Evaluation of hydrological modeling using climatic station and gridded precipitation dataset

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ABSTRACT. The conventional rainfall data estimates are relatively accurate at some points of the region. The interpolation of such type of data approximates the actual rainfield however in data scarce regions; the resulted rainfield shows that gridded data highly overestimates the climatic station data. Similar results were observed in the comparison of flow simulated by SWAT model. The Peak flood calculated from JRA-55 overestimates while the Era-Interim peak floods are comparable to that of climatic stations in two of the three catchments.

Key words – Hydrological modeling, Gridded data, Accuracy assessment.

1. Introduction

The hydrological modeling in Pakistan is carried out using the rainfall data of conventional rain gauges. Due to the high cost of climatic stations and its monitoring the rain gauges are often limited in number. In order to estimate the spatial variabilty of rainfall a dense network of rain gauges is required which is not possible in the developing countries due to its high cost. Even in the technologically advanced nations, the data collected from the rain gauges do not represent the actual precipitation and the situation is worse in the less developed nations.
(Wilheit, 1986). The spatial variability of rainfall is better estimated by the radars which are limited in developing countries due to high cost of radars.

The satellite images are now used for estimating the rainfall events and various methods have been proposed for estimating the rainfall from different electromagnetic spectrum bands (Dingman, 2002) and the most important is obtained from the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al., 2000). In this research ERA-Interim and JRA-55 estimates were evaluated through comparison with the precipitation data of raingauges and through the estimation of stream flow using the semi distributed model i.e., Soil and Water Assessment Toll (SWAT). The main objective of this research is to examine whether the ERA-Interim and JRA-55 estimates are helpful to the rainfall-runoff models in the data scarce regions. The focus of the study is to use these estimates only for hydrological modelling rather than developing new rainfall estimates.

2. Satellite based estimated rainfall

Information regarding the different components of the hydrological cycle can be obtained from the satellite images. Even before the launch of the first meteorological satellite i.e., TIROS in April 1960, it was assumed that the occurrence of rainfall might be detected from the parent cloud system (Petty, 1995). With the development of the Micro-Wave Sensors, estimation of rainfall based on the Infrared and Visible wavelength of light were improved (Ramage et al., 2003).

For the hydro-meteorological studies, many researchers suggest the use of gridded data (Lutz et al., 2014). Around twelve widely used precipitation datasets were tested based on the basin wise mass balance equation for Upper Indus Basin (UIB) and all the datasets were underestimating the precipitation except European Reanalysis-40 (ERA-40) and the ERA-Interim for some parts of the UIB (Khan, 2015). TRMM data was evaluated for the tributary of Amazon through a large scale model and it was found that the hydrographs obtained from the TRMM data is comparable with the observed hydrographs (Collischonn et al., 2008). The latest global atmospheric reanalysis product is ERA-Interim which is developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-15 is the first reanalysis product for almost 15-years spanning 1978 to 1994. The second product is ERA-40 for almost 40-years spanning 1957 to 2002 and is replaced by Era-Interim data which ranges from 1979 till date (Dee et al., 2011). The second reanalysis project carried out by the Japanese Meteorological Agency (JMA) is the Japanese 55-years reanalysis data known as JRA-55 which provides the high quality climatic data from 1958. Many of the deficiencies in the JRA-25, the first project of JMA, were alleviated by JRA-55 (Kobayashi et al., 2015).

