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Application of SWAT Model for Hydrological Modelling in Beas Watershed, Himachal Pradesh

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Abstract—*In recent years, distributed watershed models have been increasingly used to implement alternative management strategies in areas of water resource allocation, flood control etc. Among these hydrological models, one such model SWAT, a semi distributed and continuous model (Arnold ,1998) has been used by researchers around the world for distributed hydrologic modeling and management of water resources in watershed with various climate and terrain characteristics.*

In this case study/report, SWAT has been calibrated and validated on the hydrologic component of runoff for the mountainous complex terrain of North India- Beas Valley. Beas is a river in high altitude region largely fed by snow. SWAT ability to comprehend snowmelt and snowfall runoff was observed here.

SWAT model was calibrated and validated by using stream flow measured at the Pandoh station. The observed data from 1996 to 2003 were split for calibration (1996-2000) and validation (2001-2003) purposes. SWAT along with SWAT-CUP software was used to calculate coefficient of determination for various scenarios.

Monthly results for calibration and validation were 0.89 & 0.85 respectively. Daily calibration & validation result was 0.65 & 0.44. It shows clearly that SWAT is better at simulating monthly runoff than daily for a snow fed region rivers like Beas.

However, SWAT is not a user friendly software for snow related studies and lacks precision in its snow fed region results. It needs expert & experienced handling for snow studies. Although it shows a good trend in rainfall-runoff studies on monthly basis, making it a good tool for water management purposes.

1. INTRODUCTION

Water is a scarce and most important resource for the planet. 71% of Earth is covered with water, out of which 96.5% is in oceans and only 2.5% is available as fresh water. Various rivers, lakes, Glaciers and ice caps contribute to 2.5% fresh water. Good water management strategy is the need of the hour.

With growth in technology, increasing population, floods, change in land use scenarios, there is an invincible need to develop strategies that will lead to ecological and economic distribution of water for various purpose at the district, state and national level.

In recent years, distributed watershed models have been increasingly used to implement alternative management strategies in areas of water resource allocation, flood control etc. Among these hydrological models, one such model SWAT, a semi distributed and continuous model (Arnold ,1988) has been used by researchers around the world for distributed hydrologic modeling and management of water resources in watershed with various climate and terrain characteristics.

In this report SWAT has been calibrated and validated on the hydrologic component of runoff for the mountainous region of North India- Beas Valley.

In this study, SWAT is further coupled with a model SWAT-CUP to calculate the statistical R2 to judge the performance of SWAT model for calibration and validation purposes.

The main objective of the study is:

I. To evaluate the performance of the SWAT model and assess the feasibility of using SWAT for hydrological modelling of the Beas basin
II. To compare the performance of model on a monthly time frame and daily time frame.

2. STUDY AREA

The study area of Beas Bain is situated in Himachal Pradesh between 31.7N – 32.42N and 77.05E – 77.73E. The sub basin of Beas is drained by the Beas River System. Beas is one of the 5 tributaries (Jhelum, Chenab, Ravi, Satluj and Beas) of Indus River System.

The Beas River starts from Beas Kund (a small ice body) at an elevation of 4038 m on the eastern slope of Rohtang Pass in western Himalayas. It flows about north south direction and takes a turn near Larji towards west in a right angle towards west and then it maintains its flow upto Pandoh dam (Singh,1992).

A total area of 5,381 sq.km stretching from Manali to Pandoh is taken for modelling the runoff. The study area is surrounded by important north India Hydropower station, Bhakra Dam and Pong Dam.

The outlet point of the study area, Pandoh is another reservoir for generation of hydropower.

As the valley is surrounded by Great Himalayas in north, it receives a significant glacier flow due to snowmelt peaks. Unique combination of intense seasonal precipitation and steep topography makes the hydrology in the region very complex.

Length of Beas river upto Pandoh is 116 km. Among its tributaries Pārbati and Sainj Khad are glacier fed. Other tributaries which join upstream of Pandoh dam are Pārbati near Bhunter, Tirthan and Sainj rivers near Larji, Bakhli Khad and Luni near Pandoh (Fig.1)

