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ACCURACY ASSESSMENT OF DIFFERENT MODELS USED IN WAPDA FOR FLOW FORECASTING IN DIFFERENT CATCHMENTS OF UIB

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By

Syed Hammad Ali[1] , Adeel Hassan & Wasim Khan

Abstract

Large Asian rivers heading in the Hindukush-Karakoram-Himalayan Mountains, and whose stream flow consist of considerable proportion of snow-melt and glacier-melt, may be highly vulnerable to climate warming and pattern changes. Millions of people depend on these stream flows for agriculture and power generation. Dependable forecasts of water availability are therefore required for batter planning under a changing climate. "All models are wrong, but some are useful". This famous George Box quote was first recorded in 1976 in the paper "Science and Statistics," published in the Journal of the American Statistical Association. It is usually considered to be applicable to not only statistical models, but to scientific models generally. This study presents the accuracy assessment of the different models (i.e. UBCWM, SRM+G and BJP and Statistical Model) used by various formations of WAPDA for the short term (10-daily) as well as long term (Seasonal (Kharif & Rabi)) flow forecasting for Indus at Tarbela, Jhelum at Mangla and Kabul at Nowshera. The study also provides the graphical representation/comparison of observed and forecasted flows of different models from April to September 2020 (Kharif) & October to March 2021(Rabi) which shows a very good relationship between observed and forecasted flows with exception of unexpected low flows. Model efficiency can be defined in term Nash-Sutcliffe efficiency (NSE) which is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance. The NSE values for all the models used in WAPDA are above 0.75 for all catchments for short term (10-daily) as well as for long term (Seasonal) forecasts. This implies that the all models imitates the main glacio-hydrological processes in these catchments using the ideal parameter sets with a rating of 'very good' on the scale of Moriasi et al. (2007). The study allows us to evaluate performance of different models in such basins and also useful for the improvement of modeling techniques and future prediction of flows and to define hydro-power potential and other water resource management.

Key words: Glacio-hydrological processes, UBCWM, SRM+G, BJP, Nash-Sutcliffe efficiency

1. Introduction

The Indus River ('The Father River') is one of the major rivers flowing through the Indian subcontinent. The river originates from Tibetan plateau in the vicinity of lake Mansarovar in the Tibet Autonomous Region of China and flows first to the northwest, turns southwest at Gilgit in Pakistan and then flows south and southwest through the country. The river has total basin area of 1,116,086 km^2, of which 555,450 km^2 lies within the HKH region (Bajracharya and Shrestha, 2011). The river has an estimated annual flow of around 207 km^3, the 21st highest in the world. The major Indus basin divided into three basins the Kabul, Upper Indus, and Panjnad. The

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upper Indus basin includes the Gilgit, Hunza, Shigar, Shyok, Zanskar, Shingo, Astor, and Uppar Indus sub-basins.

The economy of Pakistan is agriculture-based and highly reliant on the Indus irrigation system. The Indus River is the main source of water in Pakistan. In other words the sustainability of Pakistan's economy and food security is reliant on these water resources (snow and glaciers) of HKKH ranges and their management. Any change in these available water resources through climate variability, socio-economic factors or international policies will have a serious influence on food security and the environment in Pakistan (Tahir et. al. 2011). Therefore it is of paramount importance to study the snow and glacier and their impacts on the hydrologic regime of this Upper Indus region under climate variability to manage the available water resources.

2. Study Area

I. Indus River Basin:

The transboundary Indus river basin has a total area of 1.12 million km^2 distributed between Pakistan (47%), India (39%), China (8%) and Afghanistan (6%). The Indus river basin stretches from the Himalayan Mountains in the north to the dry alluvial plains of Sindh province in Pakistan in the south and finally flows out into the Arabian Sea. In Pakistan, the Indus river basin covers around 520,000 km², or 65% of the territory, comprises the whole of the provinces of Punjab and Khyber Pakhtunkhwa and most of the territory of Sindh province and the eastern part of Balochistan. Tarbela is the first controlling storage on the River Indus and most of the annual Upper Indus River influx stored at Tarbela is derived from the snow and glacier melt in Hindu Kush-Karakoram-Himalaya (HKKH) ranges. This stored water is then supplied to the downstream irrigated lands through a network of barrages, canals and small watercourses. The Tarbela watershed is located between latitudes 34° to 35°12'N and longitudes 72° 07' to 73°40' E. The elevation of this catchment varies from 364m to 7,970 m above mean sea level (a.m.s.l) as shown in figure 1.

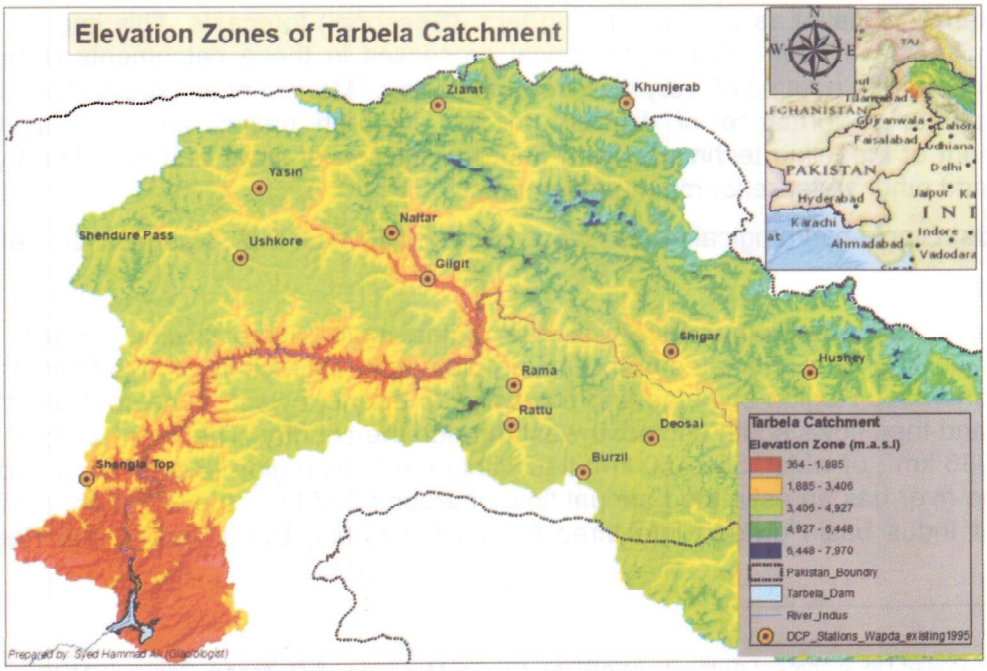


Figure-1: Map of Tarbela Catchment (along with GMRC Stations)

II. Jhelum River Basin:

The Jhelum River originates in the Kashmir Valley, about 54 km east of Anant Nag, and is 816 km long with a catchment area of 39,200 km^2. The river has ten major tributaries, including Neelum/Kishan Ganga (the largest tributary, is 260 km long with a catchment area of 3,968 km^2), Kunhar, Poonch and Kanshi. The Mangla watershed is located between latitudes 33° to 35°12'N and longitudes 73°07' to 75°40' E. The elevation of this catchment varies from 300m to 6,282 m above mean sea level as shown in figure 2. About 55% of the catchment area lies in Indian held Kashmir and 45% lies in Pakistan including Azad Kashmir.