3. Soil conservation curve number method

The rainfall runoff modelling in hydrology is as important as other modelling techniques in other fields (Donigian et al., 1995). We model things because of the limitation of the procedures and techniques to record the various components of the hydrological modelling (Beven & Freer, 2001). Another use of hydrological modelling is to see the effect of one parameter on changing certain conditions (Donigian et al., 1995). The documentation of the hydrological modelling started in the mid-19th century and the first model which is now known as rational formula was first described by T.J. Mulvaney in 1851 (McCuen, 1998). This is known as the marking point of documentation of hydrological modelling. In 1871, Saint Venant developed the surface water equation for flow of water in one dimension (Maidment, 1993). Manning developed the equation of open channel flow in 1891. One of the most popular model the field of hydrology is the Green and Ampt model which was developed in 1911. The Horton model was introduce in 1919. Sherman developed the concept of unit hydrograph in 1932 (Todini, 1988). Horton also described the theory of infiltration in 1933 which is known as the most important theory of infiltration. In 1939, McCarthy introduced the hydrological method which later on published as Muskingum Routing method. Cung in 1969, showed some improvements into the Muskingum method. The simplest model for calculating runoff from rainfall is the Soil Conservation Services (SCS) Curve Number (CN) model now known as the Natural Resources Conservation Services (NRCS) Curve Number model. For small catchments hydrolgy, the engineers and hydrologists recommend this model (Mishra & Singh, 2013). For small catchments, the initial abstraction ratio (λ) in the NRCS-CN greatly affects the results (Baltas et al., 2007). The value of the initial abstraction ratio must be selected by considering the climatic condition (Ponce & Hawkins, 1996). The value of λ = 0.2 in the original NRCS-CN model is ambiguous and this value must be determined for a given watershed. A value of 0.05 was confirmed by studying 307 U.S. watershed’s rainfall runoff data (Woodward et al., 2003). In the Three Gorges area of China, different watershed studies defined the range for the initial abstraction ratio as 0.010 to 0.154 (Shi et al., 2009). Data from 237 U.S watershed showed a value of λ = 0.01 (Mishra et al., 2004). Data from 186 Australian watersheds suggested a value of λ = 0.05 (Beck et al., 2009). All the watershed characteristics and climatic factors are combined in one entity called the Curve Number (CN) in the SCS-CN model.
The values of the curve number can be selected using the tables; however, this value can be better estimated based on the rainfall-runoff data of a watershed. Various procedures are available for estimating the curve number and there is no agreement on a single method of determining the curve number (Soulis & Valiantzas, 2012). SCS-CN model and the proposed models' performance were checked based on the CN value selected from tables and CN value calculated using event-based rainfall-runoff data. The result showed that model performance was good in case of CN calculated from the event-based rainfall-runoff data (Ajmal et al., 2015). Fifteen watershed with eight different rainfall-runoff models including the SCS-CN model, SCS inspired models and proposed models for the watershed by the researcher with modified initial abstraction ratio was used and it was found that the proposed model performed well as compared to the other models (Ajmal and Kim, 2014).

4. Methodology

The quality of the ERA-Interim and JRA-55 estimates were assessed by comparing the daily data with the raingauge daily precipitation data over the three catchments. SWAT was used with daily time step with ERA-Interim, JRA-55 and raingauge data as inputs to simulate the flow.

The study area is briefly explained in the section “Watershed Description”. The availability of data is described in the section “Data Collection”. The SWAT model is described in “Soil and Water Assessment Tool”. Calibration of the model and the stream flow comparison is mentioned in “Accuracy Assessment of Data and Stream Flow Comparison”. The peak flood estimation is briefly explained in the “Estimation of Peak Flood”.

4.1. Watershed description

This study focuses on the hydrology of three small dams located in Federally Administered Tribal Area (FATA) now part the Khyber-Pakhtunkhwa (KP) province of Pakistan. Fig. 1 shows the location of dams on the topographic map based on digital elevation model (DEM) of KP and FATA.
Climate of Pakistan is dry with deficient precipitation during most of the year (Kottek et al., 2006). Despite the fact that FATA has scarcity of both water resources and land, the people are more dependent on the agriculture and livestock activities. In order to store the flood water in the streams and to bring more areas under irrigation command, the FATA Development Authority (FDA) has put forward to construct Small Dams. In this regards several small dams have been constructed while various projects are still under construction.

Pindiali Small Dam in Mohmand Agency-FATA is located on Pindiali Khawar (Stream) with a catchment area of 17.15 sq. Miles. The area falls in the rainfall zone of about 17.96 inches (456 mm). The annual inflow of the stream is about 2033 Acre-ft and 19.4 acre-ft of sediments per annum. The flood water will be stored in a reservoir and will be used to irrigate 300 acres of land at 109% intensity.

Sarobi Small Dam in North Waziristan Agency -FATA is located on Ping Algad (stream) with a catchment area of 8.9 sq. Miles. The area falls in the rainfall zone of about 12.96 inches (329 mm). The stream has perennial flow of about 0.5 cusecs and is estimated to bring 1035 AF inflow and 18 acre-ft of sediments per annum. The flood water will be stored in a reservoir and used to irrigate 450 acres of land at 100% intensity in command area.

Dande Small Dam in North Waziristan Agency -FATA is located on Dawagar Algad (Stream) with a catchment area of 59.12 sq. Miles. The area falls in the rainfall zone of about 14 inches (355.6 mm). The stream has no perennial flow is estimated to bring 88.68 acre-ft of sediments per annum.

### 4.2. Data collection

#### 4.2.1. Observed data

Observed hydrological data and Gridded data was used in this study. Observed data (Rainfall and Temperatures) was provided by the Pakistan Meteorological department (PMD), Lahore and Water and Power Development Authority (WAPDA). The River Flow Data was obtained from WAPDA. Detail about the data for different stations obtained from PMD and WAPDA is given in Table 1.

