperature and precipitation are extremely diverse in this region. The temporal variability of mean annual area weighted temperature and rainfall of catchment based on climate research unit data (CRU) is illustrated in Figures 3a and 3b. The study area lies in the Upper Indus Basin (UIB) hence the water resources of the Indus River play an important geopolitical role in the region (Immerzeel et al., 2015).

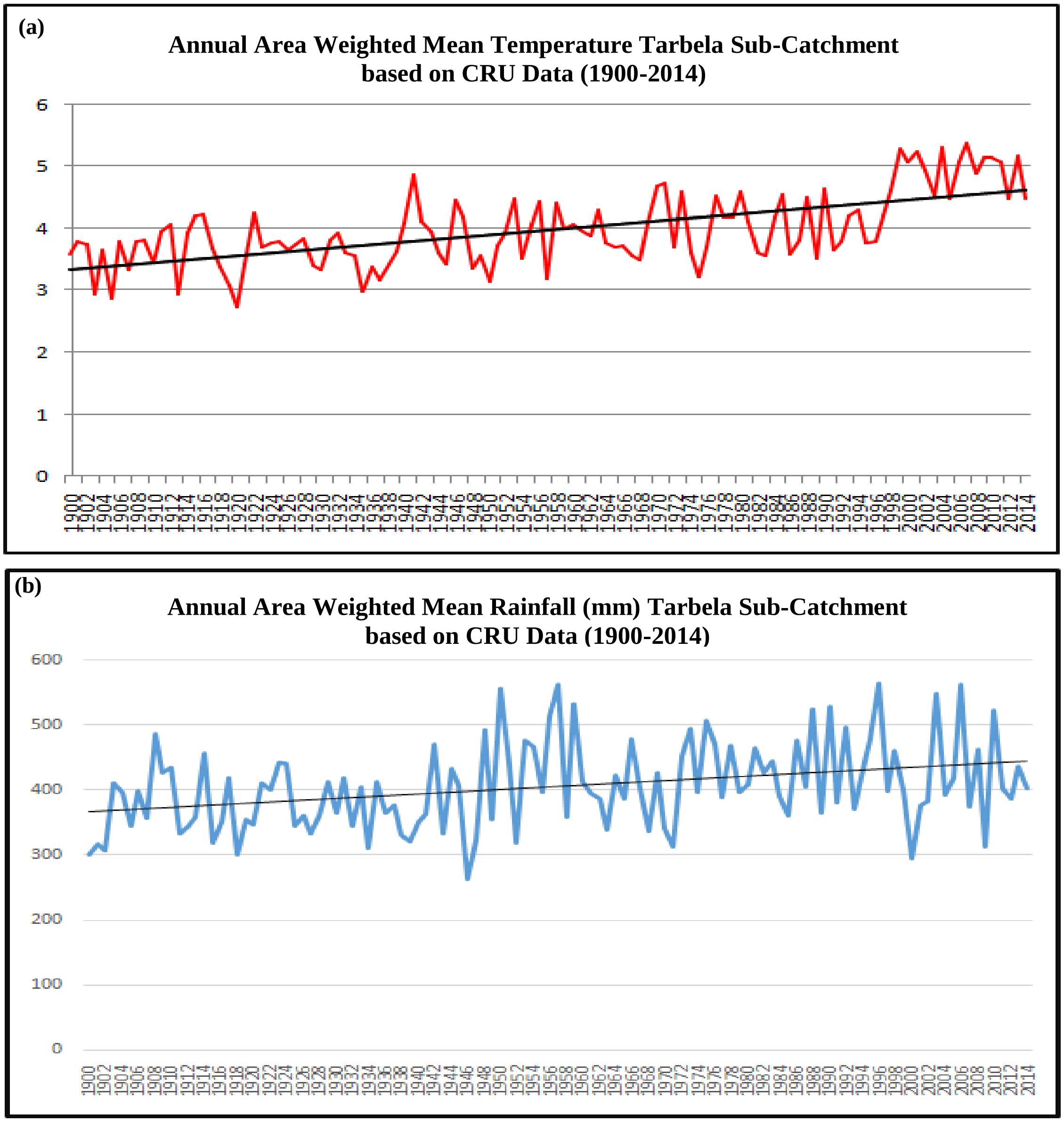


Figure 3: (a) Annual mean temperature and **(b)** Annual rainfall from 1900-2014.

