ORIGINAL RESEARCH ARTICLE

Hydrological Modeling of the Paligad Watershed (India) Using HSFP model

Comment [r1]: ABSTRACT

Abstract

For hydrological studies, it is well known that each hydrological system behaves differently and in order to effectively manage those systems, it is necessary to understand their behavior. The hydrological component of Hydrological Simulation Program – FORTRAN (HSPF) model was set up and calibrated for Paligad watershed which is a sub-basin of Aglar watershed in the Uttarakhand state of India. The calibration of the model was done manually and an expert advice system called as HSPEXP+ was used to aid calibration. The values of evaluation indicators such as coefficient of determination (R^2), Nash-Sutcliffe efficiency, PBIAS and the mean error (RE) were found to be within acceptable range which also indicated good calibration and validation results. The validation results showed that the model nearly simulated the mean monthly runoff with the coefficient of determination (R^2) as 0.83 for the year 2015-2016. The total observed annual runoff volume was 32.26 inches, where the value of annual simulated runoff volume was found to be 30.37 inches indicating an error of -5.84% in the estimation of total annual runoff volume. The effect of change in land use/ land cover of the catchment can be evaluated using this model. This study offers more scope on the management of watershed output in the form of runoff and the impact changes in land use/ land cover on the streamflow from the basin.

Keywords: HSPF; Watershed modelling; Runoff; Hydrological modelling; Hydrology

Comment [r2]: 1. .INTRODUCTION

1.1 Introduction

Watershed modeling has nowadays turned out to be one of the most powerful tools for interpreting the hydrological response of a watershed and for simulating various processes occurring on a watershed scale. In the last two decades, many efforts were made to better understand the impacts of land use change on hydrological processes. The spatially distributed hydrological models were widely employed to predict the hydrological responses to land use change (Singh et al., 2015; Li et al., 2018b) [1,2]. Conventionally, this is done by setting up a hydrological model for a baseline land use scenario (LUS). After calibrating and validating the model, it is then re-processed for different LUSs using the same meteorological inputs. Subsequently, the differences between these simulations are compared. However, it is widely acknowledged that hydrological modelling is subject to a wide range of uncertainties, which are commonly from the measured input data, model parameters and model structure (Xu et al., 2007; Ma et al., 2018). [3,4] Considering these sources of uncertainty, it seems reasonable to doubt the reliability of the estimated hydrological responses to land use change, especially when minor or moderate responses were observed (Brath et al., 2006; Huisman et al., 2009; Yin et al., 2017). [5, 6, 7]. The models are not only effective in evaluating the impacts of land use/ land cover (LULC) and climate change scenarios on the watershed services, but are also critical in the disaster prevention and mitigation in a watershed. Modeling plays a crucial role in identification of the factors that drive the watershed related processes and often acts as a precise tool helping the planners to make decisions related to water resources, quality and other issues. Various management strategies related to watershed can only be applied once the related components of a watershed are taken into consideration. There are a number of hydrological models available at a watershed scale that can continuously simulate runoff from a watershed. Among those models, some of the most widely used and well-known models include SWAT (Soil & Water Assessment Tool), TOPMODEL, SHE and HSPF. Every model has its own area of application and limitation when applied to a particular watershed. In India, appreciable work has been done on SWAT model and the model may be considered as the most popular watershed hydrological model. HSPF model has been successfully applied in a number of watersheds across various parts of the world especially, in USA and China. However, with respect to the humid and semi-humid climatic conditions of India, very little work has been done on simulating runoff using HSPF. Several studies related to HSPF model development especially towards the development of model calibration method, extension of model function and parameter sensitivity analysis are still undergoing. Keeping in view all of these concerns, it was necessary to introduce the concept of watershed hydrological modeling using HSPF for the Paligad, sub-basin of the Aglar watershed. The HSPF Model is a U.S. EPA program for simulating the hydrological and water quality parameters in a watershed. The model is essential towards the simulation of runoff accurately and estimation of various factors playing role at the watershed system scale. The objective of this research work is to calibrate, validate and evaluate the performance of hydrological component of the HSPF model in Himalayan conditions. The calibrated model hence developed could be used in the later stages to evaluate the impacts of climate change scenarios and different management practices on the basin characteristics.