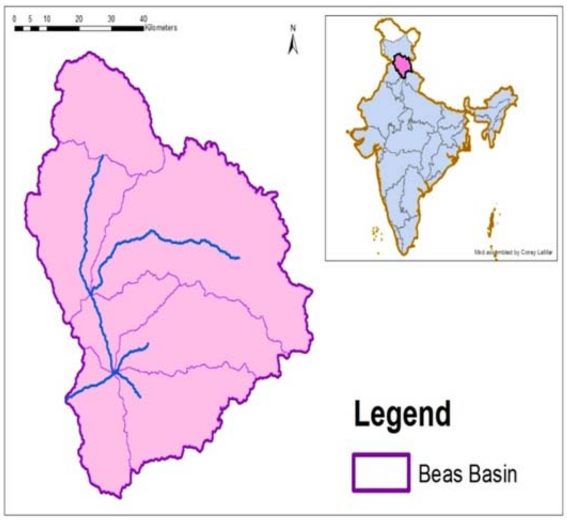


Fig. 1: Study area of Beas

3. ABOUT THE SWAT MODEL :

Soil and Water Assessment Tool, known as SWAT, is a semi distributed physically based continuous hydrological model developed by Jeff Arnold (1998) and jointly developed by U.S Dept. of Agriculture – Agriculture Research Services (USDA-ARS) & Agriculture Experiment station in temple TEXAS. The model's main use is in the field of agriculture and to predict the impact of land management practices on water yield, agriculture chemical yields, sediment in large ungauged complex watersheds.

SWAT is a semi distributed and time continuous simulation model operating on daily, monthly and yearly time step. Major components of SWAT include weather conditions, soil properties, hydrology, erosion, plant growth, land management, nutrients, pesticides and stream routing. The model uses physically based inputs such as weather variables, soil properties, topography, vegetation and land management practices occurring in the catchment. A detailed documentation of Input/output variables is given by Neitsch et al (2005).

Water force is the driving force behind everything that happens in a watershed to accurately predict the hydrologic cycle, sediment or nutrient movement. The hydrologic cycle simulated by SWAT is based on the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{\text{day}} - Q_{\text{surf}} - E_a - w_{\text{seep}} - Q_{\text{lat}} - Q_{gw})$$

where, SWt is the final soil water content (mm H2O), SWo is the initial soil water content (mm H2O), t is time in days, R day is amount of precipitation on day i (mm H2O), Q surf is the amount of surface runoff on day i (mm H2O), Ea is the amount of evapo-transpiration on day i (mm H2O), wseep is the amount of percolation and bypass exiting the soil profile bottom on day i (mm H2O), Qgw is the amount of return flow on day i (mm H2O).

SWAT model uses Green & Ampt method to calculate hourly surface runoff of the basin. The model estimates runoff volume by using Soil & Conservation Service (SCS) Curve number technique (USDA, 1972). In this study Penman Monteith method is used for estimation of potential evapo-transpiration. SWAT coupled with SWAT-CUP is used for calculation of the coefficient of determination R2, to judge the performance of the model.

4. SWAT-CUP SOFTWARE :

SWAT Calibration & Uncertainty Program is a computer program for calibration of SWAT models. This program links SUFI2, PSO, GLUE, Parasol and MCMC procedures to SWAT. It enables sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT models. In this program the calibration requires that the uncertain model parameters are systematically changed, the model is run and the required outputs (corresponding to the measured data) are extracted from the model output files. The main function of an interface is to provide a link between the input/output of a calibration program and the model.

In this case study, SWAT coupled with SWAT-CUP is used for calibrating, validating and calculating of the coefficient of determination R2, to judge the performance of the model. R2, is most often used in linear regression. Given a set of data points, linear regression gives a formula for the line most closely matching those points. It also gives an R-Squared value to say how well the resulting line matches the original data points. The value of R2 ranges from 0 to 1, a value between 0.6 to 1.0 indicates a good correlation (Moriasi et al,2007).

SWAT-CUP is a mathematical software that performs permutations and combinations on the range of input values of various hydrological parameters provided to the software. The best combination of various parameters that gives best fit is used for validation of the model on a different time scale.

The best parameters applicability is to be checked on practical hydrological scenarios. In the software database there is a file named Absolute SWAT Values which contains a list of all parameters to be fitted with their minimum and maximum ranges. There are variety of other statistical measures like Nash-Sutcliffe Coefficient, Percentage Error, RSR, MNS etc. to measure the performance of SWAT. For more insights on different files of SWAT-CUP, refer to user manual _swat cup (Abbaspour, 2015) from the official website swat.tamu.edu

5. LITERATURE REVIEW :

Jain et al (2010) applied the hydrological modeling for Himalayan watershed using the SWAT model. In this study the authors used the Arc View GIS. SWAT was integrated into this framework showcasing the application of AVSWAT for estimation of surface runoff and sediment yield for an intermediate watershed in Satluj river basin, from Suni to Kasol. Meteorological data from 1993 to 1997 was used. They made statistical and graphical method to assess the capability of model in simulating the runoff and sediment yield on daily and monthly basis.