Air temperature shows increasing trend from 1900 to 2014. Figure 3a depicts the sharp rising trend of temperature from 2000 to 2010. According to the World Meteorological Organization (WMO) 2011 report, the (2001 -2010) was the warmest decade recorded over the globe (Zaidi et al., 2013). In response to increasing air temperature over the basin, mountains glaciers are expected to shrink. Similarly, the variation of precipitation as shown in Figure 3b lies between 300 to 600 mm recorded in the study area from 2000-2010. In view of the topographic variation in this area, the high altitude precipitation is considerable under estimate (Immerzeel et al., 2015). The increasing trend of temperature is alarming for this region because the glacier and seasonal snow cover are the most dominant features of the region. The increasing trend of temperature has directly reduced the solid precipitation (Bolch et al., 2012) and increased the high altitude rainfalls. Global warming and climate change have directly influenced the cryosphere and hydrological cycle of the basin.Regional warming is also affecting the hydrology of the Upper Indus Basin (Immerzeel et al., 2009). The rise in temperature and extreme rainfalls will accelerate the melting of glaciers and ultimately will result in the increase in river discharges. Therefore, Precipitation and temperature are the important climate indicators as their variability may affect the quality, quantity and the spatial distribution of water resources on the earth surface.

Data and Methodology

Among advanced data collection technologies, satellite has emerged as a powerful tool for assessment and monitoring of remote areas. The methodological flow chart is given in Figure 4. The method consists of satellite images, observed and reanalysis and climate data along with available literature. The data were analyzed in the GIS environment and the hydrographs were generated. The hydrological analysis was performed using Digital Elevation Model (DEM) and hydrology tools. The watershed database was created using geographical information system (GIS). After the digitization of watershed, a database for hydrological model was prepared using the HEC-GeoHMS extension in GIS environment. The rain-fall runoff modeling was done using the HEC-HMS model. European Centre for Medium-Range weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim) data of precipitation, temperature, evaporation and snow-melt for un-gauged areas and available observed climate stations data were used in the study. These data-sets were used as an input in HMS model. The model was run for July 2010 flood event.

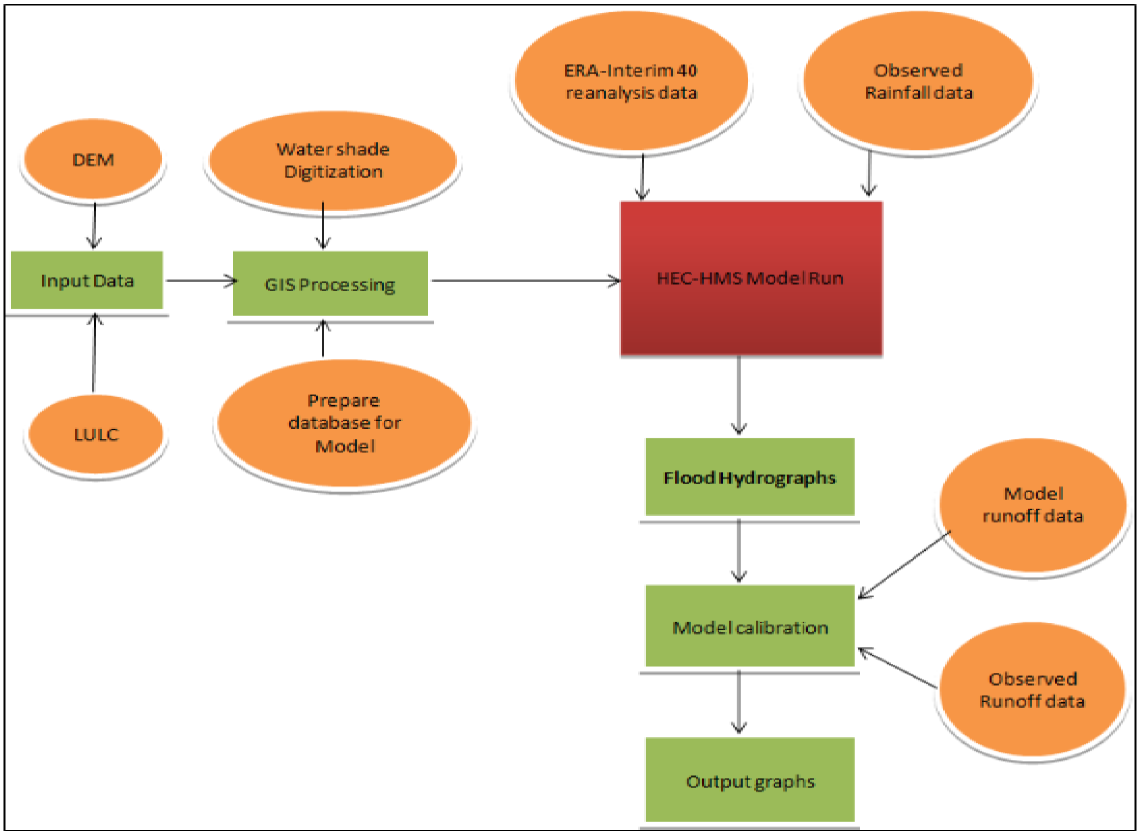


Figure 4: Flow Diagram.