2.2 Materials and Methods

Comment [r3]: 2. MATERIAL AND METHODS

2.1.1 Study area

Comment [r4]: 2.1 Study Area

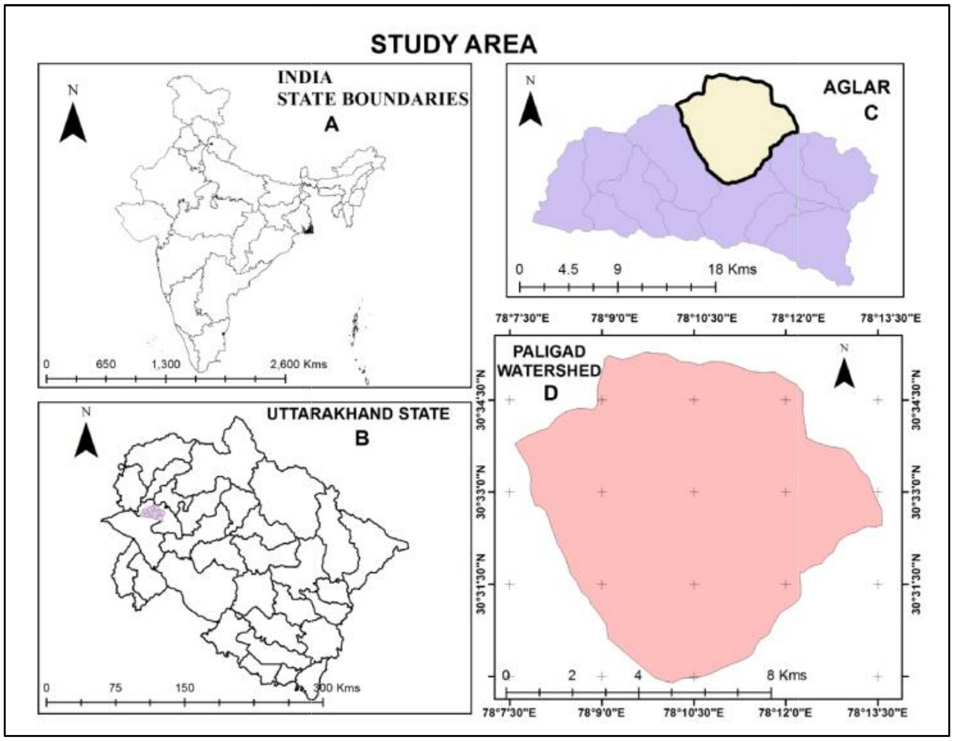

Fig1. Location of the study area

The present study area of Paligad watershed is located in the Lesser Himalayan region in the Tehri Garhwal district of Uttarakhand state in India fig 1. The total drainage area of the watershed is 59 km^2. Geographically, the area consists of lower Himalayas, sub-Himalayas, structural hills, terraces, flood plains, etc. The maximum and minimum elevations of the study area are 1172 m and 3011 m respectively. The area is also known for frequent landslides and is also erosion prone. The mean annual precipitation of the area is around 2023 mm comprising of rainy, winter and summer seasons ~~(Saha and Singh, 1991)~~. [8] The mean monthly minimum temperature ranges from 2 ^{0}C in January to 16 ^{0}C in July, whereas mean monthly maximum temperature in the study area varies from 11 ^{0}C in January to 26.0 ^{0}C in June. The rainy season begins with the onset of monsoon almost in the mid of June and continues till 2nd week of September. A considerable amount of rainfall (about 70%) in the region is received from July to September when the South-West monsoon is active in the region. The total number of rainy days varies from 70 to 80 in a year. The gauging station lies at 30°29'48.44" N and 78° 9'44.44" E at the outlet of the Paligad watershed. The data of runoff received at the outlet of the watershed was obtained from the numerous measurements of stream discharge made over a range of stream stages readings using a rating curve developed for the gauging station.

2.1.2 HSPF model description

Comment [r5]: 2.2 HSPF Model Description

HSPF model developed by U.S. Environmental Protection Agency (USEPA) is a continuous simulating and distributed watershed model for simulating the quality and quantity of water at any point within watershed. HSPF model is included in the USGS's watershed management system called BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) (Donigian, 1995). [9] BASINS plays a very important role as a watershed assessment tool and is utilized for downloading data, delineating the watersheds, building modeling projects, assessing information, and creating reports. In the underlying advancement, capacities and procedures incorporated into HSPF were originally derived from the previous existing models that simulated data related to water quality and quantity separately. The development of FORTRAN version called HSPF funded by ER Laboratory in Athens was an integration of three programs: Hydrologic Simulation Program (HSP), Nonpoint Source Runoff Model (NPS) and Agricultural Runoff Management Model (ARM), into a more compact and better-structured model fig 2.