Shivhare et al (2014) used SWAT model for estimation of surface runoff in an interstate basin of MP and Maharashtra, Tapi sub catchment area. The performance of model was evaluated using statistical method of coefficient of determination. The comparisons among simulated monthly flow with observed flow values showed good results.

Fang et al (2013) selected Laohahe river basin located in North East China as a case study to quantify the magnitude of changes in land use and land cover (LULC) during the period from 1970 to 2010 and its quantitative effects on surface hydrology based on SWAT model and remotely sensed data.

Shi et al (2013) evaluated the performance of SWAT for hydrologic modeling in the Xixian River Basin in China. The authors in their case study also compared three methods of calibration and uncertainty analysis (Sequential Uncertainty Fitting, Generalized Likelihood Uncertainty Estimation & Parameter Solution)& used them to setup the model. Their results showed good performance of SWAT in their selected watershed and their calibrated model could be further used to deduce the effects of climate and land use changes on local water resources.

This review indicates widespread use of SWAT by researchers all around the world for distributed hydrological modeling and management of water resource in watersheds with various climate and terrain characteristics. Therefore, the model is used in this current study to check its performance on mountainous region's watershed Beas. Further the effect of spatial variability of Beas watershed on runoff is also determined. SWAT2012 with the interface of ArcGIS 10.2 was selected for the present study.

6. METHODOLOGY :

Model Inputs

The spatial data acquired in this study includes LULC maps, DEM, Soil Maps, Climate Data & Observed basin discharge data. The source of all the above data is discussed in detail in the subsequent section:

- DEM (Digital Elevation Model) of Beas catchment area is derived from Shuttle Radar Topography Mission (SRTM). DEM dataset with 90m spatial resolution Source website: htttp://srtm.datamirror.csdb.in/
- Land use maps derived from SWAT website:swat.tamu.edu/software/India. Dataset/

Land use map is based on 2001-2002 MODIS data with a spatial resolution of 500m.

- Soil maps obtained from Harmonized World Soil Database (HWSD)- Food & Agriculture (FAO) are used in the present study.
- A Hydrometeorological observation network was set up in the Beas River System by Bhakra Beas Management Board (BBMB).Daily rainfall data from 1990-2005 was derived from five rain gauge stations placed at Bhunter, Larji, Manali, Pandoh & Sainj inside the beas catchment area. Minimum and maximum temperature data from weather stations at Bhunter, Larji, Manali, Pandoh were derived for the same time period. Wind speed, relative humidity, sunshine was derived from the weather generator integrated in SWAT2012 database, to fill in the missing values.
- Daily runoff data at the outlet of Beas basin i.e. Pandoh station is derived from the office of BBMB for a time period of 1996 – 2003 for calibration & validation of the modelled runoff.

Model Set-up

Once all the input data is ready. The following steps are followed for model application- Project Setup, Watershed Delineation, HRU Analysis, Write Input Tables, Edit SWAT Input & Swat Simulation. SWAT automatically delineates a watershed into sub basins based on DEM. 8 sub basins, and streams and outlet points at important stations were delineated by Swat in this study area as shown in Fig.2 and Fig 3.

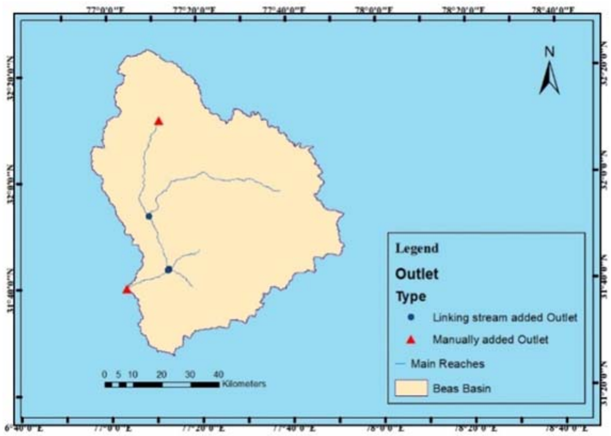


Fig.2 a.