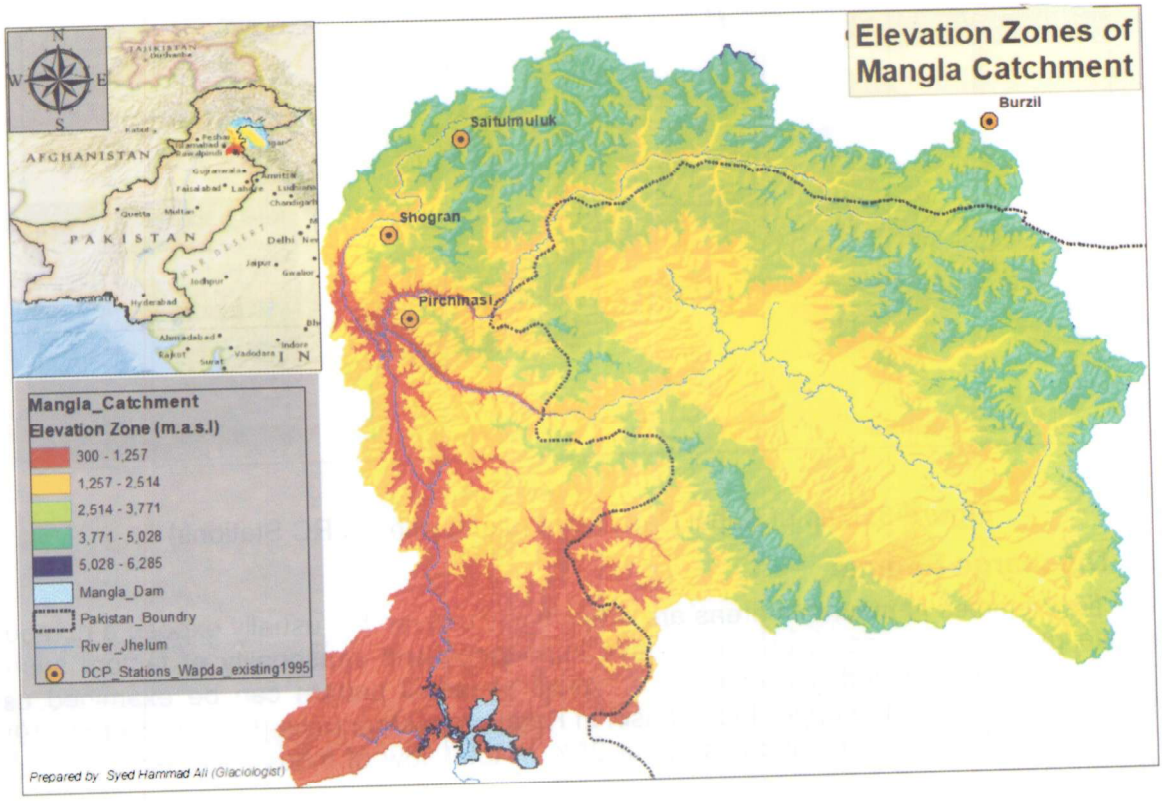


Figure-2: Map of Mangla Catchment (along with GMRC Stations)

III. Kabul River Basin:

Kabul River Basin (KRB) is an important water resource in the Khyber Pakhtunkhwa province of Pakistan and a major contributor to Afghanistan's freshwater needs. Geographically the Kabul River is located in the northwestern region of Pakistan. For many decades; it has been providing water for multi-purpose uses such as power generation, irrigation, industries and for domestic usage. About 45% of the total catchment area fall in the Pakistan territory and rest 55% is a fall in Afghanistan. Kabul River Basin drains an area of 90,919 km^2 into River Indus at its confluence near Kund, district Nowshera, Khyber Pakhtunkhwa. Chitral, Kunar, Kabul and Swat rivers are the major tributaries of Kabul River. The elevation of this catchment varies from 300m to 6,285 m above mean sea level as shown in figure 3.

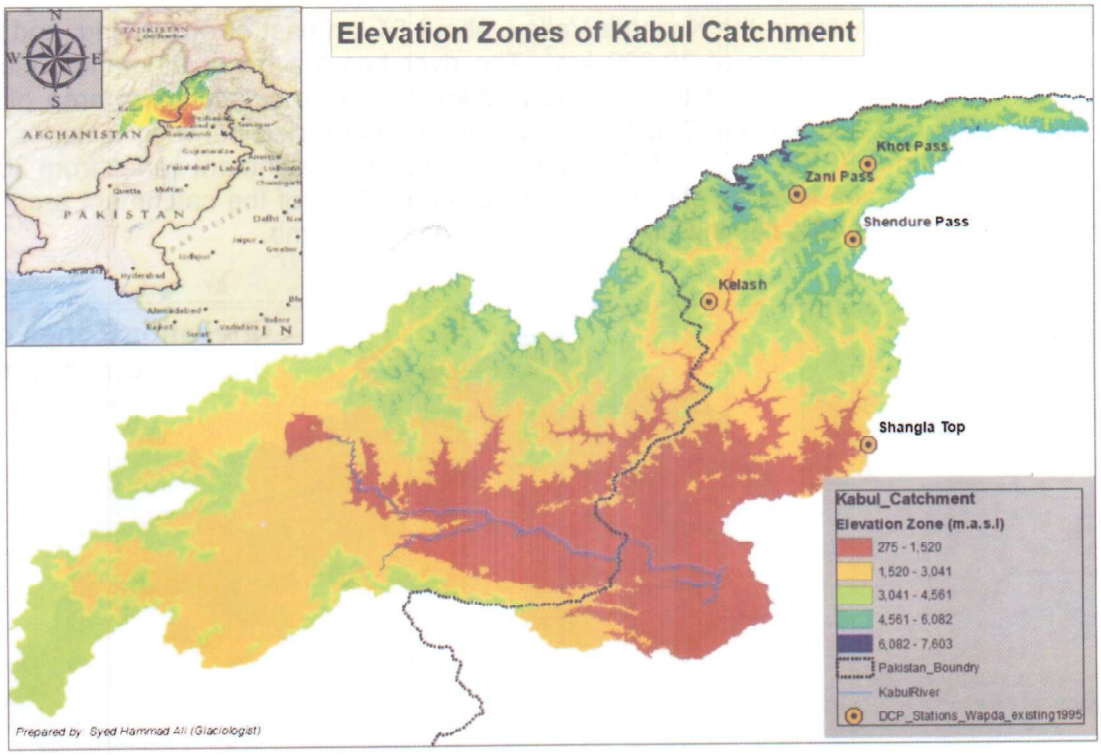


Figure-3: Map of Kabul Catchment (along with GMRC Stations)

3. Discharge Regime

Stream flow regimes in mountain areas are often highly uneven but usually expose a number of distinctive patterns depending on the relative importance and seasonality of factors such as precipitation, snowmelt and glacier melt. A typical seasonal pattern can be examined using stream flow regimes for the upper Indus basin in Karakoram Mountains (Ferguson et al., 1984). The Karakoram Mountains contributes about 25% of total flow of Indus from about 15% of its catchment area.

Discharge starts to increase in March at the lower stations as snowmelt commences but not until May and June in upper Indus. Between 40% - 70% of total runoff is in July and August, when discharges are between 15 to 40 times those in March (WAPDA, 1979). Genetic components of stream flow for the Hindu Kush Karakoram, Pamir and Tien Shan mountains have been established by (Dreyer et al., 1982). The method is based on regular changes in stream flow structure during the year. Rivers are fed by groundwater from November to February. Snowmelt begins in the lower parts of basin in March, and groundwater discharge increase to maximum in July – August, until September Rivers are fed by groundwater, ice melt, snowmelt and precipitation. Snowmelt ceases by October in high mountains and rivers are fed solely by groundwater. In low mountain areas the hydrograph is occasionally complicated by one or two day rain floods.