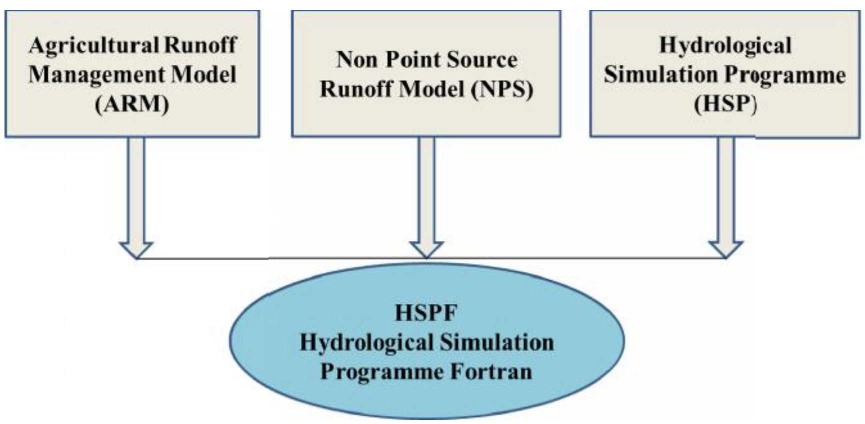

Fig 2. Development of HSPF Model

HSPF has three application modules, i.e., PERLND, IMPLND, and RCHRES. The PERLAND module simulates hydrological responses over pervious land such as grassland, agriculture etc., IMPLND simulates hydrological parameters related to quality and quantity of water over impervious land segments such as paved roads, parking lots, whereas the RCHRES is for simulation over watershed reaches such as rivers and reservoirs (Bicknell et al., 2001). [10]. PWATER module may said to be one of the intrinsic part of the module PERLND primarily used to predict the total runoff from a pervious area. HSPF utilizes the idea of HRU (Hydrologic Response Unit) to partition the watershed into homogeneous portions called as reaches. The soil layers are also divided vertically in each HRU into lower-zone, upper zone, and groundwater zone contributing actively to the flow. The approaches adopted for simulating hydrological processes such as surface runoff, infiltration, snowmelt runoff and channel routing in HSPF model include Chezy-Manning, Philip equation, Energy balance and Kinematic wave approach respectively.

~~2.1.3 HSPF input data requirements~~

Comment [r6]: 2.3 HSPE Input Data Requirements

HSPF model setting up requires input data consisting of a land use map, digital elevation model (DEM), meteorological data, stream network and runoff data. The minimum data needed for running the HSPF model for a watershed is shown in Table 1. Quality data with good resolution will give better results.

Table 1. Data required for HSPF model set up

Data type	**Scale**	**Source**	**Data Attributes**
Topography	10 m	USGS Data Interface https://earthexplorer.usgs.gov/	DEM
LULC	30 m	USGS Data Interface https://earthexplorer.usgs.gov/	Classified into LULC classes
Meteorological	Daily Data	Precipitation measured in the watershed	Daily Rainfall, Daily Max. and Min. Temperature, Daily PET
Hydrological	Daily Data	Measured at the watershed outlet	Daily Observed Discharge
Stream Network	Polyline Shape file	Geo-processing digital elevation data	Drainage network

~~2.1.4 Hydrological modeling and calibration~~

Comment [r7]: 2.4 Hydrological Modeling and Calibration

The suitability and accuracy of a model to a study area depends on how well the observed data matches with the simulated data. The calibration of the model is done by adjusting the model parameters that are sensitive to the simulation of hydrologic processes in HSPF model. The main aim of the calibration is to bring the runoff simulated and observed in agreement with each other. The model is the validated to determine its applicability to a particular watershed and accuracy of calibration. The observed data in the form of discharge was recorded from 01/04/2014 to 16/04/2016 for the Paligad watershed. The model was calibrated for a period of one year from 01/04/2014 to 31/03/2015 and validated from 01/04/2015 to 31/03/2016. In order to simulate runoff for a discharge gauging station by HSPF model, observed runoff is required as an input to the model. The available data is saved in the input time series .Wdm file. The whole area is divided into 5 reaches consisting of different LULC categories. All the data which are required as an input for the model are analyzed and processed in the BASINS interface. A watershed characterization report generated from the BASINS gives an idea of the different types of LULC category existing in the study area is as shown in fig3 and their distribution in table 2.