#### 4.2.2. Gridded data

Two types of Gridded precipitation and temperature data used are

(i) ERA-Interim data for the period of 1979-2010 was download from http://apps.ecmwf.int/datasets/data/interim-full-daily/

(ii) JRA-55 data for the period 1979-2010 was downloaded from https://rda.ucar.edu.datasets/

### 4.2.3. Soil, land use and digital elevation model

Apart from the precipitation and temperature data, some other types of data necessary for the preparation of SWAT model are:

(i) Food and Agriculture Organization (FAO) of the United Nations global soil data was download from http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/

(ii) The Glob Cover 2009 Land Use data was download from the link http://due.esrin.esa.int/page_globcover.php/
The digital elevation model (DEM) used in this research was accessed from the link http://srtm.csi.cgiar.org/

4.2.4. Data required for accuracy assessment

The data required for accuracy assessment is:

(i) Actual Evapotranspiration (ET_{act}) Data of ERA-Interim available at http://apps.ecmwf.int/datasets/data/, FAO available at http://gaez.fao.org/Main.html#, Willmott and Matsuura (W&M) PET data available at http://climate.geog.udel.edu/ for the period 1999-2010 have been used in this research

(ii) Ground Water Recharge Data of World-wide Hydro-geological Mapping and Assessment Program (WHYMAP) available at http://www.whymap.org/whymap/EN/Downloads have been used in this research.

(iii) Potential Evapotranspiration (PET) Data of ERA-Interim available at http://spirits.jrc.ec.europa.eu/files/ecmwf/int/asia/evpt/, Potential Evapotranspiration data of FAO available at http://gaez.fao.org/Main.html# for the period 1999-2010 have been used in this research.

4.3. Soil and water assessment tool

Numerous computer models are present in order to evaluate the watershed hydrology. Among them, SWAT is most widely used semi-distributed physical model (Arnold et al., 1998). A large input data is required for SWAT model which makes the parameterization and calibration of the model complicated. The SWAT model can be calibrated manually or a using a semi-automated procedure known as SWAT calibration and uncertainty procedure (CUP) (Arnold et al., 2012). The hydrology of the Upper Illinois River Basin was simulated using two different models in order to check the suitability of the model and it was found that the SWAT Model best simulates the low flow as compared to the other model (Singh et al., 2005). Another study compared the SWAT model with the Hydrologic Simulation Program-Fortran (HSPF) model and showed that for agriculture watershed SWAT showed an element of robustness as compared to the HSPF in estimating the stream flow (Van Liew et al., 2003). In order to check the capabilities of the SWAT model, data from three nested watersheds was used and it was found that once the SWAT model is calibrated, it can be used to for providing adequate simulation in case of climate change on water resources (Van Liew & Garbrecht, 2003). Another study revealed that the calibration of the HSPF model as compared to the SWAT model was less user friendly and time consuming because of the numerous parameters to adjust and greater data preprocessing (Saleh & Du, 2004). In this study the SWAT model has been used in order to evaluate the flow from different types of precipitation datasets.

4.4. Accuracy assessment of data and stream flow comparison

SWAT model was calibrated using the conventional raingauges data. Since no flow data is available at these three small dams, therefore, nearest possible flow measuring stations were delineated. The flow measuring station near to Pindiali dam is Chakdara station at River Swat and that near to Sarobi and Dande dam is Thal station at River Kurram.

The accuracy assessment of the data is important for calibrating the nearest catchments. The accuracy assessment was carried out using the Basin-Wise Mass Balance Equation (Reggiani & Rientjes, 2015). The proposed equation is

\[ Q + ET_{act} - P = \pm \Delta S \]  

where, 

- \( Q \) = average annual flow (mm/year)  
- \( P \) = Total annual precipitation (mm/year)  
- \( \Delta S \) = Change in storage  
- \( ET_{act} \) = Actual Evapotranspiration