4. Glacio-Hydrological Modelling

Modelling is the concept or explanation of real world or reduction of intricacy. It helps in decision or policy making with sufficient accuracy. Furthermore, glacio-hydrological models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding glacier dynamics and hydrologic processes.

5. Types of Glacio-Hydrological Models

Glacier component is added in the hydrological modelling in order to estimate the discharge from glacierized basin. Following are the different types of glacio-hydrological models:

I. Simple/lumped/black box or empirical

In simple model you provide the input data and the model gives the output and you really do not get the information regarding the processes that are going on. In these models you need lesser amounts of input data and it takes a basin as a single object. Parameters of Lumped hydrologic models do not vary spatially within the basin and thus, basin response is assessed only at the outlet, without clearly accounting for the response of individual sub basins. The most commonly active procedure is area weighted average (Haan et al., 1982). The representation of hydrologic process in lumped hydrologic models is usually very simplified however they can often lead to satisfactory results, especially if the interest is in the discharge prediction only. Examples of lumped models are Rainfall runoff model, Positive Degree Day Model etc.

II. Semi distributed/grey box or conceptual

These models integrate the concept of the natural processes occurring in the nature. In this model basin is divided into numbers of units. This type of model is widely used. There are further two main types of semi-distributed model: a) Kinematic wave theory models (KW models), such as Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS), and b) probability distributed models (PD models, such as TOPMODEL). The KW models are simplified versions of the surface and/or sub-surface flow equation of physically based hydrologic models. In the PD models spatial resolution is accounted for by using probability distributions of input parameters across the basin. The main advantage of semi-distributed model is that their structure is more physically based than the structure of the lumped models, and that they are less demanding on input data than the fully distributed models. Some of this type of model is HBV-96 (HydrologiskaByransVattenbalansavedelning), HEC-HMS, Hydrocomp Forecast and Analysis Modelling (HFAM), Soil and Water assessment Tool (SWAT), SWMM (Storm Water Management Model), TOPMODEL, University of British Columbia Watershed Model (UBCWM), Snowmelt Runoff Model (SRM) and etc.

III. Fully distributed/ white box/ process oriented

These models are process oriented and physically based. Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modelling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation- runoff behaviors. Distributed models generally require large amount of (often unavailable) data for parameterization in each grid cell. However, the governing physical process are modelled in detail, and if properly applied, they can provide the highest degree of accuracy. TOPKAPI, Waterloo Hydrological and Flood Forecasting System (WATFLOOD) etc are some examples of distributed model.

6. Existing Flow Forecasting Procedures in Pakistan

Water and Power Development Authority (WAPDA), Indus River System Authority (IRSA) and Punjab Irrigation Department (PID) are involved in generating flow forecasts at rim stations. In this study the procedures developed by these organizations were reviewed and are described below.

I. Flow Forecasting by WAPDA

WAPDA serves as a technical member to IRSA and develops flow forecasts for the Indus River and its tributaries including Kabul River at RIM stations on seasonal as well as short term (10-

Daily) basis. While Water Resources Management Directorate (WRMD) of WAPDA uses traditional statistical method for developing seasonal flow forecasts, Glacier Monitoring Research Centre (GMRC) (previously Snow and Ice Hydrology Project) of WAPDA uses deterministic approach and employs University of British Columbia (UBC) Watershed Model with quasi real time weather data obtained from high altitude automatic weather data collection and transmitting network, installed in Upper Indus Basin, for developing seasonal as well as short term (10- daily) flow forecasts for Indus at Tarbela, Jhelum at Mangla and Kabul at Nowshera. The methodology of flow forecasting adopted by various formations of WAPDA is given in following paragraphs.

a) Water Resources Management Directorate (WRMD)

WRMD of WAPDA carries out seasonal (Rabi and Kharif) flow forecasts for Indus at Tarbela, Jhelum at Mangla, Chenab at Marala and Kabul at Nowshera. It has got more than 60 years record of observed mean daily flows at these gauging stations. Premises of flow forecast is that in any of the Upper Indus basin (UIB) rivers Rabi flows are indicators of the following Kharif flows and Kharif flows are indicators of the following Rabi flows. Therefore, a statistical method has been developed to forecast Kharif flows by looking at historic Rabi flows and vice versa. For instance, for forecasting Kharif flow volumes of Kabul at Nowshera, WRMD calculates latest Rabi (October – March) flows volume and looks for the years in the historic record when this amount of volumes, within 5 to 10 percent variations, occurred in Rabi. For the selected years, Kharif flows that followed the matching Rabi flow volumes with selected variations are considered. The volumes of Kharif flows for such years are calculated thus creating an ensemble of Kharif flow volumes. Average of the ensemble is used as the forecasted flow volume for Kharif season. Selection of variation is debated and qualitative weather forecast from Pakistan Meteorological Department for UIB is also considered for arriving at final percentage of variation. The selected volume for the season is distributed to 10-daily flows from the probability tables, prepared on seasonal basis every year through statistical analysis of 10-daily observed flow data.

b) Glacier Monitoring Research Centre (GMRC)

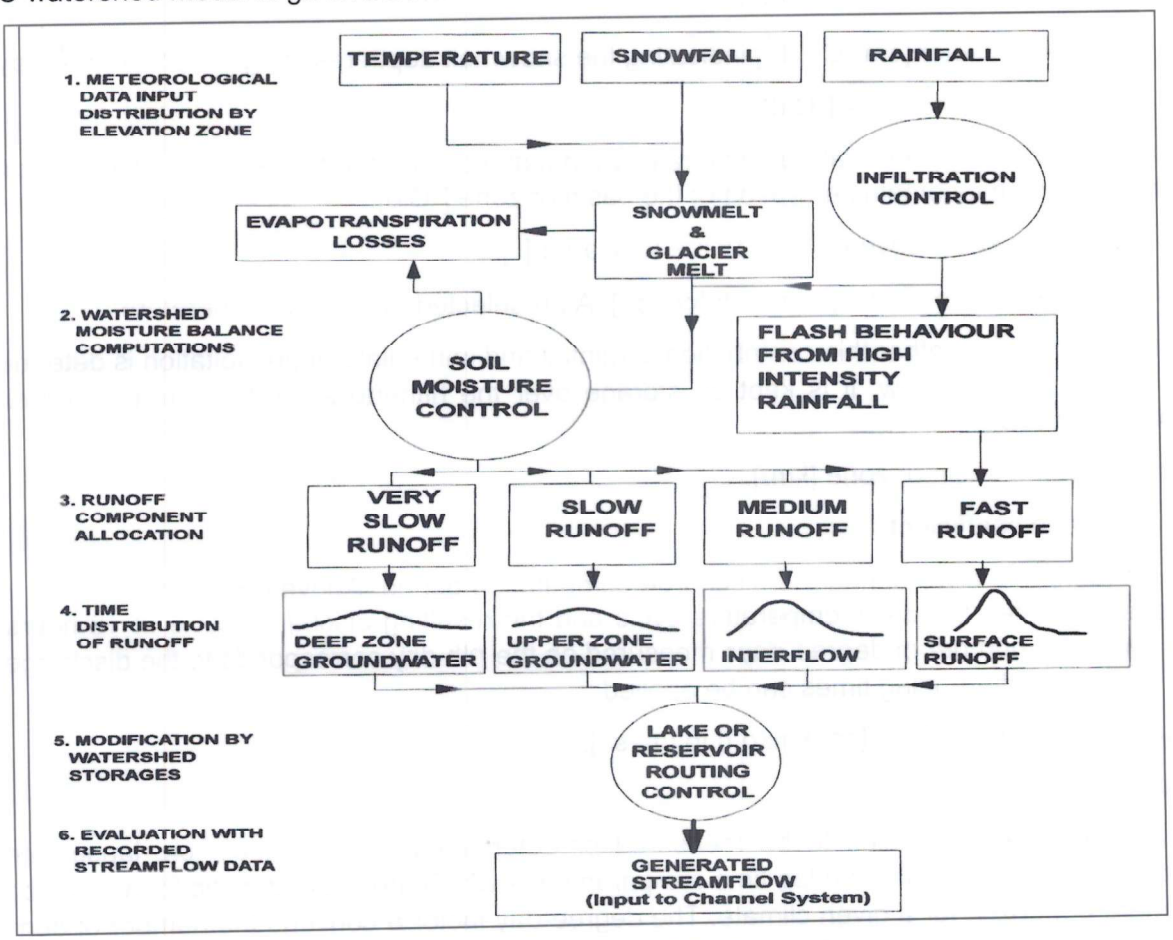
Glacier Monitoring Research Centre (GMRC) of WAPDA prepares and issues seasonal as well as short-term (10-daily) flow volume forecasts for River Jhelum at Mangla, River Indus at Tarbela and River Kabul at Nowshera. GMRC employs University of British Columbia (UBC) Watershed model (since 2000), BJP and SRM+G (recently added (2020)) and uses weather data from 20 high altitude automatic weather recording and transmitting stations network for flow forecasting of all the aforementioned three rivers.