Hydro Meteorological and Climate Data

The river flow and climate data (rainfall, temperature, humidity and wind) were obtained from Pakistan Meteorological Department (PMD). Total 7 stations are installed in the study area. The river flow data of 2010 were acquired from Flood Forecasting Division (FFD) at Partab Bridge and Tarbela. The weather stations of PMD are generally installed at low altitudes, in remote areas. PMD has installed an automatic weather station (AWS) for which the recorded data set is available after 2010. The weather stations are sparsely located in the catchment. The uppermost part of the catchment contains a few stations, however, the Himalayan portion has even fewer no station. Figure 5, represents the PMD climate stations and ERA-Interim data points available at the high altitudes. The ERA-Interim data re-gridded at 0.125^{o} resolution were used in the un-gauged areas. The meteorological data of seven climate stations of Tarbela sub-catchment have been used in the analysis for a period of July 2010.

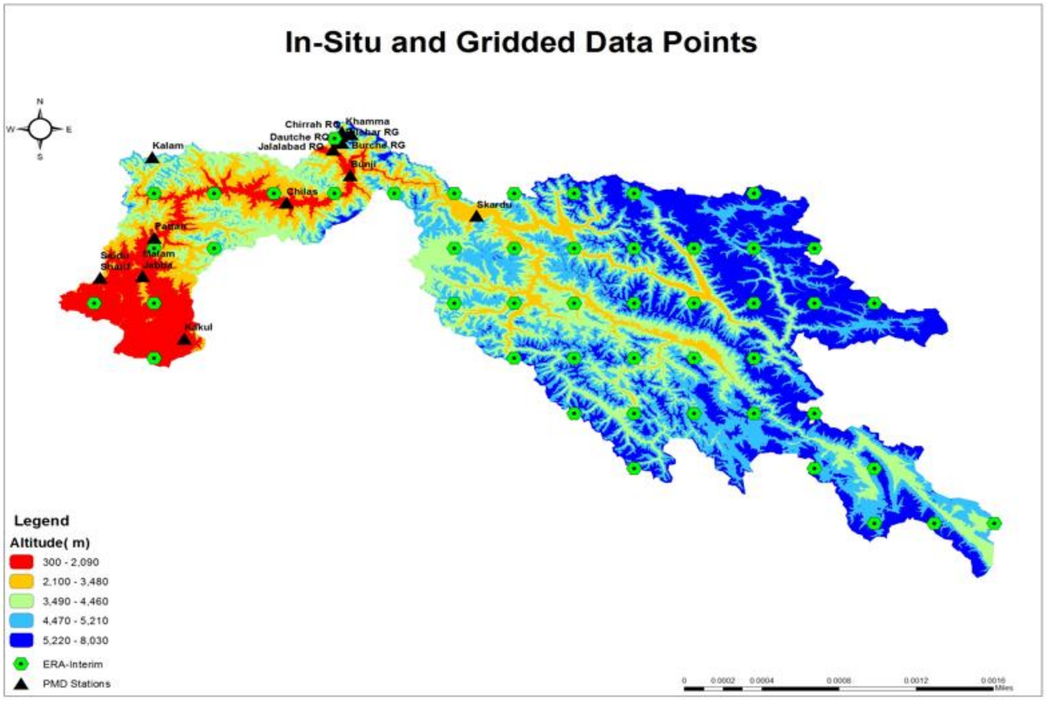


Figure 5: Location of Climate Stations and distributions of ERA-Interim point along the DEM.

Watershed Delineation

The following GIS and hydrology tools are used for terrain analysis and hydrological network generation of sub-catchment Tarbela.

- Arc-Hydro version 10.1 for the Terrain Analysis.
- HEC-GeoHMS10.1 for hydrological Geo-database generation.

Digital elevation models (DEM) present valuable hydrological information for a basin. Therefore, the Aster Global Digital Model (Aster GDEM) 30m x 30m resolution was used to delineate the drainage lines and catchment of Tarbela. HEC-GeoHMS was used to create input files for HEC-HMS model. The project point was added at Tarbela dam that generated the project area. The necessary information was computed for basins such as river length, river slope, basin slope and longest flow path.

Soil Properties and Curve Number

Soil properties and curve number play an important role to find out the relationship between rainfall and runoff and the amount of surface runoff reaching the nearby channel. The infiltration properties of a watershed depend on the soil properties of the area. Figure 6 depicts the soil properties and curve numbers of the basin. Mostly the soil texture is loam, sand and sandy loam and the drainage properties are imperfectly and moderately well. The soils are classified into hydrological soil groups (HSG), which are A, B, C and D. these hydrological soil groups were used to determine the runoff curve numbers. A hydrological soil group HSG indicates the transmission rate or infiltration and percolation rate of a catchment. HSG group a soil was observed in the Tarbela sub-catchment. The soil group A has low runoff potential and high infiltration rate. The soil texture of group A is mostly sand, loam and loamy sand.