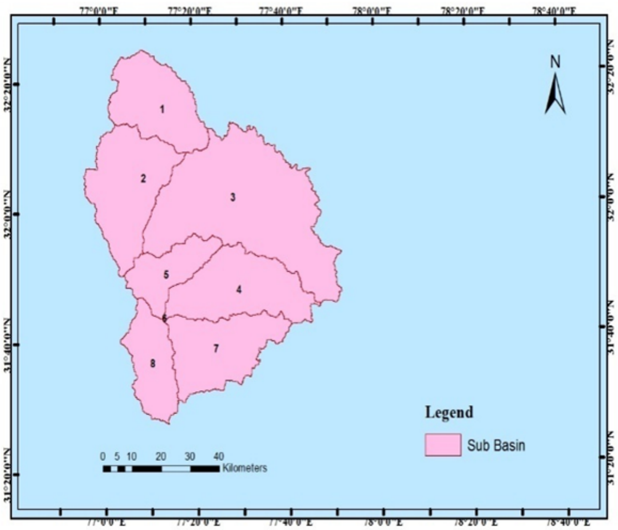


Fig 2 b.

Fig.2a) Main Stream network and gauge stations at Beas watershed

2b) Sub Basins (Post delineation) of Beas watershed

HRUs are hydrological response units that divides the watershed into homogeneous units based on unique combination of land use, soil type and slope at each grid.Fig.3 (a, b, c)

The above three maps are overlaid & give rise to a total of 89 HRUs. (Fig.3 d)

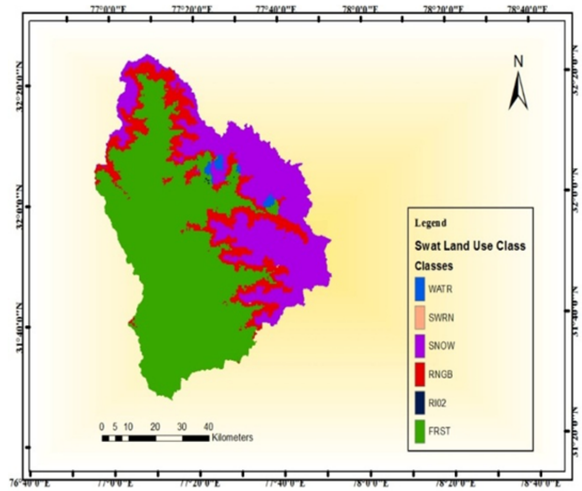


Fig.3 a

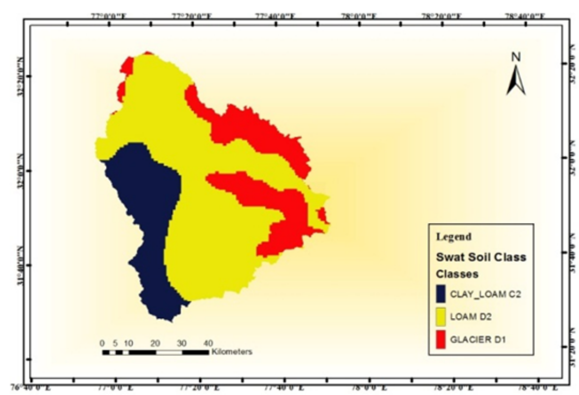


Fig.3 b.

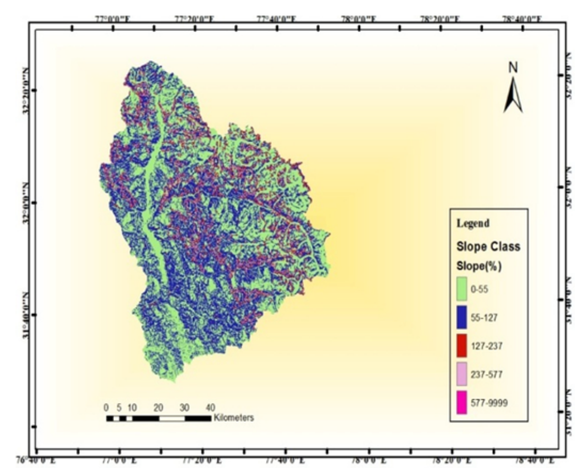


Fig.3 c

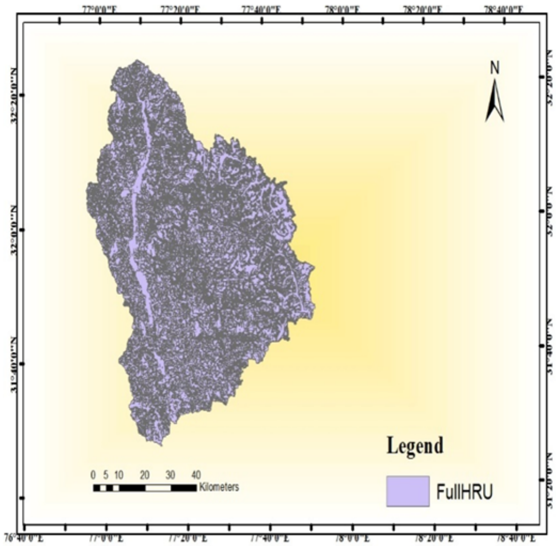


Fig.3 d

Fig. 3 a) Land use/Land cover Classification b) Soil texture classification c) Slope classification d) 89 HRUs of Beas watershed.