i. University of British Columbia (UBC) Watershed Model:

UBC Watershed Model (UBCWM) is a deterministic semi lumped hydrologic model developed by University of British Columbia Vancouver Canada for mountainous regions. It requires daily values of maximum and minimum temperatures and precipitation as an input to generate daily hydrograph. Discharge data is required for the purpose of comparison; calibration and validation of the model. UBCWSM uses energy budget method for melting of snow and uses variable melt rates as the melt season progresses. It also considers the change in albedo (reflectivity of sunlight) over the aging snow and hence melts rates accordingly. Whereas snow cover is considered as dynamic in UBCWSM, glacier is taken as a static body of frozen water with high melt rates.

For flow forecasting UBCWSM considers antecedent watershed conditions i.e. amount of snow present at different altitudes in the catchment, its cold content, catchment saturation etc. In forecasting mode, the calibrated and validated Model is primed by running the model with the

latest one-year hydro-climatic data and setting the start and end forecasting dates. In absence of weather data for forecasting period the primed Model is subjected to historic weather observed at the selected stations used in the calibration, validation and priming process by using batch program. In this process, the present antecedent watershed conditions of the catchment are subjected to the weather conditions that occurred in historic years. For example, to generate 2018 Kharif flow forecasts for River Indus at Tarbela the primed model (October – 30 March 2018) for the Indus basin will be subjected to historic weather conditions occurred during forecasting period (1 April – 30 September) of different years say 1991, 1992 1993.... 2017 one after the other. Each weather year will generate a hydrograph that will include present watershed conditions subjected to that year weather conditions and will be designated as the water scenario corresponding to that year. Individual volumes of all such scenarios thus generated are worked out and 90th percentile, average, and 10th percentile of scenarios are reported as minimum, average and maximum expected forecast values. The Flow Diagram of UBC watershed model is given below.



Flow Diagram of UBCWM

ii. Snowmelt Runoff Model + Glacier (SRM+G)

This model is a further development of the snowmelt runoff model (SRM) and can calculate the glacial melt (G) as well (Schaper et al. 1999). The model is tested in several basins and found high accuracy even in basins with 67% glaciated areas on three alpine basins Rhine-Felsberg, Rhône-Sion and Ticino-Bellinzona in Switzerland (Schaper and Seidel, 2000). The accuracy of runoff modelling in high alpine basins is considerably improved by evaluating separately the

snow coverage over glaciers and over glacier-free areas of each elevation zone. This approach takes into account the specific melt factors of glacier and the actual elevation of glaciers within the respective elevation zones. Each day, the water produced from snowmelt and from rainfall is computed, superimposed onthe calculated recession flow and transformed into daily discharge from the basin according to the equation given below:

$$Q_{n+1} = \left[c_{Sn}\ a_n (T_n + \Delta T_n) S_n + c_{Rn} P_n\right] \frac{10000}{86400} A (1 - k_{n+1}) + Q_n k_{n+1}$$

where:

Q = daily discharge [m^3/s].

c = runoff coefficients [-] expressing the losses as a ratio (runoff/precipitation), with

c_S referring to snowmelt and c_R to rain.

a = degree-day factor [cm $°C^{-1}$ d^{-1}] indicating the snowmelt depth resulting from 1 degree-day.

T = number of degree-days [°C d].

ΔT = adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone [°C d].

S = ratio of the snow-covered area to the total area [-].

P = precipitation contributing to runoff [cm d_{-1}]. A preselected threshold temperature,

T_{Crit}, determines whether this contribution is rainfall and immediate. If precipitation is determined by T_{Crit} to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur.

A = area of the basin or zone [km_2].

k = recession coefficient

n = sequence of days during the discharge computation period. Above equation is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the nth day corresponds to the discharge on the n+1 day. Different lag times can be applied.

$\frac{86400}{1\ 0000}$ = conversion from [cm·km_2 d_{-1}] to [m_3 s_{-1}].

T, S, and P are variables to be measured or determined each day, c_S, c_R, lapse rate to determine ΔT, T_{Crit}, k and the lag time are parameters which are characteristic for a given basin or, more generally, for a given climate. The degree-day factor a converts the number of degree-days into the daily snowmelt depth.

Apart from the improvement of the runoff modelling, the independent computation of glacier melt is an important step towards evaluations of glacier behavior with regard to global warming.

To illustrate the procedure, the modified SRM formula can be arranged as follows:

$$Q_{n+1} = Q_n k_{n+1} + (1 - k_{n+1}) \sum_{i=1}^{ri} (\text{Qrain,n,i} + \text{Qnewsnow,n,i} + \text{Qsnowmelt,n,i} + \text{Qglaciermelt,n,i})$$

$$\text{Qrain,n,i} = A_{total,i}\ c_r P_r \left(\frac{10000}{86400}\right)$$

$$\text{Qnewsnow,n,i} = A_{total,i}\ c_s a_{n,i} T_i (1 - S_{total,i}) \left(\frac{10000}{86400}\right)$$

$$\text{Qsnowmelt,n,i} \quad A_{nogal,i}\ c_s a_{n,i} T_i (S_{nogal,i}) + A_{gl,i}\ c_s a_{n,i} T_i (S_{gl,i}) \left(\frac{10000}{86400}\right)$$

$$\text{Qglaciermelt,n,i} \quad A_{gal,i}\ c_{gl} a_{n,i} T_i (1 - S_{gal,i}) \left(\frac{10000}{86400}\right)$$

Most of the parameters are same as SRM as explained above except the glacier related parameters which are newly incorporated, namely:

a_g = Degree-day factor for glacier [cm °C^{-1} d^{-1}].