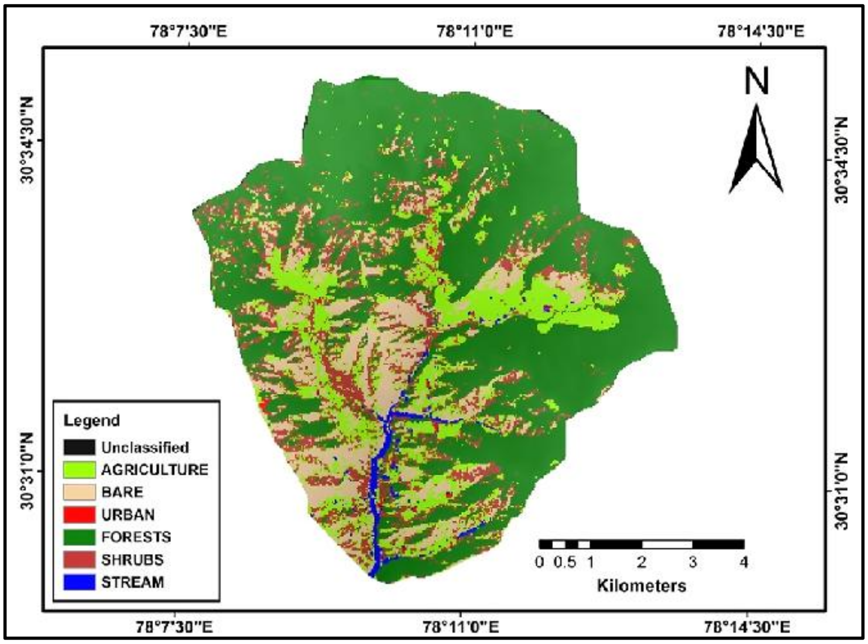

Fig 3. Map showing spatial distribution of LULC categories within the study area

Table 2. Watershed characterization report for Paligad watershed

Description	Area(km^2)	Portion of watershed (%)
Agriculture	9.98	16.83
Bare	7.36	12.41
Forests	32.5	54.8
Shrubs/Grassland	8.34	14.06
Water-body	0.87	1.47
Build-Up	0.24	0.41
Totals	59.3	100

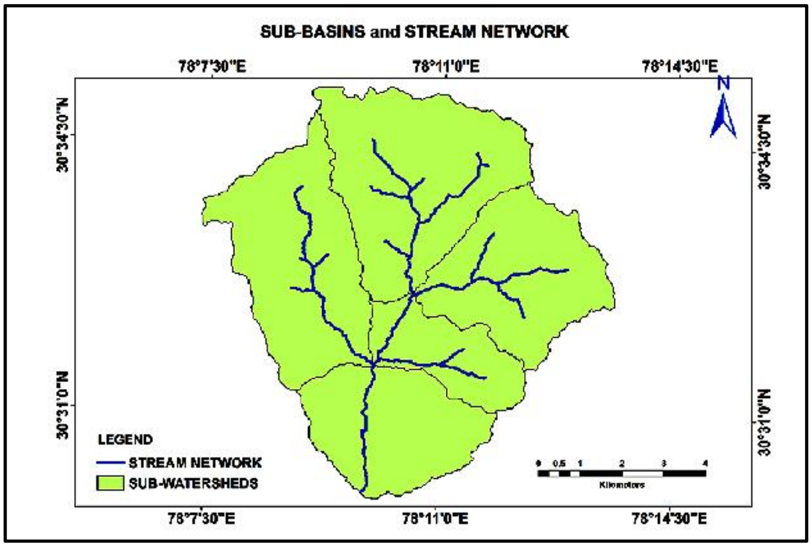

Fig 4. Showing stream network and Sub-basins of Paligad watershed

For HSPF hydrological modeling, it has been found out that there are certain parameters for simulating the pervious land hydrology which are the components of the simulation equations. Each parameter will affect the flow volume differently. Around nine key model parameters including six from PERLND and three from IMPLND were selected for capturing the major processes occurring in the watershed. The basins technical note 6 was used as a reference for selecting the optimum values of the parameters (USEPA). Based on the observed flow data measured at the outlet of the Paligad watershed, calibration of these parameters was done. All these model parameters have been used for calibration of the model and all of them are process based and cannot be measured directly. There were certain parameters such as AGWRC and DEEPFR which found to be highly sensitive fig 4 and table 3. It was found that for the study area, the LSUR and SLSUR values were very different from the common types of low relief watersheds, since it being a rugged terrain.