Further weather input tables were written using daily rainfall data at five gauge stations of Bhunter, Larji, Pandoh, Sainj & Manali for the years 1991-2007. Maximum and minimum temperature recorded using daily data of four weather stations at Bhunter, Pandoh, Larji & Manali.

The other meteorological parameters of relative humidity, wind speed and sunshine were simulated by the weather generator in SWAT database. Sub-basin was divided in nine elevation bands containing snow melt and snow fall parameters. Model is prepared for Initial Run from 1996 to 2000

7. CALIBRATION & VALIDATION :

SWAT model was calibrated and validated by using stream flow measured at the Pandoh station. The observed data from 1996 to 2003 were split for calibration (1996-2000) and validation (2001-2003) purposes.

Automated Monthly Calibration & Validation :

SWAT input parameters are process based and must be held within a realistic uncertainty range. The first step in the calibration and validation process in SWAT is the determination of the most sensitive parameters for a given watershed or sub watershed. In the watershed of Beas Basin, the following parameters Table 1 were adjusted with a fixed uncertainty range based on both sensitivity analysis and expert guidance.

Table 1. Most sensitive hydrological parameters taken for Calibration/Validation with their respective ranges (monthly basis)

S. No.	Parameter	Range		Mode of change
		Min	Max	
1	CN_2	-0.20	0.20	Relative (r)
2	TLAPS	-10	10	Replace (v)
3	GWQMN	0	1000	Replace (v)
4	GW_DELAY	30	450	Replace (v)
5	SFTMP	-5	5	Replace (v)
6	GW_REVAP	0.02	0.2	Replace (v)
7	SOL_AWC	-0.2	0.2	Relative (r)
8	ESCO	0.01	1	Replace (v)

For deeper insights on above parameters and its effect on runoff flow refer to SWAT Input\Output Documentation 2012 and SWAT Theoretical Documentation 2005.

Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty. Model calibration is performed by carefully selecting values for model input parameters (within their respective uncertainty ranges) by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions.

This step is performed by SWAT-CUP. Then parameters with a fixed range (Table 1) are fed in CUP. Performing subsequent steps, CUP gives the values of best parameters that give simulated closest to the observed discharge at the outlet point (Pandoh). The values of the best parameter are shown in Table 2.

Table 2: Best fit Parameter value for calibration & validation (monthly basis)

S. No.	Parameter	Best Value
1	CN_2	-0.18
2	TLAPS	-4.97
3	GWQMN	59.06
4	GW_DELAY	103
5	SFTMP	0.75
6	GW_REVAP	0.13
7	SOL_AWC	-0.03
8	ESCO	0.15

The final step is validation for stream flow. Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations. In this case study, Parameters (Table 2) were taken for validation. Once the results are collected for monthly calibration and validation (discussed in the next section). The model is studied for daily time series.

8. AUTOMATED DAILY CALIBRATION & VALIDATION :

The most sensitive parameters are fed in CUP with a practical uncertainty range (Table 3.). CUP is run to get the best parameters in a similar way as was done for monthly simulations. The Best Parameters deduced, are shown in Table 4. Parameters deduced in Table 4 were taken for validation. Thus, integrating both the SWAT (CUP) & SWAT software's results for Monthly (Calibration & Validation) and Daily (Calibration & Validation) time series, hydrological modelling of Beas basin was performed.

Table 3. Most sensitive hydrological parameters taken for Calibration/Validation with their respective ranges (Daily basis)

S. No.	Parameter	Range Min	Max	Mode of Change
1	CN_2	-0.20	0.20	Relative (r)
2	TLAPS	-10	10	Replace (v)
3	GWQMN	0	1000	Replace (v)
4	GW_DELAY	30	450	Replace (v)
5	SFTMP	-5	5	Replace (v)
6	GW_REVAP	0.02	0.2	Replace (v)
7	SOL_AWC	-0.2	0.2	Relative (r)
8	ESCO	0.01	1	Replace (v)

Table 4: Best fit Parameter value for calibration & validation (daily basis)

S. No.	Parameter	Best Value
1	**CN_2**	**-0.098**
2	**TLAPS**	**-4.91**
3	**GWQMN**	**133.67**
4	**GW_DELAY**	**51.14**
5	**SFTMP**	**1.30**
6	**GW_REVAP**	**0.14**
7	**SOL_AWC**	**-0.002**
8	**ESCO**	**0.94**