S_{gal} = ratio of the glacier exposed area to the total area [-].

A_{gal} = Glacier exposed area or zone [km^2].

A_{nogal} = Snow covered area or zone [km^2].

The model having the extension of the specific glacier module is named SRM+G.

SRM+G can be used for the following purposes:

Simulation of daily flows in a snowmelt season, in a year, or in a sequence of years the results can be compared with the measured runoff in order to assess the performance of the model and to verify the values of the model parameters. Simulations can also serve to evaluate runoff patterns in un-gauged basins using satellite monitoring of snow-covered areas and extrapolation of temperatures and precipitation from nearby stations. Short term and seasonal runoff forecasts the computer program SRM+G includes a derivation of modified depletion curves which relate the snow-covered areas to the cumulative snowmelt depths as computed by SRM. These curves enable the snow coverage to be extrapolated several days ahead by temperature forecasts so that this input variable is available for discharge forecasts. The modified depletion curves can also be used to evaluate the snow reserves for seasonal runoff forecasts. The model performance may deteriorate if the forecasted air temperature and precipitation deviate from the observed values, but the inaccuracies can be reduced by periodic updating.

iii. Bayesian Joint Probability Forecast Modeling Approach (BJP)

BJP is a statistical modeling method for generating ensemble stream flow forecasts. The centerpiece of BJP is a transformed multivariate normal distribution model, which describes the multidimensional relationships between climate and hydrological variables. The parameters of the model are inferred from historical data using robust Bayesian methods designed to work in a wide range of environments (Schepen et. al. 2018). As a forecasting model, BJP generates a forecast distribution for future variables (i.e. predictands) conditional on known values of the other variables (predictors). BJP typically produces very reliable ensemble forecasts that accurately convey forecast uncertainty in ensemble spread (Bennett et. al 2017).

The general steps of the approach are:

- Transform each variable using a normalizing transformation
- Fit a multivariate normal distribution model to describe the relationships between variables using Bayesian inference and historical data

- Create a predictive forecast distribution by conditioning the multivariate normal distribution model on known values of transformed predictors
- Randomly sample ensemble members from the predictive forecast distribution
- Back-transform to obtain forecasts in the original data units.

More formally, denote the set of variables to be modeled as the random vector $y = (y_1, y_2, y_3, \ldots, y_n)$. Each y_i may be classed as either a predictor variable or as a predictand variable and placed in the subset y_1 or y_2, respectively. The first step in BJP is to transform each variable so that the data are approximately normally distributed and the variance can be assumed to be constant. The resulting ith transformed variable is $z_i = \Psi_i (y_i \mid \Delta_i)$ where Ψ_i denotes a normalizing transformation function with transformation parameters Δ_i.

The two parameters log-sinh transformation is used to transform hydrological variables with a zero bound such as streamflow and precipitation:

$$\Psi_{LS}(y) = \frac{1}{\lambda}\log(\sinh(\varepsilon + \lambda y))$$

The single parameter Yeo-Johnson transformation is used to transform other variables that are not bounded at zero:

$$\Psi_{YJ}(y) = \begin{cases} ((y+1)^{\lambda} - 1)/\lambda & \lambda \neq 0, y \geq 0 \\ \log(y+1) & \lambda = 0, y \geq 0 \\ -[(-y+1)^{2-\lambda} - 1]/(2-\lambda) & \lambda \neq 2, y < 0 \\ -\log(-y+1) & \lambda = 2, y < 0 \end{cases}$$

A point estimate of the transformation parameters is obtained by finding the parameter set that maximizes the Bayesian posterior distribution. Next, it is assumed that the transformed variables follow a multivariate normal joint distribution

$$z \backsim N(\mu, \Sigma)$$

where $\boldsymbol{\mu}$ and $\boldsymbol{\Sigma}$ are the mean vector and covariance matrix respectively and $\boldsymbol{\theta}$ the set of parameters $\boldsymbol{\theta} = \{\boldsymbol{\mu}, \boldsymbol{\Sigma}\}$. The multivariate normal distribution applies to continuous variables. Rainfall and streamflow data cannot always be considered to be continuous variables because they are bounded at zero. This may result in a mixed discrete-continuous distribution with a discrete point mass at zero and continuous distribution for non-zero values. To model data with a discrete-continuous distribution using a continuous multivariate normal distribution we treat data that take values of the bound (z_c) as censored data. This treatment assumes the censored values have a value that is less than the censor threshold (z_c) with an unknown precise value (Wang and Robertson, 2011).

Bayesian inference is used to find the posterior distribution of the model parameters

$$p(\theta \mid D) \propto p(\theta)\, p(D \mid \theta)$$

where **D** is a data matrix for all variables and **T** events, $\mathbf{p}(\boldsymbol{\theta})$ is the prior distribution of the parameters, and $p(D \mid \theta)$ is the likelihood. By setting an appropriate prior distribution, it is possible to formulate Gibbs sampling to numerically sample $p(D \mid \theta)$. Once representative parameter samples are available, the BJP model can be used in predictive mode. The posterior predictive distribution of the predictand variables subset z_2 is given by

$$f(z_2) = \int p(z_2 | z_1 \theta) p(\theta | D) d\theta$$

where z_1 is the subset of predictor variables. Again, Gibbs sampling can be formulated to numerically sample $f(z_2)$. By back-transforming each of the sample members, a calibrated ensemble forecast of y_2 is produced. The data transformation and joint probability modelling methods are available as R and Python packages and the R implementations have been used in this study.

II. Indus River System Authority (IRSA)

Indus River System Authority (IRSA) deploys the same statistical forecasting procedure as adopted by Water Resources Management Directorate (WRMD). Further, IRSA got developed flow forecasting model of Upper Indus at Tarbela using SRM+G model. The model was developed by NESPAK-AHT (2015). The model incorporates the glacier melts along with flows generated through snow melt.

III. Punjab Irrigation Department (PID)

PID also uses statistical flow forecasting, similar to WRMD of WAPDA for defending their water availability case with IRSA as per Water Apportionment Accord of 1991. Recently, NESPAK-AHT has also developed an SRM+G model for Chenab River at Marala for Kharif season only.

7. Assessment of Model Accuracy

Reliability refers to the statistical similarity between the forecast probabilities and the relative frequencies of events in the observations. The World Meteorological Organization (WMO 1986) carried out a comprehensive comparison of snowmelt runoff models in 6 selected test basins and published the accuracy of the models applying the following error norms:

I. Nash-Sutcliffe coefficient (NSE)

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). NSE = 1, corresponds to a perfect match of the model to the observed data. NSE = 0, indicates that the model predictions are as accurate as the mean of the observed data, Inf < NSE < 0, indicates that the observed mean is a better predictor than the model. The Nash-Sutcliffe coefficient is computed using equation.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2)}{\sum_{i=1}^{n}(Q_i - Q_i'')^2)}$$

where,

Q_i is measured daily discharge;

Q'_i is computed daily discharge;

Q'' is average daily discharge for the Simulation period; and n is number of daily discharge values.

II. Volume Difference (VD)

The smaller value of VD shows the better model results. The volume difference, VD, is computed using following equation.

$$VD[\%] = \frac{V_R \quad V_R'}{V_R} * 100$$

Where

V_R is measured runoff volume;

$V_{R'}$ is simulated runoff volume.