The curve number (CN) is an index which describes the initial abstraction and infiltration capacity of a watershed based on the soil properties and vegetation curve of the watershed. The CNs are generated with the combination of soil conditions and the land use/cover. In Tarbela sub-catchment, the CN is maximum in water bodies and glacier covered areas. If CN is high then higher will be the runoff potential in the watershed (P. Schiariti, P.E., CPESC). Minimum CN is found in glacier free areas due to previous surface or vegetation cover. The initial abstraction was slightly greater in the downstream Partab Bridge that reduced the rainfall-runoff potential at Tarbela inlet.

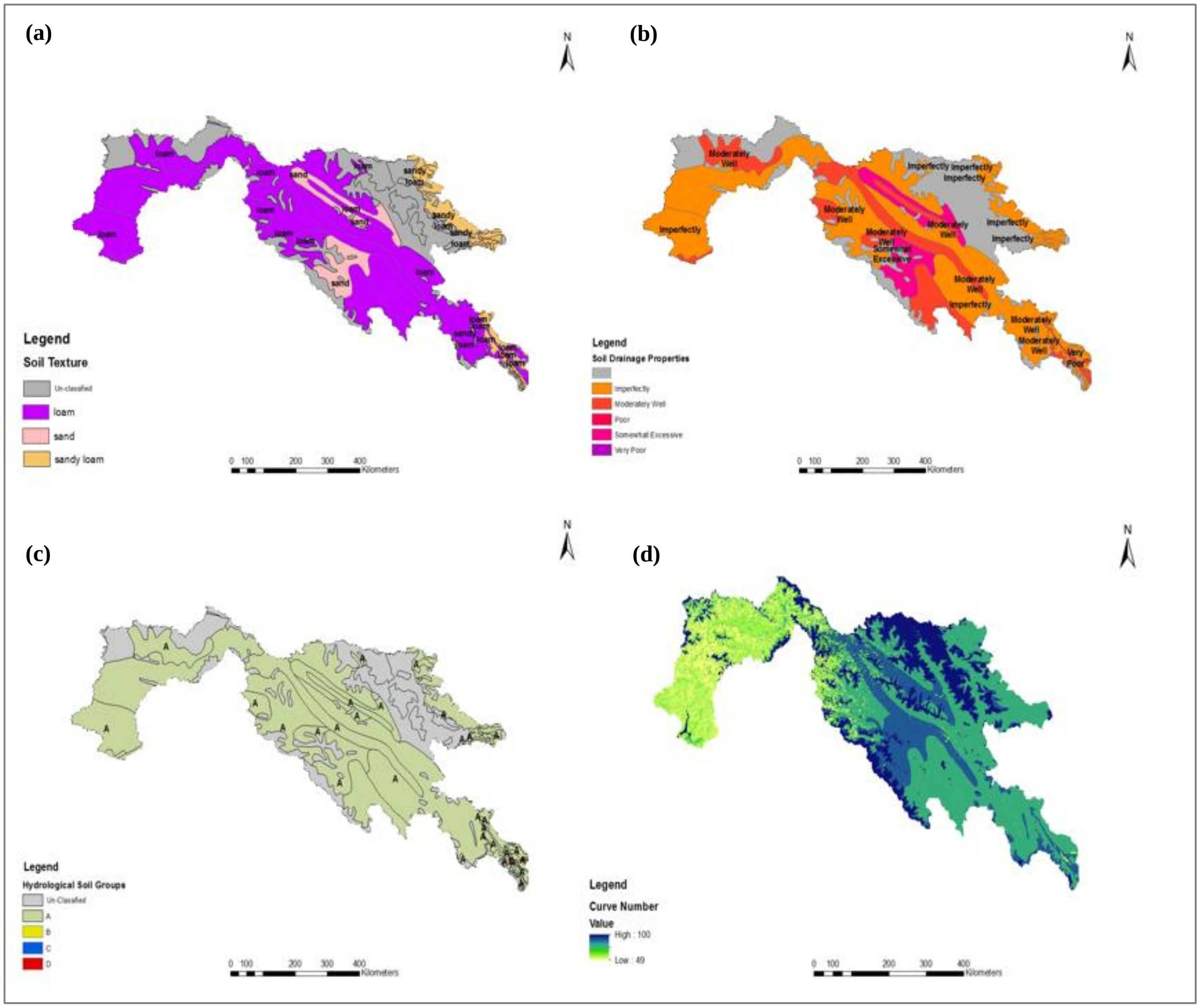


Figure 6: (a) soil texture, **(b)** soil drainage properties, **(c)** hydrological soil groups and **(d)** curve number

Results and Discussion

This research aimed at rainfall runoff modeling in a complex area. The sub-catchment drainage of river Indus has two major parts, its upper part that is mostly snow and glacier-fed and the lower part from Partab Bridge up to the Tarbela reservoir that is dominantly rain-fed area. This research focused on 2010 flood event that happened on 27-30th July. Ali et al., (2014) conclude that the rainfall event occurred from 27-30th July 2010 is one of the major extreme events in the history of Pakistan. Figure 7 representing the daily hydrograph, shows that Tarbela received high and very high flood peaks of 577,750 cusecs, 680,667 cusecs on 29th and 30th respectively. On the same date, at Tarbela up-stream at Partab Bridge, the recorded high flows were 316400 and 352075 cusecs.