Three limits \( L_1, L_2 \) and \( L_3 \) were defined for the accuracy assessment and they are given below:

\[ L_1 = Q + (ET_{act} + nGWR)_{\text{min}} \]  
\[ L_2 = Q + (ET_{act} + nGWR)_{\text{max}} \]  
\[ L_3 = Q + (PET + nGWR)_{\text{avg}} \]

where,

\( (ET_{act})_{\text{minimum}} = (ET_{act})_{\text{average}} - (ET_{act})_{\bar{d}} \)  
\( (nGWR)_{\text{minimum}} = (nGWR)_{\text{average}} - (nGWR)_{\bar{d}} \)  
\( (ET_{act})_{\text{maximum}} = (ET_{act})_{\text{average}} - (ET_{act})_{\bar{d}} \)  
\( (nGWR)_{\text{maximum}} = (nGWR)_{\text{average}} - (nGWR)_{\bar{d}} \)
\[ nGWR = \text{Net ground water recharge} \]

\[ PET = \text{Potential evapotranspiration} \]

\[ \bar{\sigma} = \text{Standard deviation of the relative parameter} \]

The data that lie in between the limit 1 and limit 2 is considered of good quality while the data that lie above the limit 2 and limit 3 is overestimation and the data that lie below limit 1 is underestimation (Khan, 2015). In our case, the climatic station data is considered of good quality as compared to the gridded dataset and hence this data is used for calibrating the models. The calibrated parameters of River Kurram at Thal station were used for Sarobi and Dande dam while that of River Swat at chakdara were used for Pindiali dam and the flow was then simulated using ERA-Interim, JRA-55 and conventional rain gauges data as inputs to the SWAT model.

4.5. Peak flood estimation

Design flood was estimated using Hydrologic Engineering Center (HEC) Hydrologic model system (HMS). HEC-HEC is a software that calculates the flood hydrograph at different junctions of the stream by entering the catchment area, the loss rate in terms of curve number, the lag time and the time distribution of rainfall as input. The time of concentration \((T_c)\) for the catchment was calculated using the Kirpich’s equation.

\[ T_c \text{(minutes)} = \left( \frac{11.9 \times L}{H} \right)^{0.385} \]  

where,

\[ L = \text{length of longest flow path (miles)} \]

\[ H = \text{the difference between the highest and lowest point (feet)} \]

The Synthetic unit hydrograph (UH) has been developed using the parameters of the curvilinear dimensionless UH and the SCS triangular unit hydrograph through the HEC-HMS rainfall-runoff model. The peak storm is estimated using the Gumbel Extreme value-I distribution and SCS Type-II distribution has been used for hourly distribution of peak storm. To estimate the direct runoff, the most widely used model is the SCS-CN model. The slope adjusted curve number is calculated by the SWAT model using soil, land use and slope data. The SCS curves for initial abstraction ratio \((\lambda)\) are obtained using the equation:

\[ Q = \frac{(P - \lambda \times S)^2}{[P + (1 - \lambda) \times S]} \]  

where,

\[ Q = \text{runoff volume in inches} \]

\[ P = \text{rainfall in inches} \]

\[ S = \text{soil retention parameter in inches after runoff} \]

\[ \lambda = \text{Initial abstraction ratio} \]

5. Results and discussion

5.1. Mean basin rainfall comparison

Rainfall data was obtained for all the three dams from different sources as explained in the “Data Collection” section. Accumulated mean daily precipitation for gridded and climatic station data for all the three catchments is shown in Fig. 2.

Fig. 2 shows that both Era-Interim and JRA-55 estimates are very far from that of raingauge estimates, when the rainfall is averaged over the catchments. In terms of the total amounts of rain during the 32-years period, the results are very different.

In order to explore the seasonal variations, basin average rainfall was compared on monthly basis as shown in Fig. 3. Monthly averages were calculated for a period of 32 year from 1979-2010 and during this period, both the JRA-55 and Era-Interim data overestimates the climatic station data in the wet as well as the in dry season. However, the seasonal variability is well distinguished both by JRA-55 and Era-Interim datasets.

5.2. Comparison of mean inflow at dam site

The accumulated mean daily inflow estimated from SWAT model for gridded and climatic station data for all the three catchments is shown in Fig. 4.

Fig. 4 shows that both Era-Interim and JRA-55 estimates of inflow are very far from the flow generated from the precipitation of raingauge, when the flow is averaged over the catchments. The results are also different in terms of the total amounts of flow for 32-years period.

In order to explore the seasonal variations based on the inflow in the streams, basin average inflow to the Dam site were compared on monthly basis as shown in Fig. 5.
Fig. 2. Accumulated mean daily rainfall over the three different catchments for Era-Interim, JRA-55 and climatic station.

Fig. 3. Average monthly precipitation based on different types of datasets for all the three Dams.
Fig. 4. Accumulated mean daily inflow over the three different catchments for Era-Interim, JRA-55 and Climatic Station

Fig. 5. Average monthly precipitation based on different types of datasets for all the three Dams
Monthly averages were calculated for a period of 32 years from 1979-2010 and during this period, both the inflow generated from JRA-55 and Era-Interim data overestimates the flow from climatic station data in the wet as well as the in the dry season. However, the seasonal variability is well distinguished both by JRA-55 and Era-Interim datasets.