8. Comparison of Forecast by different Models

Followings are the results of the forecasts (10-daily and seasonal) generated using different models for Indus at Tarbela, Jhelum at Mangla and Kabul at Nowshera for the period of April to September 2020 (Kharif Season) and October 2020 to March 2021 (Rabi Season).

i. Indus at Tarbela:

c) 10-Daily Forecast:

The SRM+G model has not been developed for 10-daily forecast for Indus at Tarbela. The results of the other models for 10-daily and Seasonal forecasts are as follows. The NSE values for the average 10-daily forecast are 0.95, 0.98 and 0.94 for BJP, UBC and WRMD respectively. The values for Volume difference are 6.99, 2.02 and 11.49 for BJP, UBC and WRMD respectively.

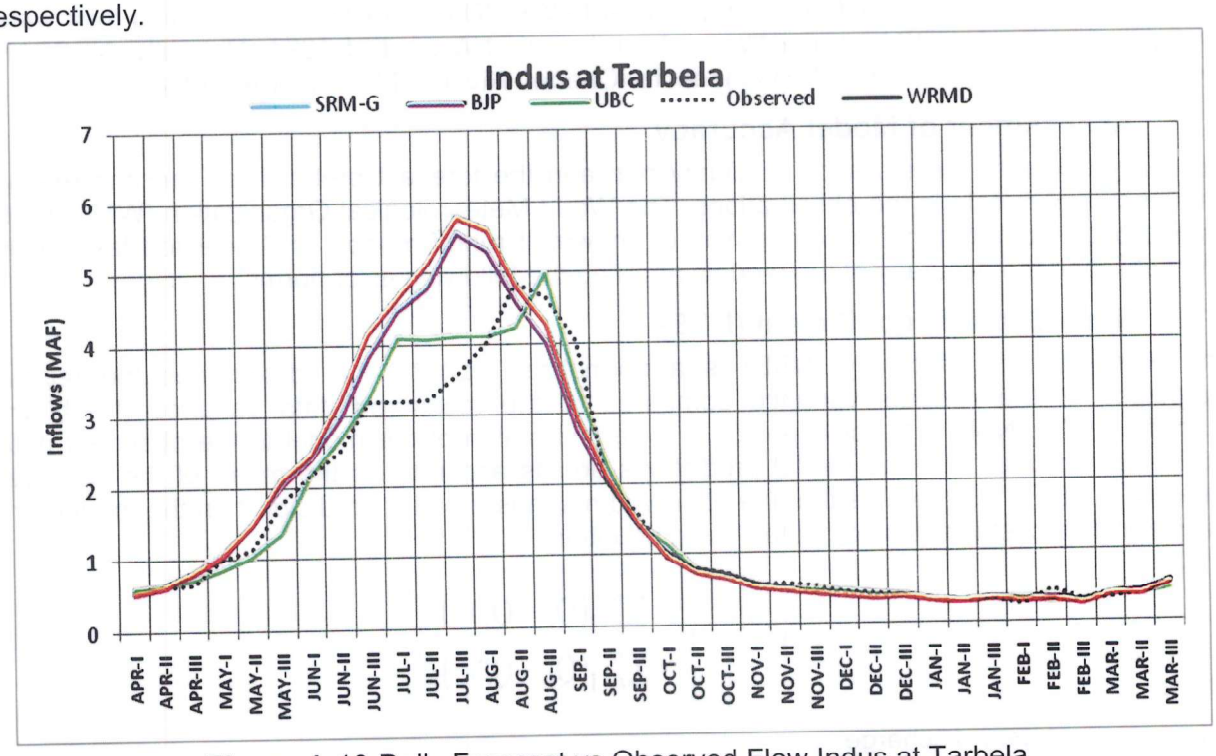


Figure-4: 10-Daily Forecast vs Observed Flow Indus at Tarbela

d) Seasonal Forecast:

On the other hand the NSE values for the Seasonal forecasts are 0.98, 0.98, 0.95 and 0.96 for BJP, SRM+G, UBC and WRMD respectively. The values for Volume difference are 7.69, 12.49, 12.30 and 11.28 for BJP, SRM+G, UBC and WRMD respectively.

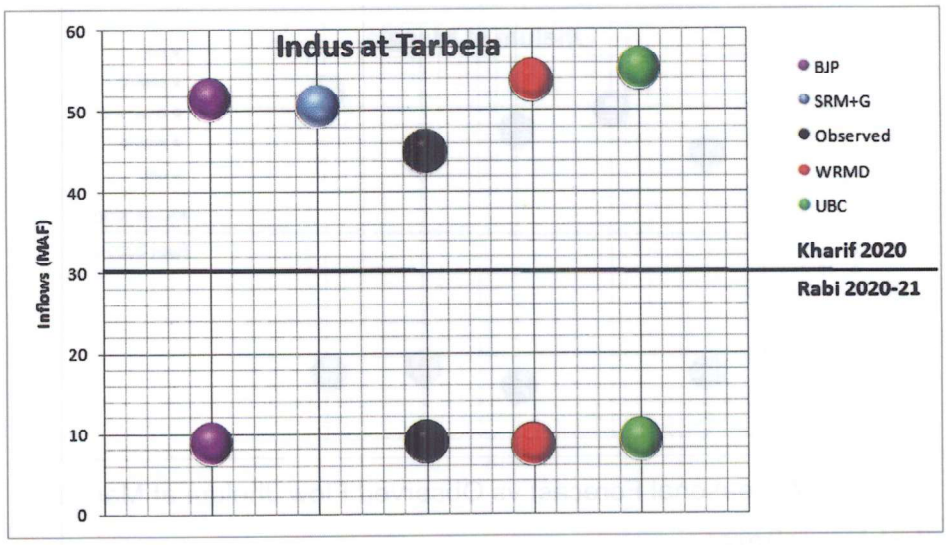


Figure-5: Seasonal Forecast vs Observed Flow Indus at Tarbela

ii. Jhelum at Mangla:

e) 10-Daily Forecast:

The SRM+G model has not been developed for 10-daily forecast for Jhelum at Mangla. The results of the other models for 10-daily and Kharif Season 2020 are as follows. The NSE values for the average 10-daily forecast are 0.86, 0.90 and 0.79 for BJP, UBC and WRMD respectively. The values for Volume difference are 15.63, 9.92 and 8.98 for BJP, UBC and WRMD respectively as shown in figure 6.