The Tarbela sub-catchment is divided into two parts, glaciated and non-glaciated areas. The non-glaciated area, from Partab Bridge to Tarbela, was found with least glacier cover and therefore, rainfall was considered as a generic source of river discharge. According to Mukhopadhyay and Khan (2014), a significant amount of monsoonal rain falls near downstream catchment of the basin. In July 2010, 389 mm rainfall was recorded at Kakul rain gauge and 322 mm at Pattan rain gauge. The amounts of rainfall of these stations are higher than previous 30 years July normals. Figure 8 shows observed and normal rain fall of July 2010.The rainfalls recorded in Kakul and Pattan is were above normal that created the flooded condition in the rivers.

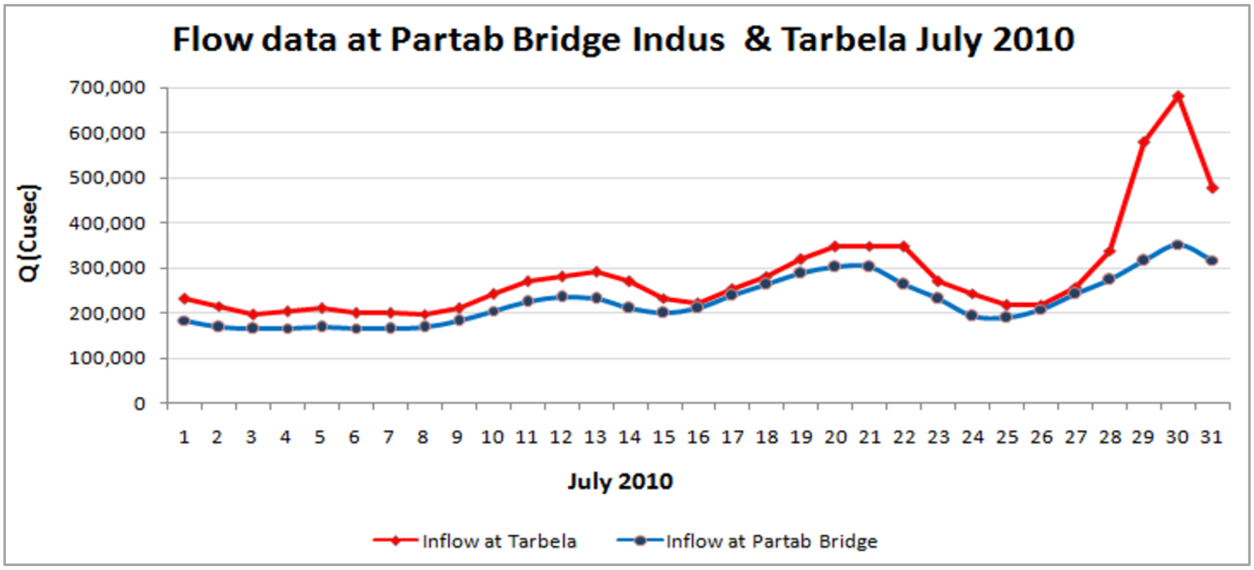


Figure 7: Daily Observed hydrograph at Partab Bridge and Tarbela.