Table 3 Average slope of assumed overland flow path

Perland	Class	SLSUR
101	Agriculture/Crop Land	0.35
102	Bare	0.50
103	Build-up	0.31
104	Forests	0.49
105	Waterbody	0.28

~~3.1 Results and Discussion~~

Comment [r8]: 3. RESULTS AND DISCUSSION

Comment [r9]:

3.1 Model Verification

Comment [r10]: Add this subtitle

The performance of HSPF model in Paligad watershed can be evaluated on the basis of the statistical parameters and visual analysis of maps and graphs. The appropriate range parameters relating to the watershed hydrologic and flow characteristics hence evaluated help to understand the hydrological behavior of the Paligad watershed. It is established upon calibration that few hydrological parameters viz. LZSN, DEEPFR, INTFLW, AGWRC and UZSN have a significant impact on the model output. It is observed that the watershed is sensitive mostly to the ground water related parameters (DEEPFR and AGWRC) than near surface parameters which suggests that a major portion of precipitation reaches outlet of the watershed as subsurface flow. The difference between the peak of rainfall and runoff indicates that a major portion of runoff follows subsurface route to reach the outlet of the watershed. It is well know fact that the INFILT and interception is usually high for forests than other LULC classes which were used here in the model calibration table 4. The model usually takes values of interception constant through all the period of simulation which in reality is not the case. The interception varies with the seasons and months with higher values during rainy seasons.

Table 4 **Final calibrated values of model calibration parameters**

Parameter	Definition	Range	Calibrated Value
$LZSN^{101}$ **$LZSN^{104}$**	Lower Zone storage nominal	**3-8 inches**	**3 inches** **4.21 inches**
DEEPFR	Fraction of GW inflow to deep recharge	**0.0-0.20**	**0.1 for all PERLANDS**
INFILT	Index to infiltration capacity	**.01-0.25**	**0.17/0.11/0.09/0.15**
LZETP	Lower Zone ET	**0.2-0.7**	**0.1 for all PERLANDS**
INTFW	Interflow parameter	**1-3 inch/ hr**	**2 for 104 and 2 for all PERLANDs**
$AGWRC^{101}$	Groundwater recession rate	**0.92-0.99** / day	**0.975**
AGWETP	Fraction of remaining ET	**0-1**	**0.3**

	from active GW		
UZSN	Upper zone nominal soil storage	**0.1-1 inches**	**1 for 104 PERLAND**
IRC	Inflow Recession Constant	**0.3-0.85 /day**	**0.7**

*PERLANDS: -101- Agri. land, 102- Bare, 103- Buildup, 104- Forests, 105-Waterbody

It can be observed from the plot (Fig. 5) on the basis of precipitation that the model is very sensitive to precipitation. The topography of the watershed allows the rapid flow to appear at outlet within a short time. Any abrupt storm results in an increase in the discharge where as during times where there is no precipitation, the discharge is remaning constant. There has been no proper simulation between the initial months from April to July. It can be observed that the initial values of storage of active groundwater is one of the reasons. The parameters of active groundwater storage is called AGWS and finding its appropriate value is far challenging. If too high or too low, base flow remains skewed or excessively low for several months or years, depending on AGWRC and KVARY. Accordingly the values of GWVS should be set to 0.0 and AGWS to 1.0 inch and for initial simulation runs. The desired simulated values were obtained only once the AGWS was set to 0.975 which show that appreciable amount of water reaches the outlet as delayed interflow. It can also be observed that the initial results were skewed with very high peaks. After calibration, the error in average storm peak decreased to -9.415% while the acceptable rangle is 15%. The rate at which interflow is discharged from storage is affected by IRC (Interflow recession parameter). Thus IRC affects the hydrograph shape in the recession/ falling limb which is the region between base flow commencement and peak storm flow. The maximum value range is 0.3 – 0.85, with lower values on steeper slopes; values near the high end of the range will make interflow behave more like baseflow,while low values will make interflow behave more like overland flow. Based on whether simulated storm peaks recede faster/slower than measured, IRC should be adjusted once AGWRC has been calibrated. A value of 0.7 IRC was found to be optimum for the present study area which indicates that more flow enters the stream as interflow.

