Hydrological Simulation using Process Based and Empirical Models for Flood Peak Estimation

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Abstract This study introduces about the parameterization of hydrological modelling for Asan and Song river basin the whole Doon Valley. SWAT an empirical hydrological model, VIC a physical hydrological model and HEC-HMS a semi distributed hydrological model are used for flood peak generation at predetermined locations. The land cover mapping of Doon Valley was attempted using remotely sensed images of Landsat and Google Earth imagery. The specific objectives are hydrological modelling for peak flow hydrograph generation, to observe LULC change scenarios between 1995, 2005 and 2014 year, comparison and validation of the simulated runoff using three different hydrological models (VIC, SWAT and HEC-HMS). The VIC model performance was found good and a close agreement between the observed and simulated values was obtained for 2014 LULC map. Model performance was also found good for other subbasins. The various input parameters are the meteorological data, discharge and sediment data were processed as per requirement of the SWAT model. The model was calibrated for the year 2006 to 2010. The Hydrological modeling indicates that the curve number is most influence parameter into the total discharge. Land use and vegetative cover play an important role in watershed runoff and stream flow discharge patterns over time, including peak flows. Increased human interventions have caused rapid transitions in land cover, adversely affecting the watershed processes and hydrological cycle in the long run. It may be concluded that the impact of land cover changes are most pronounced during low flows and that during high flows, role of land cover becomes comparatively less.

Keywords Coefficient of determination; Hydrological modelling; HEC-HMS; LULC; SWAT; VIC

1. Introduction

Hydrology is defined as the science dealing with the movement of water over and under the land surface and a hydrological model can be defined as a mathematical representation of the flow of water and its constituents on some part of the land surface or sub-surface environment. Hydrologic modeling has been going on for at least 150 years. Over the last century, land use land cover (LULC) in the lower Himalayan region shifted from perennial, cropping, fallow land to built-up area. Historical LULC change impacted the annual water balance in many basins by decreasing annual evapotranspiration (ET), water yield and increasing runoff (Yong et al., 2015).

Recent expansion of the industry and urbanization may lead to future LULC changes from needed plantation to urban (Garg et al., 2012; Engman et al., 1996). The little change in LULC, affects the
hydrological processes and lastly the water balance. In matter of comfort and development, human being keeps on changing the environment especially LULC resulting in huge urbanization that significantly influence hydrologic variations (Bradford et al., 2007). The continuously changing environment makes it necessary to realize and compute various hydrological components for competent water resource management. The water resources management requires a systems approach that includes not only all of the hydrological components, but also the interactions, links, consequences, relations and implications among these components (Islam et al., 2014). A thorough knowledge and understanding of the different hydrological phenomena and hydrological cycle as a whole is required in studying the implications of these changes (Bhattacharya et al., 2013).

In this regard, the hydrological modeling technique can help to gain an understanding of the hydrological system in order to provide reliable information for managing water resources in a sustained manner at smaller scale and larger scale (Kiriwongwattana & Garg, 2013). In this study, Variable Infiltration Capacity (VIC) semi-distributed hydrological model, SWAT (Soil and Water Assessment Tool) a physical based semi distributed hydrological model and HEC-HMS (Hydrological Engineering Corporation - Hydrologic Modeling System) a semi distributed hydrological model has been used for hydrological simulation.