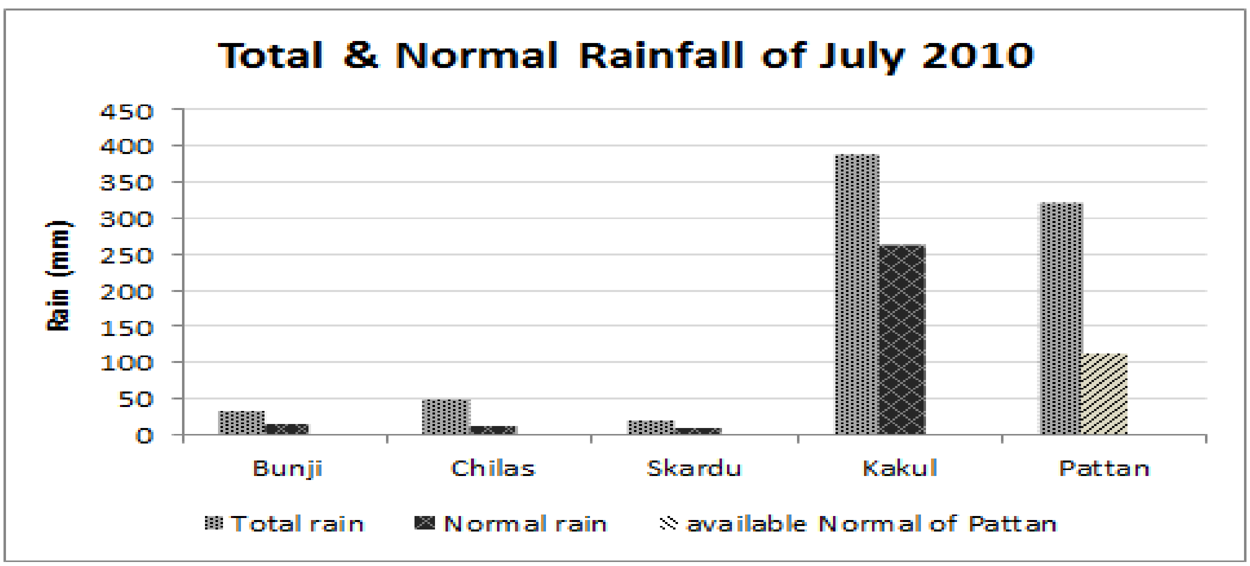


Figure 8: Total rain-fall received and normal rain in months of July.

Gridded Dataset

The gridded dataset ERA-Interim is used in HMS for runoff modeling. ERA-Interim is a global atmospheric reanalysis data, spatial resolution of data is approximately 80 km. ERA-Interim offer re-grided data at 0.125^{o} x 0.125^{o} resolution. The data set produced by European Centre for Medium-Range weather Forecast (ECMWF). Since we don't have observed data points of the upper parts of the study area, The runoff estimates, based on ERA-Interim precipitation agrees, reasonably well with the observed ones (Immerzeel et al., 2015). The temperature and precipitation are the main input to the model.

Runoff Model

This study presents the hydrological modeling of Tarbela sub-catchment. The HEC-HMS model was selected for runoff generation. The NRCS runoff curve number method was applied on the watershed. It is a useful method to empirically derive the relationship between rainfall, land covers and the physical properties of a catchment to calculate the discharge at its outlet. HMS offers different component, in meteorological component specified hyetograph and specified evapotranspiration method are selected to model the rainfall and evapotranspiration of a catchment. The Soil Conservation services (SCS) curve number and SCS unit hydrograph method were used as a sub-basin loss method and transform method respectively. The data limitation of this study is the insufficient information about the vegetation cover, surface cover and base flow of the watershed. Runoff routing is the process of predicting a spatio-temporal variation of a flood wave as it travels through a channel or stream. Several routing methods have been present in HMS. Muskingum a common method for channel routing was selected in this research. The meteorological component includes snow melt methods. HMS has two snow melt approaches, (1) Temperature melt index and (2) Gridded temperature index. The temperature melt index was selected for estimating the melt rate of watershed. Several researchers used temperature melt index for snowmelt runoff (M. Azmat 2015; Fazel, et al., 2014; Gyawli and Watkins 2012; Yilmaz et al. 2011).

Every hydrological model is based on mathematical equations for runoff calculation. In this study, the methodology used to calculate the surface runoff based on the following NRCS runoff equation (Eq. [1]).

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \dots\dots\dots\dots\dots\dots\dots.(1)$$

Equation (1) represents the relationship between accumulated rainfall and accumulated runoff.

The equation is based on the following assumptions;

Q= accumulated direct runoff (inches or mm)

P= accumulated rainfall (potential maximum runoff) (in. or mm) (24-hours rainfall depth versus frequency values)

I_a= initial abstraction including surface storage, interception, evaporation and infiltration prior to any runoff occurring (in. or mm)

S=potential maximum soil moisture retention after runoff begins (in. or mm)

Note: for P<= I_a, Q=0

Drainage area is divided into sub-basins because the, catchment is non-homogenous and rainfall is not uniformly distributed over the region. NRCS curve number method was used to compute the surface runoff. Initial abstraction and potential maximum retention generally correlated with the land cover and soil properties of the basin. In cases where accurate soil abstraction information is not available, the initial abstraction is usually approximated by the following empirical equation (Eq. 2).

$$I_a = 0.2S \qquad \dots\dots\dots\dots\dots\dots(2)$$

The observed and gridded data sets were used in the model to generate hydrographs. In the present study, the rainfall-runoff process was simulated on a daily basis for July 2010 flood event. Figure 9 Shows the conceptual model of HEC-HMS where the study area is divided into 22 sub-basins. As already discussed, the study area is also classified as glacier/snow covered area and glacier/snow free area. The hydrological response of both glaciers covered and glaciers free areas are different. Moreover, the extent of snow cover area changes with time because of the change in air temperature over the catchment. Such changes in the region influence the hydrological response of the catchment. It is noted, that the rainfall-generated runoff is dominant in glacier free areas. As the global warming persists, the runoff regimes become more rain dominated (Immerzeel et al., 2015). The rainfall-generated runoff is less dominant in the glaciated areas, especially the upper basin area.