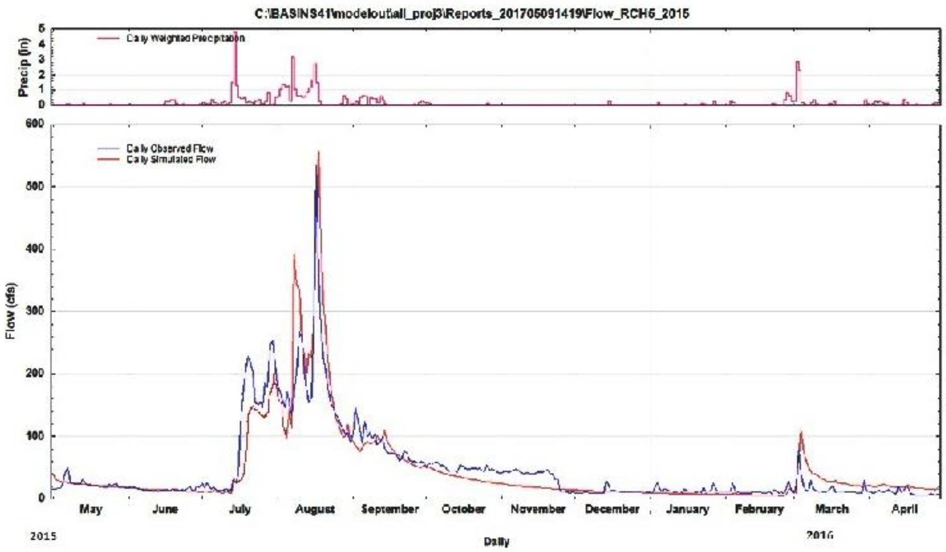

Fig 5. Time-Series Plot of Daily Observed and Simulated Streamflow at Paligad

The results for the year 2015-2016 were evaluated on daily and monthly basis. Most of the rainfall is mainly seen between the months of June and October which corresponds to the rainy season in the area. Precipitation leaves the watershed either as stream flow or evaporation. Initially the model over-simulates the streamflow, it is observed that the annual simulated evapotranspiration less than the actual observed evapotranspiration for the area. A multiplication factor for evapotranspiration was found to be 1.18 which was used to adjust the values of evapotranspiration. This was done to improve the evapotranspiration, the low value of which otherwise causes the model to over simulate. The greater the evapotranspiration volume from the catchment, the lesser water would end up in Stream network. The HSPEXP+ software gives results to aid calibration in the form of graphs and certain statistical criterion's such as coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), PBIAS and RMSE error. Certain hydrograph characteristics such as recession curve trends, peak matching and any general agreement are observed visually through visual comparison fig 6.

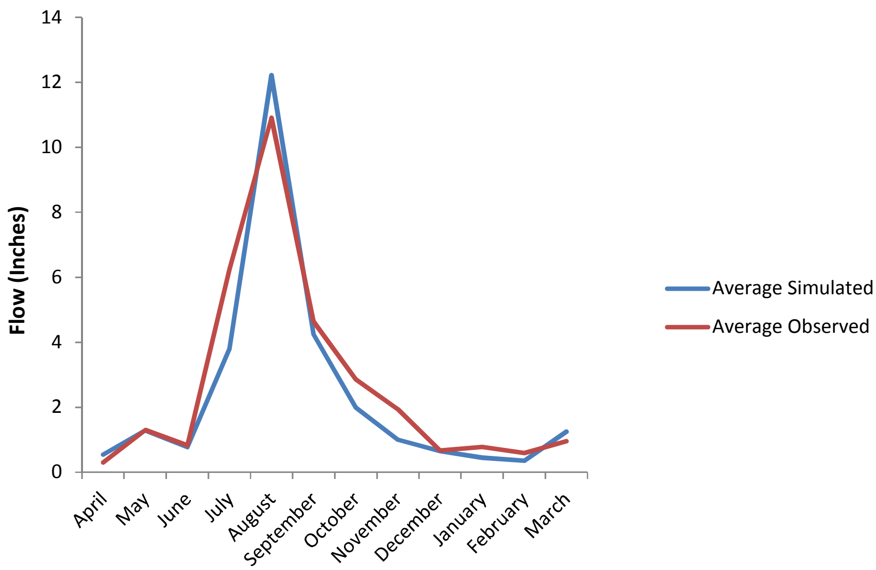

Fig 6. Observed and Simulated Mean Monthly Streamflow for Paligad

It can be observed during validation that the model output for the monthly flow there is a total residual difference of 3.904 inches in the total flow. The error is quite significant in the July month. There may be a difference in soil moisture conditions and the antecedent precipitation between the storm events. For the low flow values of streamflow, it was found that simulated values of the flow were close to the observed ones. These results indicate the suitability of the HSPF model for the study area. HSPF model applied to Paligad watershed showed better results and it can be concluded that the model is a better semi-distributed model for simulation of hydrology. The efficiency of HSPF model for simulating hydrology comes from the fact that it can simulate and output all the components of water-balance. HSPF has the capability to model the segments separately including the evaporation losses. The values of two times series TS1 and TS2 are given below for observed and calibrated stream flow (Fig. 7). The estimated and observed daily streamflow were analyzed by comparing the value using a flow duration curve as shown below**.** It can be observed that in general, the agreement between the observed and predicted FDCs is reasonably good (Figure 7) where R is greater than 0.80 for all percentages (Q_p) of FDC.