1.1. Study Area

Valley is situated in Dehradun district of Uttarakhand, it is lying geographically between 29°50 N-0°30 N Lat. and 77°35-78°20 E long. Maximum length of Doon valley is 80 km and 25 km in width. In the Sub Himalayan region it is considered as one of the largest ‘duns’. River Ganga flows in eastern and river Yamuna flows in western side of Doon Valley. Two rivers, Song and Asan river systems drained in Doon Valley. These rivers receiving water through a number of perennial and non-perennial streams originated in Lesser Himalayan rocks in north and Siwalik in south direction and finally contribute to the discharges of Ganga and Yamuna River in east and west, respectively (Dudeja et al., 2011). The
Dehra-Asarori water divide, running NE-SW from Clement Town, Dehradun city to Rajpur, separates the NW flowing river Aasan from SE flowing river Song. Generally temperature of this area is temperate. Depending upon the altitude of the area temperature varies greatly from tropical to severe cold. The district is hilly so that temperature variations possible because of difference in elevation. Summer is pleasant in hilly regions but in the Doon, the heat is often intense, although not too much temperature as in the plains of the adjoining district. During the summer months, the temperature varies between 36°C and 16.7°C. The winter months are colder with the maximum and minimum temperatures moving from 23.4°C and 5.2°C respectively. The average rainfall of the area is 2073.3 mm. Most of the annual rainfall in this area is achieved during the months from June to September and the rainiest months are July and August (Singh et al., 2013).

1.2. Data and Materials

ISRO GBP LULC 1995, 2005, 2014 developed by Indian Institute of Remote sensing, Dehradun was used for mapping land cover in the region. Originally the map was prepared for 14 classes at a scale of 1:50,000 but as the extent was limited to Indian region only, the map was reclassified and recoded to 9 classes as present in Global land use land cover map so that it can be merged with it and facilitate information for Aasan and Song watershed (Doon Valley) extending beyond Indian boundary. ASTER Global Digital Elevation Model (GDEM) was used in the present study. Cloud free Satellite data of Landsat 5 dated 17-Nov-1994, 18-Feb-1994, 10-Jun-1994 & 27-Mar-1996 and Landsat 8 dated 13-Mar-2014, 23-Oct-2014 and 12-Feb-2015 with special resolution of 30m for the year 1994, 1996, 2014 & 2015 corresponding to the study area were downloaded from the global land cover facility (GLCF) website to quantify the changes in the land use/land cover type of the area and to analyse its impact on surface runoff and sediment. Digitized soil maps of Doon Valley lying in India were obtained at 1:50,000 scale. Soil mapping for Indian region has been done by NBSSSLUP (National Bureau of soil survey and Land use planning), Nagpur. Some of the associated soil properties were also derived from it. Daily metrological data such as rainfall, minimum and maximum temperature, pan evaporation data were obtained from Automatic Weather Station (AWS), Dehradun and National Institute of Hydrology (Roorkee). The daily rainfall was used as an input to the ArcSwat Model, HEC-HMS Model, and VIC Model. The maximum and minimum temperature was used to calculate potential evapotranspiration (El-Sadek and Salem, 2015).

2. Methodology

Variable Infiltration Capacity (VIC) model is a grid-based macroscale hydrological model designed to represent surface energy and hydrological fluxes for large river basins (Terrestrial Hydrology Research Group, Princeton University, 2007). Most important characteristic of this model include sub-grid variability in surface vegetation classes, soil moisture storage capacity and drainage from the lower soil moisture zone also known as base-flow. VIC model contain a Routing model which is based on linear transfer function to simulate stream flow for basin (Liang et al., 1994). VIC model run on VIC tool that was developed as a part of the ISRO-GBP project on LULC dynamics and impact of human inversion in Indian River basins. The input layers required for the model are Terrain (Elevation, Slope, Flow Direction), LULC, Vegetation properties (LAI, Albedo, Root Distribution, Canopy Resistance), Soil properties (Layer-wise physical texture and hydraulic properties), River discharge data, Meteorological inputs from downscaled GCM (Precipitation, Temperature). The input files which are used to calibrate and validate VIC model are grid files (Latitude, Longitude, Grid number, Run grid, Soil_1, Soil_2, Slope, Elevation, Rain), soil database file (describe the characteristic of the soil layers for each grid), vegetation parameter file (contains land cover characteristics on a monthly average basis), forcing file (daily maximum and minimum temperature (in °C) and daily precipitation (in mm)) and global parameter file as input in VIC tool, the model runs if it stops at any place encountering error in any of
missing file the model will restart. The VIC model runs in CYGWIN rather than in the tool. The VIC tool has an added feature that can generates a tabular analysis of output fluxes. Primary input files required to run Routing model are Flux file (containing fluxes of surface runoff, evapotranspiration, base flow, soil moisture), Flow direction file, Fraction file (contains fraction of each grid), Station location file (contains details of row and column in the grid shape file) and unit hydrograph file. Calibration has been done by adjusting the infiltration parameters and the base-flow parameters at which non-linear base-flow takes place. The soil parameters have been altered since VIC primarily considers the infiltration capacity curve and nonlinear base-flow curve that occurs predominant at the lower layers of the soil. The process continues until the simulated stream flow is almost equal to pragmatic stream flow at given outlets.