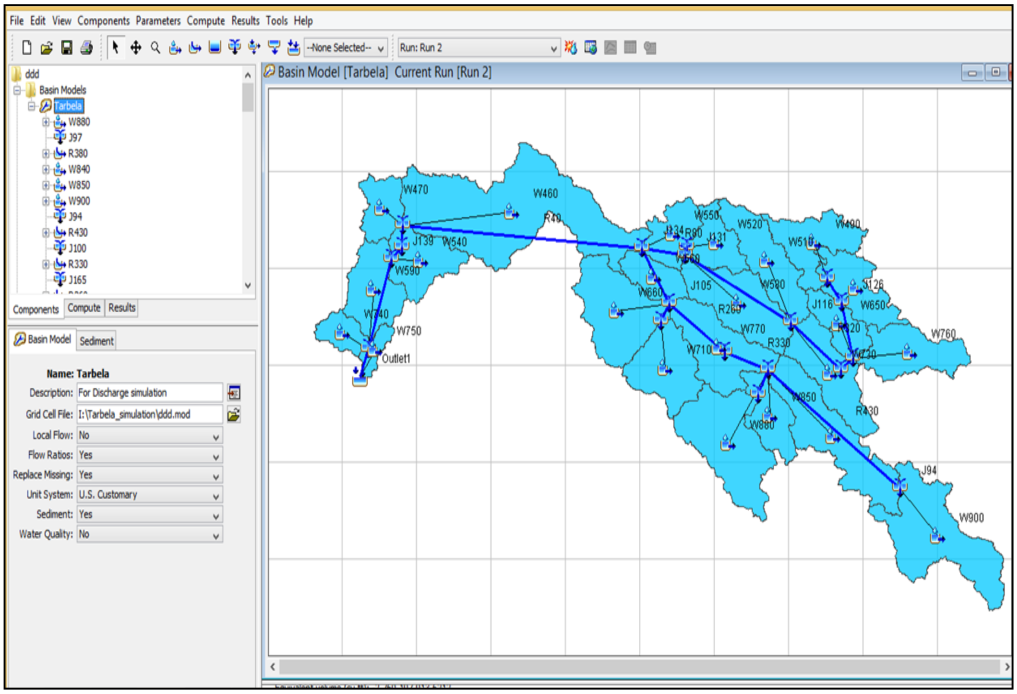
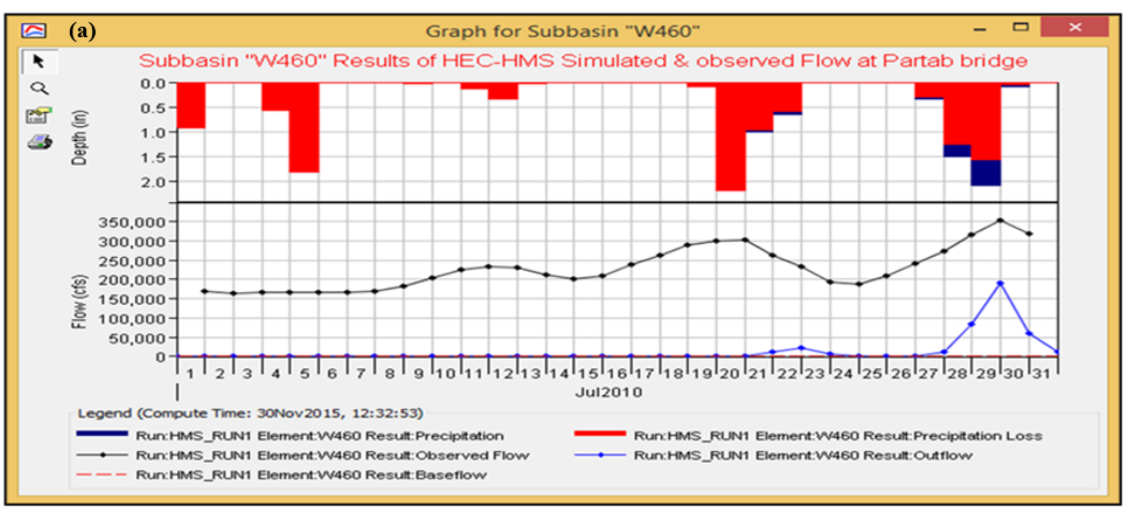


Figure 9: Conceptual HEC-HMS Model of Sub-basin Up-stream Tarbela Catchment.