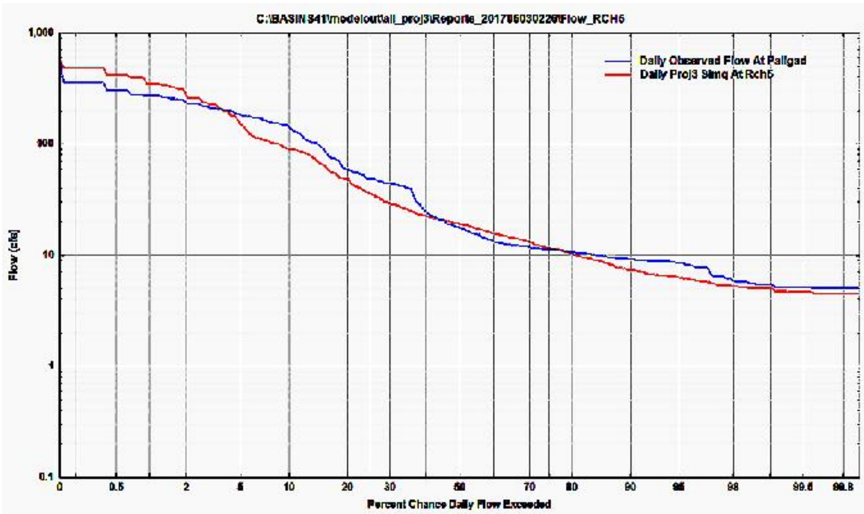

Fig 7. Flow Duration Frequency Curve between Observed and Simulated Flows

~~3.1.1 Evaluation of model output~~

Comment [r11]: 3.2 Evaluation of Model Output

There are certain statistical parameters on the basis of which the performance of a model can be evaluated. The output of the calibrated model HSPF for the monthly flow estimated values of simulated flow and that of the observed flow are close to each other. The accuracy with which the values are simulated can also be confirmed from the flow duration curve (Fig 7). For monsoon events the over under-simulation for the month of July which could be some error in the observed data for that period. The performance status of a model can vary from unsatisfactory to very good. For the present study the coefficient of determination for the daily and monthly flow for the year April 2015-April 2016 were evaluated. Any error in the total annual streamflow volume for the entire one year run was calibrated first. For total one year run, the volume of total observed flow was 32.26 inches, where the value simulated flow was 30.375 inches. So there was an error of -5.84% in the estimation of total annual runoff from the catchment. It was found for the present study during validation that the correlation coefficient on daily and monthly basis at reaches 5 (outlet) are 0.84 and 0.94 respectively. The values of correlation coefficients suggest that the performance of model in relation to the estimation of total flow volume for the entire period was in close conformity to the observed flow volume. Another criterion for evaluating the performance of the HSPF model was to find the coefficient of determination. The coefficient of determination also pronounced as the R square and denoted as r^2 or R^2 is an indication of the proportion of variance in the simulated flow that is predicted from the input independent variable. The range of values for R^2 lies in between 0 to 1. R^2 value of 1 points to a perfect fitting of data on the regression line.

$$R^2 = \frac{\left[\sum_{i=1}^{n} (y^i_{sim} - \bar{y}_{sim}).(y^i_{obs} - \bar{y}_{obs})\right]^2}{\sum_{i=1}^{n} (y^i_{sim} - \bar{y}_{sim})^2 . \sum_{i=1}^{n} (y^i_{obs} - \bar{y}_{obs})^2]}$$

$$NSE=1- \frac{\sum_{i=1}^{n} (y^i_{obs} - y^i_{sim})^2}{\sum_{i=1}^{n} (y^i_{obs} - \bar{y}_{obs})^2}$$

$$RE = \frac{\sum_{i=1}^{n} (y^i_{sim} - y^i_{obs})}{\sum_{i=1}^{n} y^i_{obs}} \times 100\%$$

here i is day, $\bar{y}_{sim}$ is average simulated flow of simulated period y^i_{obs} is daily observed flow in i day, y^i_{sim}daily simulated flow in i day, y^i_{obs} is daily observed flow in i day, $\bar{y}_{obs}$is average observed flow of simulated period.