5.3. Accuracy assessment of data

The accuracy assessment of the data helps in determining the precipitation data for calibration of SWAT models. As explained in the section “Accuracy Assessment of Data and Stream Flow Comparison”, the basin wise mass balance equation was applied on the two catchments where flow data was available. The result of the accuracy assessment is shown in Fig. 6.

Fig. 6. shows that for both catchments, River Kurram at Thal and River Swat at Chakdara station, ERA-Interim and JRA-55 datasets show overestimation as the data lies above Limit 2 and Limit 3 while the climatic station data well represents these catchments’ precipitation as it is in between the limit 1 and Limit 2.

5.4. Calibration and validation

The nearest possible catchments were calibrated where the flow data was available and the calibrated parameters were then used in actual study area and flow was estimated. The catchment near to Dande and Sarobi small dam was River Kurram at Thal station and the near to the Pindiali small dam was River Swat at Chakdara station. The calibration period for River Kurram at Thal station was taken from Jan-1991 to December-1998 as shown in Fig. 7.

The calibration was carried out on monthly basis and shows that model performed very well having Nash–Sutcliffe efficiency (NSE) = 0.72 and correlation coefficient \( R^2 = 0.90 \). The validation period for the same model is from Jan–99 to Dec–03 on monthly basis. The validation results also show the model performance is in good range having NSE = 0.74 and \( R^2 = 0.66 \). The calibration period for River Swat at Chakdara station was taken from Jan–1991 to December–1995. The calibration was carried out on monthly basis and it shows that model performed very well having NSE = 0.91 and \( R^2 = 0.96 \). The validation period for the same model is from Jan–1996 to Dec–98 on monthly basis. The validation results also show the model performance is in very good range having NSE = 0.80 and \( R^2 = 0.91 \).

5.5. Peak flood generation

The peak floods from climatic station and gridded precipitation datasets were calculated for all the three catchments and is shown in Fig. 8.

The peak flood for Pindiali Dam was generated using HEC-HMS software. The time of concentration was calculated using the Kirpich’s Equation (Fang et al., 2008).
The peak flood from ERA-Interim and Climatic station datasets are in good agreement for Sarobi and Pindiali catchments while in case of Dande dam the peak flood from Era-Interim data is also overestimating. Peak flood calculated from JRA-55 is overestimating for all three catchments of dams. For Pindiali dam the peaks of JRA-55 and Era-Interim are 3.0 and 0.9 times of climatic station peak respectively. For Sarobi dam the peaks of JRA-55 and Era-Interim are 1.5 and 1.1 times of climatic station peak respectively. For Dande dam...
the peaks of JRA-55 and Era-Interim are 1.3 and 1.2 times of climatic station peak respectively.

It is clear that both JRA-55 and ERA-Interim overestimates the results in precipitation comparison as well as in flow comparison. Hence the use of these two types of gridded datasets in water scarce regions is recommended only after some bias correction. The peak flood estimated from era-interim is somehow comparable in two of the three catchments to that estimated from the raingauge data. This shows that daily maximum rainfall of each year for ERA-Interim matches with the daily maximum of raingauge data.

6. Conclusion and recommendation

In this study, we have compared the precipitation data from three sources i.e., Era-Interim, JRA-55 and conventional rain gauge data over three small dams in Pakistan for the period of study (1979-2010). We also compared the flow from all these data using Soil and Water Assessment Tool (SWAT). Comparative assessment showed that both JRA-55 and ERA-Interim overestimates precipitation as well as flow both in the wet and dry season. However, the seasonal variability is well distinguished by gridded datasets. Hence we conclude that the use of these two types of gridded datasets in these water scarce regions is recommended only after some bias corrections. The peak flood estimated from era-interim and rain gauge data is somewhat comparable in the two catchments. This means that daily maximum rainfall of each year for ERA-Interim matches with the daily maximum of rain-gauge data and hence frequency analysis based on both types of data produced similar results.

Since the two types of gridded data used in this research work overestimates the results, evaluation of some other types of gridded data for the said catchments is required. Moreover we conclude that the calibrated parameters of the nearest catchments may not represent the ungauged catchments, therefore, the same research work is recommended for the gauged watershed. Although SWAT model performed very well both in Calibration and Validation, however, evaluation of the performance of some other models with the SWAT model is recommended.

Conflicts of Interest: The authors declare no conflict of interest. The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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