Figure 2: Methodology flowchart of three different hydrological models

The steps which are followed to set-up the model and input database in SWAT model are watershed delineation using source DEM, land use, soil types and climate data (Merwade & Rajib, 2014). A few additional inputs are required for running the model are management data, soil data, soil chemical data, manning’s roughness coefficient and in stream water quality parameters (Betrie et al., 2002). These input files were set up and edited as per the requirements and objective of the project. Finally, the ARCSWAT model runs to simulate the various hydrological components. Calibration is done to minimize the difference between simulated and observed stream flows. In the present study the ARCSWAT model was calibrated for the year 2006-2010 based on the observed discharge and sediment data and the model was validated for monthly and daily surface runoff for the year 2006 to 2010.

Hydrologic Engineering Centre-Hydrological Modelling System (HEC-HMS) is design to simulate the hydrologic process of dendritic watershed systems. Curve Number are used for loss estimation in HEC-HMS model, it is prepared by the combination of LULC and soil map. HEC-HMS model is running
from 1 July to 1 August of 2006 year, and 29 July to 1 August of 2010 and 2012. Curve Number (CN) and initial abstraction are used for sensitivity analysis in year 2006.

3. Results and Discussion

As per the objectives, the Asan and Song River basin was delineated and various thematic maps were generated as per the requirement of the SWAT, HEC-HMS and VIC model. The various database related to climate and soils were also prepared as per the requirement of the model. Various hydrological components like surface runoff, sediment yield, Evapotranspiration (ET), PET were simulated on daily, monthly and yearly basis. The predictions of the model for weekly and monthly surface runoff and sediment yield were compared with the measured counterparts (Kumar et al., 2013). The performance of the model was also evaluated using statistical and graphical methods to decide the capability of the model in simulating the runoff and sediment yield from the Asan & Song basin. Land use/land cover change scenario and its impact on the hydrological regime is also presented and discussed in this paper.

![Watershed delineation of Doon Valley](image)

**Figure 3: Watershed delineation of Doon Valley**

Basin boundary and drainage characteristics of the watershed were derived in ArcMap10.1 software using Aster Global Digital elevation model (250m & 30m) as major input. The following operations were fill sinks, flow direction, flow accumulation, stream link, stream order, catchment polygon processing, drainage line processing, watershed and sub-watershed. Flow direction map is derived from fill sink map and subsequently a flow accumulation map is derived from it. Stream definition is derived from this flow accumulation by specifying the maximum threshold area for delineating drainages. A sub-watershed for each delineated stream is then extracted. To extract the basin boundary, an outlet at Paonta station in the Asan river basin and Rishikesh station in the Song river basin was defined. Finally, a basin for the defined outlet is delineated along with the river network. It
can further subdivide basin into desired number of sub-watersheds by specifying various outlets where the gauging station exists along the extracted (Dadhwala et al., 2010).

In order to prepare the LULC map for Asan & Song Basin, the downloaded FCC of Landsat TM and Landsat ETM satellite image for the year 1995, 2005 and 2015 were subsetted to extract the area of interest and classified with supervised classification method using maximum likelihood classifier as discussed and presented. In order to check the accuracy of the classified images accuracy analysis was also carried out using accuracy assessment classifier of Erdas imagine 2014 using ground truth information collected from field (Baishya et al., 2006).