A systematic approach was followed for evaluating the sensitivity of a parameter to affect the flow and adjustments in parameters were made one by one thereby reducing the uncertainty. More than 200 runs were made until satisfactory results were achieved. Another important criteria and statistical parameter utilized for comparing the HSPF model output results was the Percent Bias or the PBIAS table 5. It may be said to be a measure of the tendency of the data values simulated by the model to be greater or smaller than the observed data. The values of PBIAS can be either zero or greater than or less than 0. If the value of PBIAS is less than 0 or in other words it is negative, it shows that the hydrological model is under-simulating.

PBIAS values for the measurement and analysis of discharge during validation on daily and monthly basis were found to be -10.05% and -4.874 % respectively. From the result it can be concluded that there is good model fit.

Table 5 Statistical evaluation parameters for monthly discharge data

Statistical coefficient	R^2	NSE	PBIAS	MEAN ERROR
Calibration (2014-2015)	0.83	0.81	-4.874	-3.461

After validating the model for period (2015-2016), the total annual observed and simulated flows were found to be 32.26 and 30.375 inches respectively showing an error of 5.854% which is well within acceptable limits of 20%. From all these results, it can be inferred that the model accurately represented the system and the hydrological processes taking places in the system. The calibration was based on adjusting certain parameters in their suitable range. Better calibration results can be achieved if the experimental data is available for these parameters. On the basis of monthly mean flow data, it can be concluded that the simulation of HSPF for monthly runoff flow can be said to be excellent. The daily data also showed that the simulated values were also very much close to observed values. For rainy seasons, the error difference is less compared to the non-rainy seasons, showing that HSPF simulated rainy seasons better than the dry season. These results verify the fact that HSPF responds better to the rainfall.

4.1 Conclusions and Summary

Comment [r12]: 4. SUMMARY AND CONCLUSIONS

For hydrological analysis it was observed that the efficiency of HSPF (Hydrological Simulation Programme Fortran) model for simulating hydrology comes from the fact that it can simulate all the components of water balance. The value of DEEPFR which is the recharge to deep aquifers was calibrated at 0.1 which shows appreciable amount of water is lost to recharge of deep aquifers and hence not available at outlet. This result confirms that the area consists of highly dissected hills which were earlier confirmed from geomorphological map of the area (Rupke, 1974) [11] . Hydrological simulation results of HSPF model applied to Paligad sub-basin of Aglar watershed were reasonably closer to the observed data. For adjusting the shape of the hydrograph, the parameters of IRC, UZSN and INTFW parameters were calibrated. The values of IRC and UZSN were calibrated at 0.7 and 1 respectively. These values indicate that interflow and delayed interflow are the major modes of movement of water in the system. Initially the model simulated very high peaks during calibration and during validation the error in 10% highest flows got reduced to 0.731% way below acceptable limit of 20%. It was found that the calibration on a seasonal basis for the present study area was successful with statistical values within acceptable limits. Also the agreement between simulated and observed flow rates for year was found to be good. The error in the seasonal flow volumes was -14.52% which is well within acceptable limit of 25%. Any change to adjust the difference during calibration affected the accuracy of the model. The current model results are analyzed for a shorter time period from April 2015 to March 2016 of observed data availability constrains. In future, the model will be validated for longer time period data. It is also worth to mention that there is a lot of work can be done using the model developed in the present study. Based on the results regarding flow paths generated from HSPF model, it was concluded that in the upper, steep and well-drained portions of the Paligad watershed most rainfall infiltrated into the soil. The model was setup and calibrated for only hydrological component due to unavailability of observed data for quality of runoff water. However the basic aim of the present research was to evaluate the applicability of HSPF model in Himalayan condition in India to simulate runoff. Also the model was setup to provide continuous runoff data at outlet to serve as check against the observed data. The model can also be used to predict the response of the catchment to changes in land use/ land cover. This study offer more scope to the management of watershed and the effect the change of any land use will have on the streamflow from the area. The model could be used to predict future climate change scenarios. The model can be extensively used in various watershed analyses, such as in the assessments of the impacts of urbanization, climate change and LULC change, and as well as in water budget estimation. For calibration processes and model formulations, the HSPF model provides a wide range of flexibility. The model would also aid to study the functions and interactions of various inputs, and get a better understanding as to how the hydrological system actually works. Therefore more concern should be laid regarding determining the impact of precipitation and soil conditions on the model equations also.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors

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Writing of sections and subsections should follow the journal style regarding the the small and capital letters.

Captions of figures should follow the regulation of journal regarding capital and small letters to be consistent

Add subsection title : 3.1 Model Verification as shown