9. RESULTS & DISCUSSION

Monthly Assessment :

The statistic to measure the performance of the model used in the study is coefficient of determination R^2. The value of R^2 for calibration & validation is 0.89 and 0.87 respectively for runoff as shown in (Fig. 4.(a) & (b))

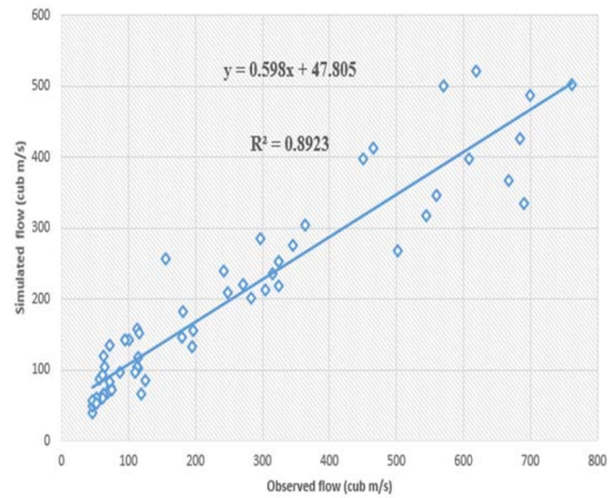


Fig. 4(a)

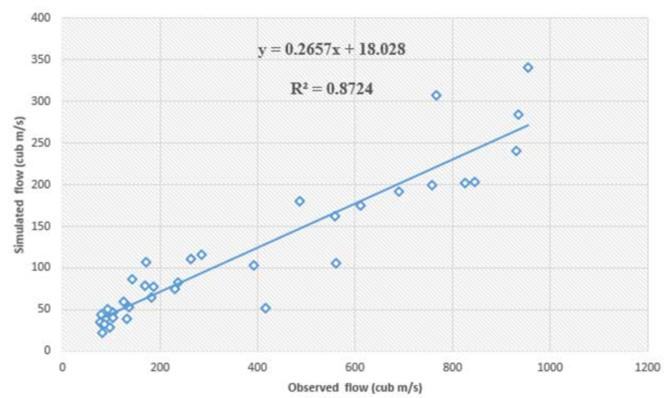


Fig. 4 (b)

Fig. 4. Simulated vs. Observed flow for monthly

a) calibration (1996-2000) & b) validation (2001 -2003)

The time series of the monthly observed and monthly simulated for calibration (1996-2000) and validation (2001-2003) were plotted for visual comparison.

(Fig. 5.(a) & (b))

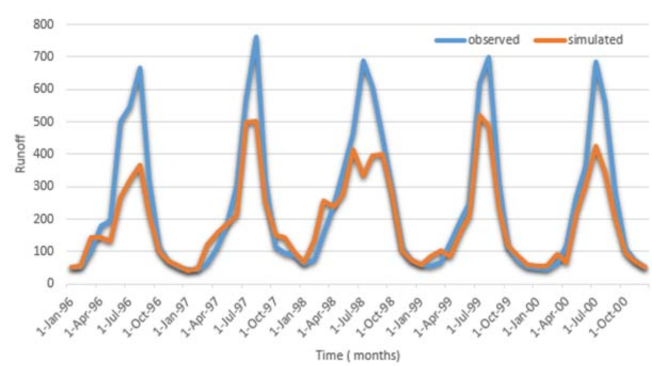


Fig.5 a)