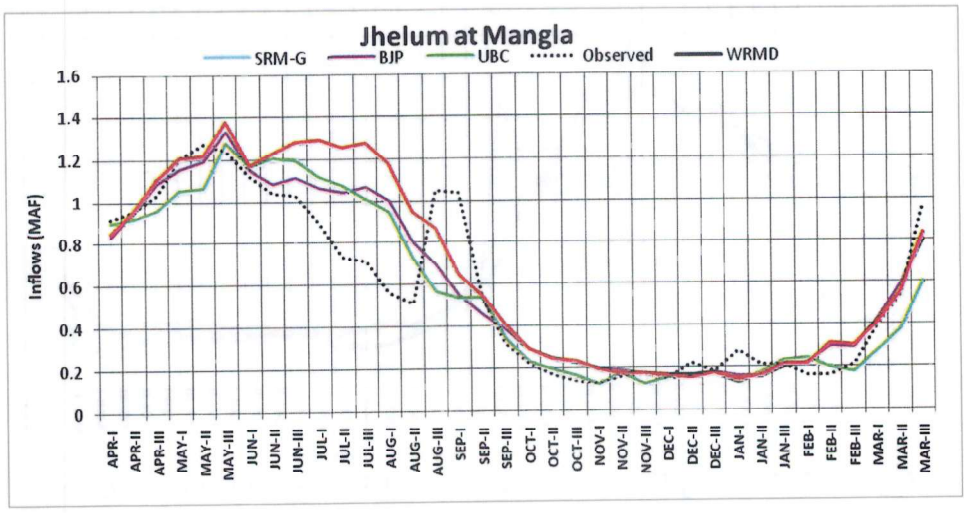


Figure-6: 10-Daily Forecast vs Observed Flow Jhelum at Mangla

f) Seasonal Forecast:

On the other hand the NSE values for the Seasonal forecasts are 1.00, 1.00, 0.92 and 0.97 for BJP, SRM+G, UBC and WRMD respectively. The values for Volume difference are 9.20, 0.19, 14.84 and 10.39 for BJP, SRM+G, UBC and WRMD respectively.

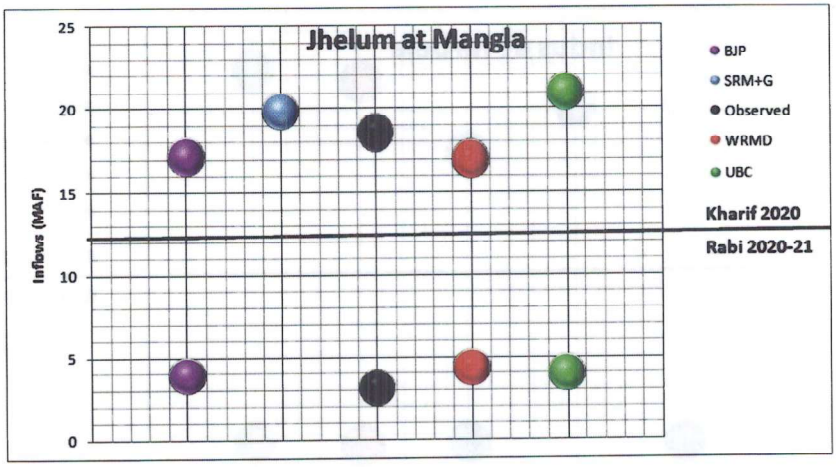


Figure-7: Seasonal Forecast vs Observed Flow Jhelum at Mangla

iii. Kabul at Nowshera:

b) 10-Daily Forecast:

The SRM+G model also developed for 10-daily forecast for Kabul at Nowshera. The results of all the models for 10-daily and Seasonal forecasts are as follows. The NSE values for the average 10-daily forecast are 0.92, 0.87, 0.92 and 0.77 for SRM+G, BJP, UBC and WRMD respectively. The values for Volume difference are 7.27, 16.62, 2.96 and 18.50 for SRM+G, BJP, UBC and WRMD respectively.

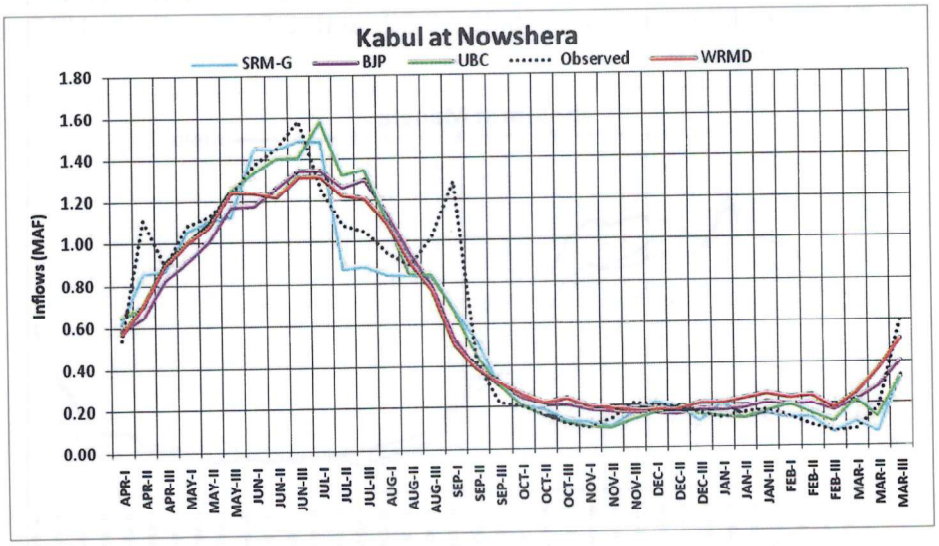


Figure-8: 10-Daily Forecast vs Observed Flow Kabul at Nowshera

h) Seasonal Forecast:

On the other hand the NSE values for the Seasonal forecasts are 0.97, 0.95, 0.95 and 0.92 for BJP, SRM+G, UBC and WRMD respectively. The values for Volume difference are 16.02, 19.05, 20.56 and 23.55 for BJP, SRM+G, UBC and WRMD respectively as shown in figure 9.

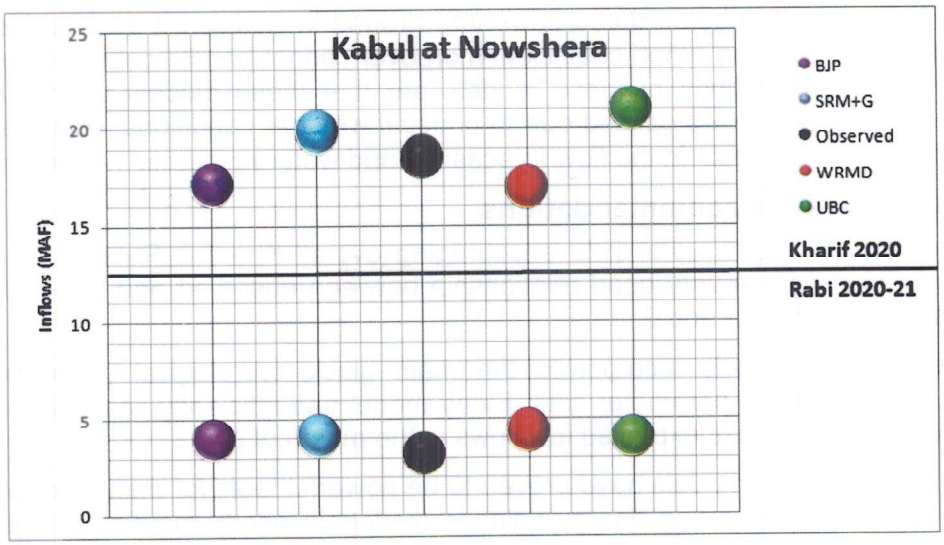


Figure-9: Seasonal Forecast vs Observed Flow Kabul at Nowshera

Accuracy of Different Models for Kharif Season 2020												
Model	Indus at Tarbela				Jhelum at Mangla				Kabul at Nowshera			
	Average 10-Daily		Kharif Season		Average 10-Daily		Kharif Season		Average 10-Daily		Kharif Season	
	NSE	VD	NSE	VD	NSE	VD	NSE	VD	NSE	VD	NSE	VD
BJP	0.92	13.83	0.98	14.40	0.88	2.32	1.00	6.60	0.94	7.03	0.99	7.51
SRM+G	--	--	0.98	12.49	--	--	1.00	0.19	0.95	6.53	0.99	7.06
WRMD	0.89	19.44	0.96	19.44	0.76	13.65	0.97	15.82	0.94	9.22	0.99	8.44
UBC	0.98	3.36	0.95	22.68	0.89	2.08	0.92	27.55	0.94	1.44	0.98	13.24