![LULC map of 1995 and 2014 year of Doon Valley](image1.jpg)

**Figure 4:** LULC map of 1995 and 2014 year of Doon Valley

**Table 1:** Change detection matrix for 1995-2014

|                | Water bodies leaf forest | Evergreen leaf forest | Deciduous leaf forest | Mixed forest | Shrub land | Plantation | Crop land | Fallow land | Built-up |
|----------------|--------------------------|-----------------------|-----------------------|--------------|------------|------------|-----------|-------------|----------|
| Water bodies   | 114.88                   | 1.58                  | 11.83                 | 8.02         | 0.19       | 0.39       | 4.53      | 0.31        | 6.77     |
| Evergreen leaf forest | 1.26                    | 317.29                | 0.55                  | 3.71         | 1.11       | 0.01       | 0.45      | 5.13        | 0.58     |
| Deciduous leaf forest | 5.05                    | 0.41                  | 684.6                 | 0.49         | 0.26       | 2.29       | 9.04      | 1.39        | 6.6      |
| Mixed forest   | 0.02                     | 4.19                  | 0.43                  | 85.25        | 0          | 0          | 0.94      | 2.51        | 1.15     |
| Shrub land     | 0.17                     | 0.82                  | 0.09                  | 2.59         | 17.07      | 0          | 0         | 0           | 0.75     |
| Plantation     | 0.24                     | 0                     | 0.13                  | 0.78         | 0          | 31.1       | 2.49      | 0.07        | 5.44     |
| Crop land      | 2.95                     | 0.42                  | 5.43                  | 0.14         | 0          | 1.45       | 247       | 2.81        | 45.87    |
| Fallow land    | 0.25                     | 0.6                   | 0.75                  | 0.03         | 0.02       | 0.07       | 2.46      | 21.53       | 1.71     |
| Built-up       | 0.13                     | 0.05                  | 0.05                  | 0.04         | 0.02       | 0.17       | 0.52      | 0           | 47.36    |
| Total          | 124.95                   | 325.36                | 703.86                | 101.05       | 18.67      | 35.5       | 267       | 33.75       | 116.2    |
To see the change in LULC of hydrological regime of Doon valley watershed mainly in built-up area change detection technique adopted. For this purpose in Erdas imagine 2014 change detection matrix has been prepared. In 2014 total 68 km² built-up area increased from 1995 and the main contribution of cropland almost 60% contributions. In the LULC change detection matrix, urban areas increased, becoming the dominant LULC type and continuously extending into around the city (Sun et al., 2013). In summary, the selected areas experienced rapid LULC change, especially urbanization, from 1995 to 2014.

A. VIC Model

The preliminary comparisons of simulated and observed daily stream flows are presented for two outlets location. The coefficient of determination showing agreement between the trends of simulated and observed stream flow records (Bhattacharya et al., 2015; Liang et al., 1996). LULC map of 2014 and rainfall data was used 2006 to 2010 for simulation and validation. Coefficient of determination is 0.732 for 2014 year. There are no heavily changes in simulation data. No consistency in the simulation results was observed which implies the need for model calibration. The time series of the observed and simulated daily monthly surface runoff. An attempt was also made to calibrate for monthly sediment for the period January-December, 2006 to 2010. For this calibration, the slope of the sub-basin, this is one of the most sensitive parameter for sediment load. Several simulation runs were then applied until a goodness-of-fit between observed and simulated flow was obtained. In order to compare the simulated values with the observed values coefficient of determination (R²).