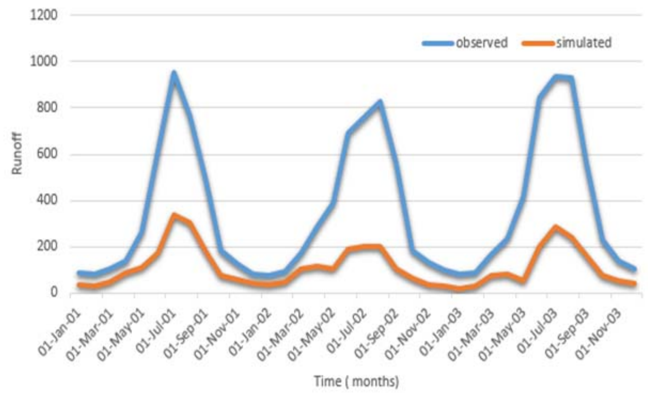


Fig. 5 Comparison of Observed and Simulated monthly run-off

a) calibration period of 1996 to 2000

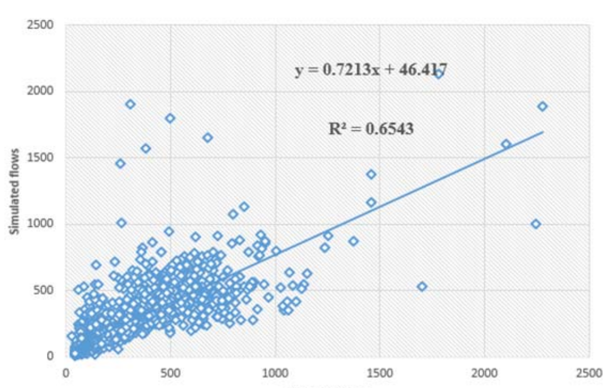
b) validation period of 2001 to 2003

Although the coefficient of determination is coming very good, but the graphs are showing water balance error because, the rain gauge stationed are available only in the lower elevation of Pandoh catchment & most of the higher altitudes are not gauged. The higher altitude is a region of high snowfall, but this is never recorded due to unavailability of accurate stations at such places. Therefore, the input rainfall judged by the low altitude gauges is not accurate as it doesn't include the effect of snowfall regions. Inaccurate and low input rainfall data is a major setback here.

The Base flow of simulated runoff is less than base flow of observed runoff. This can be attributed to low rainfall input data due to lack of gauges at high altitudes. The increase in differences in second graph is there because of different datasets for calibration & validation period.

Daily Assessment :

The coefficient of determination R^2 for calibration & validation was 0.65 and 0.44 respectively for runoff at the outlet point, as shown in the plot of observed and simulated values against each other in Linear Regression Line Diagram. (Figure 6. (a) & (b))



6 a)

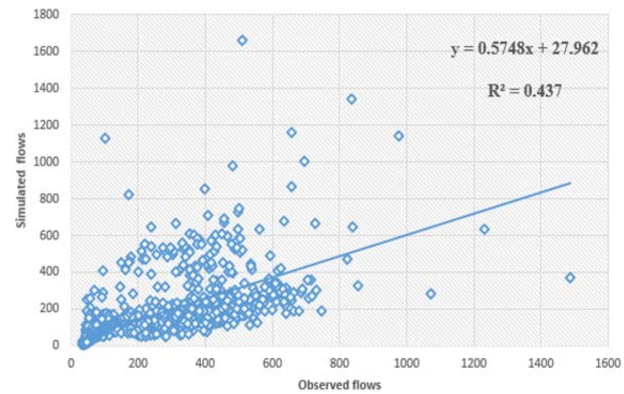
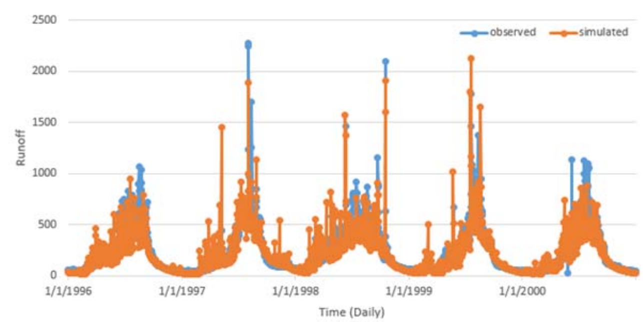


Fig. 6 Simulated vs Observed runoff for Daily

a) Calibration b) Validation

The time series of the daily observed and daily simulated for calibration (1996-2000) and validation (2001-2003) were plotted for visual comparison. (Fig. 7(a) & (b)) :



7 a)

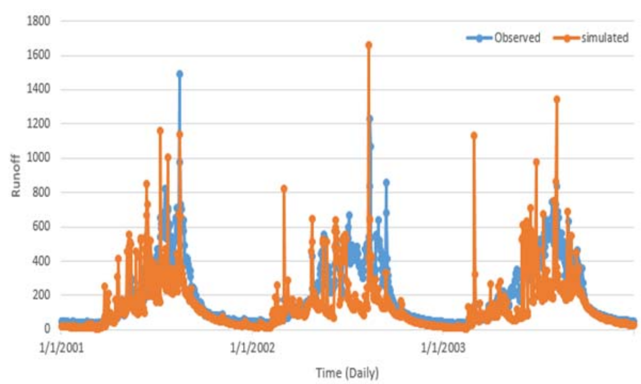


Fig 7. Comparison of Observed and Simulated daily runoff

(a) Calibration period 1996 -2000

(b) Validation period of 2001-2003

To refine the daily data and to highlight the trend of simulated and observed runoff, a ten day Moving Average method was run on above data. The refined results can be seen in Fig. 8.