Table-1: Accuracy of Different Models for Kharif Season

Accuracy of Different Models for Rabi Season 2020-21												
Model	Indus at Tarbela				Jhelum at Mangla				Kabul at Nowshera			
	Average 10-Daily		Rabi Season		Average 10-Daily		Rabi Season		Average 10-Daily		Rabi Season	
	NSE	VD	NSE	VD	NSE	VD	NSE	VD	NSE	VD	NSE	VD
BJP	0.98	0.15	1.00	0.97	0.84	28.93	0.99	11.8	0.81	26.21	0.94	24.52
SRM+G	--	--	--	--	--	--	--	--	0.89	8.01	0.90	31.03
WRMD	0.98	3.53	1.00	3.12	0.93	4.30	1.00	4.97	0.78	27.78	0.84	38.64
UBC	0.98	0.68	1.00	1.92	0.92	17.77	1.00	2.14	0.81	4.49	0.92	27.88

Table-2: Accuracy of Different Models for Rabi Season

9. Limitations of Models

Every model have some constraints like University of British Columbia Watershed Model (UBCWM) uses energy budget approach which requires the weather point data which is hard to obtain from neighboring countries as significant part of catchment areas also lie in neighboring countries. Statistical models uses matching year approach which does not look into present watershed and also the Rabi flows have weak correlation with forthcoming Kharif flows. Snowmelt Runoff Model (SRM) uses degree day approach which neither explicitly estimates the

subsurface flows, nor distributes these flows into ground in addition it uses crude method of Rainfall Runoff by employing runoff coefficient moreover cannot handle debris covered glaciers. The most important limitations of these models are that these models cannot forecast the unexpected low and high flows caused due to unusual weather conditions. However the use of the models plays a central role in the flow forecasting and water resources management.

10. Conclusions & Recommendations

The flow forecasting results were quite encouraging overall Kharif & Rabi Seasonal and 10-daily flow forecasts show a very good relationship between observed and forecasted flows as presented in above Tables 1 and 2.

This implies that all models incorporate the main glacio-hydrological processes in these catchments using the ideal parameter sets. Every model has efficiently captured both low flow and high flow, except some unexpected low flows in the month of July.

Despite their simplicity, all models have proven to be powerful tools for melt modelling, often on a catchment scale outperforming energy balance models in poorly monitored regions like the mountainous regions of Pakistan.

The successful application of the these models suggested its application to the other snow and glacier fed sub-catchments of the Hindu Kush Karakoram region to assess the water resources management under different supply and demand as well as present and future climate change scenarios.

Moreover this region is highly vulnerable to natural hazards and floods, In order to reduce the risk of floods, it is highly recommended to build new reservoirs to lower the effects of flooding and to deal with the protection of life losses, standing crops, infrastructures, as well as to preserve the water for irrigation.

The application of these models to the other snowmelt runoff dominated sub-catchments of the UIB may help manage the integrated water resources of the Indus River irrigation system. The next step of the study is to apply these models to the snow and glacier-fed catchments like Hunza, Shigar, Shyok, Astore, Gilgit and Kharmong to simulate and forecast the summer stream flow as well as to evaluate the basin wise impact of future climate scenarios.

Small improvements in the flow forecasting procedures for the planning and management of water resources could create significant economic benefits to the country. Flow forecasting plays a central role in the management and regulations of the Rivers.

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12. References

1. Bajracharya, S. R., and Shrestha, B. (2011). The status of Glaciers in Hindu Kush-Himalayan region. Kathmandu: ICIMOD.

2. Bennett, J.C. et al., 2017. Assessment of an ensemble seasonal streamflow forecasting system for Australia. Hydrol. Earth Syst. Sci., 21(12): 6007-6030. DOI:10.5194/hess-21-6007-2017.

3. Dreyer, N. N., Nikolayeva, G. M., and Tsigelnaya, I.D. (1982) Maps of stream flow resources of some high mountain areas in Asia and North America Hydrological Aspects

of Alpine and High Mountain Areas (Proceedings of the Exeter Symposium, July 1982). IAHS Publ. no. 138.

4. Ferguson, R. J. (1984) Sediment load of the Hunza River. In: Miller KJ, editor. The International Karakoram Project. Cambridge, United Kingdom: Cambridge University Press, pp 374–382.

5. Ferguson, R. I. (1984) Sediment load of the Hunza River. In: The International Karakoram Project. Vol. 2: (ed. By K. J. Miller), 581-598. Cambridge University Press, Cambridge.

6. Haan, C.T., Johnson, H.P., and Brakensiek, D.L. (1982) Hydrologic Modelling of Small Watersheds. ASAE Monograph No. 5. American Society of Agricultural Engineers, St. Joseph, MI.

7. Moriasi D.N., Arnold, J., Liew, M.W., Bingner, R.L., Harmel, R.D.,Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. Am. Soc. Agric. Biol. Eng., 50(3), 885–900

8. Nash, J. E.; Sutcliffe, J. V. (1970). "River flow forecasting through conceptual models part I — A discussion of principles". Journal of Hydrology. 10 (3): 282–290.

9. NESPAK, AHT (2015a): Development of Water Resources Management Information System (WRMIS) and Decision Support System (DSS) for Efficient Irrigation Water Management in Punjab. 1st Interim Report.

10. NESPAK, AHT (2015b): Hydrological Modelling for Flow Forecasting of Upper Indus Catchment. In: Improvement of Water Resources Management of Indus Basin to Enhance the Capacity of Indus River System Authority (IRSA). Final Report.

11. NESPAK, AHT (2016): Development of Water Resources Management Information System (WRMIS) and Decision Support System (DSS) for Efficient Irrigation Water Management in Punjab. 2nd Interim Report.

12. Schaper, J., J. Martinec, K. Seidel (1999): Distributed Mapping of Snow and Glaciers for Improved Runoff Modelling. Hydrological Processes, 13(12-13): 2023–2031.

13. Schaper, J., K. Seidel (2000): Modelling Daily Runoff From Snow And Glacier Melt Using Remote Sensing Data. Proceedings of EARSeL-SIG-Workshop Land Ice and Snow, Dresden, 308–317.

14. Schepen, A., Zhao, T., Wang, Q.J., Robertson, D.E., 2018. A Bayesian modelling method for post-processing daily sub-seasonal to seasonal rainfall forecasts from global climate models and evaluation for 12 Australian catchments. Hydrol. Earth Syst. Sci., 22(2):1615-1628.

15. Tahir, A.A., Chevallier, P., Arnaud, Y., and Ahmad, B. (2011) Snow cover dynamics and hydrological regime of the Hunza River basin, Karakoram Range, Northern Pakistan. Hydrology and Earth System Sciences15(7):2275–2290. www.hydrolearth- syst-sci.net/15/2275/2011/; accessed 4 August 2011.http://dx.doi.org/10.5194/hess-15-2275-2011.

16. United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019: Highlights. ST/ESA/SER.A/423.

17. WAPDA, 1979. Tarbela dam project: Sedimentation Base Surveys. Water and Power Development Authority, Lahore.

18. WMO(1986) Intercomparison of models of snowmelt runoff, Geneva, Switzerland.