The computed and the observed hydrograph at Partab Bridge and at Tarbela have been compared for July 2010 Figure 10. These graphs show weak agreement at Partab point and good agreement is shown at Tarbela outlet. A storm event that occurred in the last week of July simulated the rising and falling limb of the discharge peak that matched with the observed peak from 26th to 31th July when high rainfall was recorded in the lower part of the area. Different flooded peaks were recorded at Tarbela in the year 2010 flood. Main focus was on the first flood peak recorded from 27th to 31th July. The simulated hydrographs at the outlet of Partab and Tarbela due to rainfall recorded over the region.The glacial melt fraction is slightly greater than the snowmelt fraction at Partab Bridge (Mukhopadhyay and Khan, 2015). With the intensity of precipitation and the melting rate of glacier increased rapidly. Glacial melt waters from the Karakoram dominate the flows of the main Indus (K. Hewitt. 2005). Hydrograph dramatically varyied at Partab and Tarbela. In the lower part of the study area heavy rain with high intensities was observed. In the upper parts a significant amount of rainfall was recorded.



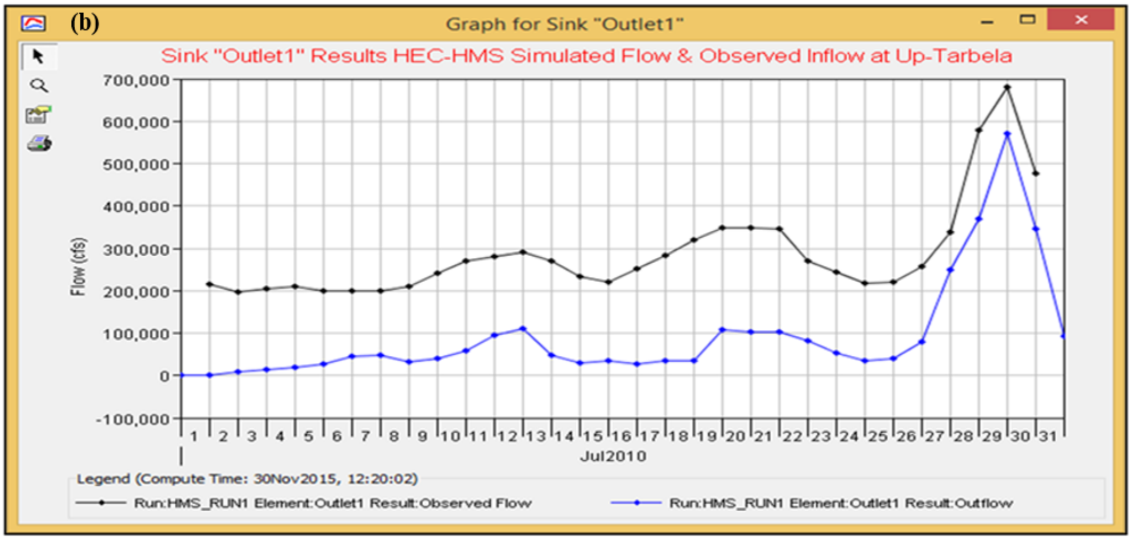


Figure 10: HMS simulated and observed hydrograph at Partab **(a)** and Tarbela **(b).**

It was found that the modeled results often varied dramatically between the observed curve and the simulated curve. For better results soil information at fine resolution is needed because soil and land cover modify the hydrograph characterstatics. HMS provided several methods for sub-basins loss and transformation methods but some of these methods are complex in un-gauged or sparely gauged watersheds because of high requirements of input parameters (M. Azmat 2015). The catchment above Partab is glacier covered, observed hydrograph is a mixture of glacier melting, snow melting and rainfall runoff. This suggests that the discharge at Partab is partially influenced by the glacier and snow melt. The simulated hydrograph is the resultant of rainfall runoff only. HMS does not incorporate the glacier and snow melting factor so the results are under estimated.

The catchment downstream of Partab has the least glacial and snow melt runoff before the storm, and therefore, it is likely that there is a maximum percentage of rainfall in the observed hydrographs. The magnitude of discharge varied between observed and simulated hydrographs, due to data limitations. The model outcomes are well compared at Tarbela from 27th to 31st July, according to simulated hydrograph at Partab and tarbela, efficiency of model was found within acceptable range.

Conclusion

HEC-HMS is a standard rainfall-runoff based model (M. Azmat, 2015). The upper part of study area is un-gauged, HMS model was run on poorly gauged catchment. The lower elevation part of the sub-catchment Tarbela was largely dominated by rainfall in the last week of July 2010. The results depict that the surface runoff received at Tarbela due to monsoon precipitation near downstream .The underestimated precipitation values can be a problem in high altitude sub-catchment (Winiger et al. 2005). The obtained results suggest that the HEC-HMS is a proper tool to estimate surface runoff from rainfall and can be applied in rain fed catchments. The model results are not satisfactory at Partab Bridge HEC-HMS which may be associated with slightly less efficiency of precise precipitation data and inaccurate soil information. However, the model depicts satisfactory result in the storm event occurred in last week of July 2010 at Tarbela. The model efficiency is rather low in glacier covered area. The Tarbela sub-catchment basin is complex since inflow at Tarbela consists of the contribution from rain, snow, glacier and base flow. The contribution of the lower part of the basin comes from the rainfall and the upper part inflow comes from a combination of snow and glacier melt.

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