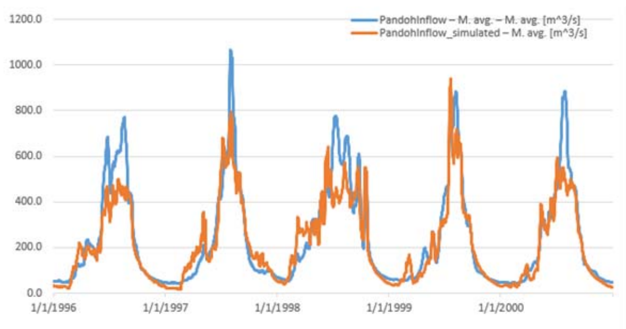


Fig. 8 Moving Average comparison of daily observed and simulated runoff

Most of the Pandoh catchment is snow fed. SWAT software is good for understanding the hydrological trend of the catchment (Fig 4.9) but it is clear from above graphs that it has limitations in analysis of snowmelt runoff, especially for a typical catchment like Beas. In the Beas valley snow accumulation takes place from October to March & snow melt in April to July. There are few permanent snow and glaciers also available in higher elevation of two sub basins – Manali & Bhunter. The presence of such amount of snow is not well accounted by SWAT, which shows up in ambiguity of its daily simulated runoff graphs.

Due to large portion of Beas basin being snow fed, the region is highly sensitive to temperature data. The accuracy of temperature data cannot be relied upon because of lack in good distribution of the temperature gauges at higher altitude. Snowmelt analysis requires detailed inputs which requires expert and experienced handling of the system. SWAT is complicated for snowmelt analysis. There are other handy tools available for snowmelt studies like WINSRM, NAM and MIKE 11.

Apart from snow fed related ambiguities, based on relativity of daily outputs and monthly outputs it can be noted that monthly simulation showed a better correlation than the daily values. It was reported that SWAT's daily flow predictions, in general, were not as good as monthly flow predictions (Jain et al, 2013).

This case study on the watershed of Himalayan watershed of Beas represents that SWAT is accurate in assessing simulations on monthly time steps. Swat's hydrological application for daily flows is not accurate for snow fed mountainous basins, whereas it is very good for monthly flows in the mountainous regions. The enhanced performance of the model could be achieved with some refinement in the input data.

10. CONCLUSION :

The Unique combination of intense seasonal precipitation, snow and steep topography makes the hydrology in the region of Beas very complex. SWAT is a model initially designed for agricultural terrains. SWAT model was applied to the Beas Sub basin to test its performance on the mountainous region.

The model was successfully calibrated and validated for the study area. The model evaluation statistics, the coefficient of determination evaluated is showing good results. Where R^2 for monthly and daily calibration is 0.89 & 0.65 respectively (1996 to 2000), for monthly and daily validation is 0.87 & 0.44 respectively (2001 to 2003).

The results show that performance of SWAT model is very good in simulating the monthly runoff from the Beas basin. The good results were verified by the criteria of Moriasi et al. (2007). For the daily simulations, the results of the study can also be assessed keeping in view the rainfall and runoff data used in the study that may involve a number of possible human and instrumental errors. The parameter values derived from various sources need to be verified in the field which is a difficult task in view of its approachability and mostly covered by dense forest.

In spite of all the uncertainties daily simulations are satisfactory. SWAT has been successful in evaluating the discharge at the outlet of the basin. The calibrated results can be further used to evaluate the most economical water management practices using the local water resources in the varying Land use practices. A limitation of SWAT that one comes across is it is not a user friendly software when it comes to snow fed regions where studying the effect of snow accumulation and snow melt is important.

SWAT appears not such a promising tool for intensive daily recordings like for flood forecasting. Although SWAT is a promising tool for extensive studies in both simple & complex terrains on land & water management in a variety of scenarios. In the present study an honest layout has been faithfully attempted to capture the latest technology in soil and water analysis in any watershed where the future prospects in the arena are promising.

A greater resolve is needed on behalf of all world countries to stand by the promises made to reduce carbon emissions to achieve our objectives by the target, 2020. Countries must work towards the common goal of reducing greenhouse gas emissions and must also abide by frameworks such as Kyoto protocol aimed at reducing global warming.

Also, reducing global warming and addressing climate change is the responsibility of not only governments but also its citizens, of each and everyone. We should collectively work to save energy by reducing unnecessary water usage, saving electricity, using public transport, recycling plastic, bottles, paper and waste.

If we make such small-small changes now in the way we live, we can avoid forced, huge positive changes in the future. Scientists, governments and individuals must work together to overcome this great threat of climate change.

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