Figure 5: Monthly mean simulated & observed runoff relationship for Doon Valley watershed (LULC 2014) using rainfall data 2006-2010
B. SWAT Model

The preliminary comparisons of simulated and observed daily stream flows are presented for 32 outlets location for this watershed simulated for whole watershed area Asan and Rishikesh together. The coefficient of determination showing agreement between the trends of simulated and observed stream flow records (Dadhwal a et al., 2010). LULC map of 2014 and rainfall data was used 2006 to 2010 on monsoon season for simulation and validation. Coefficient of determination is 0.781 for 2014 year. Model simulated runoff is only for 2006 to 2010 year on monsoon season. After calibrating the result it can observed that in below graph rainfall was increased in June to September season. That reason, water yield and sediment yield were also increased in June to September. Fluctuations rate of average monthly basin values for evapotranspiration was also seen in this season.
Figure 8: Simulated and observed runoff relationship for Doon Valley watershed 2006-2010 on monsoon season

Figure 9: Average monthly basin values for rain (mm) from 2006-2010

Figure 10: Average monthly basin values for water yield (mm) from 2006-2010
HEC-HMS is a model primarily designed to assess and evaluate short term climate and land cover changes on basin hydrology (Mishra et al., 2010). It therefore essentially ignores the effect due to human induced activities. The Asan and Rishikesh basin contains several storage reservoirs and diversion structures and the observed stream flows are thus bias and are not really appropriate for the purpose of calibration. This may be a reason of disagreement between observed and simulated discharge (Dadhwal et al, 2010). During low flows, reservoirs come into play and store most of the river waters whereas during high flows a reservoir has to throw out all waters coming into it once filled. This may be the possible reason of overestimation during low flows and underestimation during high flows. LULC 2005 map and TRMM 2006 rainfall data was used 1st July-1st August, 2006 for simulation and calibration. Coefficient of determination is 0.659 for 2006 year (Jul-Aug).
Figure 13: Simulated and observed runoff relationship for Doon Valley watershed 1st Jul-1st Aug, 2006

Figure 14: Runoff relationship for Doon Valley watershed 1st July-1st August, 2006

Table 2: Comparison between two models yearly average simulated discharge

| Year | VIC model simulated discharge (cumec) | SWAT model simulated discharge (cumec) | Observed discharge (cumec) |
|------|--------------------------------------|---------------------------------------|---------------------------|
| 2006 | 18.05                                | 19.64                                 | 23.21                     |
| 2007 | 18.76                                | 32.96                                 | 22.95                     |
| 2008 | 25.62                                | 24.72                                 | 28.28                     |
| 2009 | 13.84                                | 17.55                                 | 20.66                     |
| 2010 | 50.27                                | 44.96                                 | 45.86                     |

Table 3: Comparison between two models simulated highest peak discharge

| Year | VIC model highest peak discharge (cumec) | SWAT model Highest peak discharge (cumec) | Observed highest peak discharge (cumec) |
|------|-----------------------------------------|------------------------------------------|----------------------------------------|
| 2006 | 212.25                                  | 280.98                                   | 240.64                                 |
| 2007 | 449.89                                  | 401.46                                   | 241.64                                 |
| 2008 | 705.78                                  | 651.23                                   | 534.88                                 |
| 2009 | 188.96                                  | 150.56                                   | 101.92                                 |
| 2010 | 1485.88                                 | 1088.63                                  | 1062.48                                |
4. Conclusion

Distributed hydrological modelling offer a competent solution to appraise long term hydrological changes by allowing quantification fluctuations in stream flow patterns. Observed LULC changed scenario between 1995, 2005 and 2014 using maximum likelihood supervised classification method. Due to frequent occurrence of hydro-meteorological conditions such as floods, droughts and cyclones in recent times indicates a shift in the hydrological response of the basin ascribed to land cover changes. This study attempts to model the hydrological response of Asan and Song river basin using physically based, distributed VIC, SWAT and HEC-HMS models and assess land cover change impacts on stream flow at various points along the river. Pre-calibration and comparison of observed and simulated stream flow was done for year of 2006-2010 using 2014 LULC Map. The coefficient of determination before calibration was found 0.732 for VIC model, for SWAT model it was found to be 0.781 and for HEC-HMS model it was found to be 0.769. The relative increment in stream flow was found high in the months of July to October in all sub-basins. It is concluded that the impact of land cover changes is most noticeable during low flows.

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