HYDROLOGICAL SIMULATION OF MAHANADI RIVER BASIN AND IMPACT OF LAND USE / LAND COVER CHANGE ON SURFACE RUNOFF USING A MACRO SCALE HYDROLOGICAL MODEL

V.K. Dadhwal[a], S.P.Aggarwal[b,*] and Nidhi Mishra[b]

[a] National Remote Sensing Centre, Balanagar, Hyderabad – 500 625, India
[b] Indian Institute of Remote Sensing (NRSC), 4, Kalidas Road, Dehradun – 248 001, India

KEY WORDS: Hydrological Modelling, Landuse Landcover Change, Variable Infiltration Capacity Model, Remote Sensing

ABSTRACT:

In the present study, Variable Infiltration Capacity (VIC) a macro-scale hydrological model was used to simulate the hydrology of Mahanadi river basin of India. The analysis was carried out for the impact of land use/ land cover (LULC) changes on stream flow pattern. Surface runoff was simulated for the year 1972, 1985 and 2003 to quantify the changes that have taken place due to change in LULC. An increase by 4.53% (3514.2 x 10^6 m^3) in the annual streamflow was estimated at Mundali outlet of the Mahanadi basin from 1972 to 2003. This may attributed due to decrease in forest cover by 5.71%. The validation of VIC model showed a close agreement between the observed and simulated runoff values with the Nash-Sutcliffe coefficient of 0.821 and relative error of 0.085.

1. INTRODUCTION

Water resources management requires a systems approach that includes not only all of the hydrological components, but also the links, relations, consequences and interactions amongst all the components. Human modifications of the environment, including land cover change, irrigation, and flow regulation, now occur on scales that significantly affect seasonal and yearly hydrologic variations. It thus becomes necessary to understand and quantify various hydrological components of the catchment for efficient water resource management. Runoff representing the response of a catchment to precipitation, reflects the integrated effects of a wide range of landcover, soil, topography, climate and precipitation characteristics of the area. Hence, if one has to study the impact of changes in climate and landcover on basin hydrology, altering streamflow pattern is an important component to investigate.

Quantification of runoff and other hydrological components can be done in many ways; Hydrological modeling is one efficient way for consistent long term behavioral studies. Hydrological modelling is a mathematical representation of natural processes that influence primarily the energy and water balances of a watershed. The fundamental objective of hydrological modeling is to gain an understanding of the hydrological system in order to provide reliable information for managing water resources in a sustained manner. Powerful spatially-distributed models are based on physical principles governing the movement of water within a catchment area, but they need detailed high-quality data to be used effectively. AVSWAT (ArcView Soil and Water Assessment Tool), MIKE-SHE, Variable infiltration Capacity (VIC) model, HEC-HMS (Hydrologic Engineering Centre-Hydrologic Modelling System) are some of the physically based distributed hydrologic models.

In the present study, VIC land surface hydrologic model has been used for modeling the river flow regime. It is a physically based, macroscale hydrological model which represents the partitioning of incoming (solar and long wave) radiation at the land surface into latent and sensible heat, and the partitioning of precipitation (or snowmelt) into direct runoff and infiltration. VIC explicitly represents vegetation, and simultaneously solves the surface energy and water balances. A river routing model when coupled with VIC permits comparisons between the model-derived discharge and observations at gauging stations. Further details of the VIC model can be found in Liang (1994); Liang et. al, (1994); Liang et al. (1996); Lettenmaier (2001). An attempt has been made to model and evaluate the changes in streamflows attributable to changes in landcover throughout the Mahanadi basin. For an understanding of the distribution of the physical characteristics of such large catchments with little available data, a better insight can be provided by remote sensing techniques. The remote sensing data and GIS have already been used by hydrologists to deal with large scale, complex and spatially distributed hydrological processes. Remote sensing has held a great deal of promise for hydrology, mainly because of the potential to observe areas and entire river basins rather than merely points.

2. STUDY AREA

The river basin at the appropriate scale is generally the most logical geographical unit of streamflow analysis and water resources management. In the present study, Mahanadi River basin has been selected as study area. The Mahanadi basin encompassed within geographical co-ordinates of $80^0$30' to $86^0$50' East longitudes and $19^0$20' to $23^0$35' North latitudes as shown in Fig. 1. The total catchment area of the basin is 1,41,600 km^2. The average elevation of the drainage basin is 426 m with a maximum of 877 m and a minimum of 193 m.

The river Mahanadi is one of the major inter-state east flowing rivers in peninsular India. It originates at an elevation of about 442 m. above Mean Sea Level near Pharsiya village in Raipur district of Chattisgarh. During the course of its traverse, it drains fairly large areas of Chhatisgarh and Orissa and comparatively small area in the state of Jharkhand and Maharashtra. The total length of the river from its origin to confluence of the Bay of Bengal is about 851 km., of which, 357 km. is in Chattisgarh and the balance 494 km. in Orissa. During its traverse, a number of tributaries join the river on both the banks. There are 14 major tributaries of which 12 are joining upstream of Hirakud reservoir and 2 downstream of it. Approximately 65% of the basin is upstream from the dam. The average annual discharge is 1,895 m^3/s, with a maximum of 6,352 m^3/s during the summer monsoon. Minimum discharge is 759 m^3/s and occurs during the months October through June.

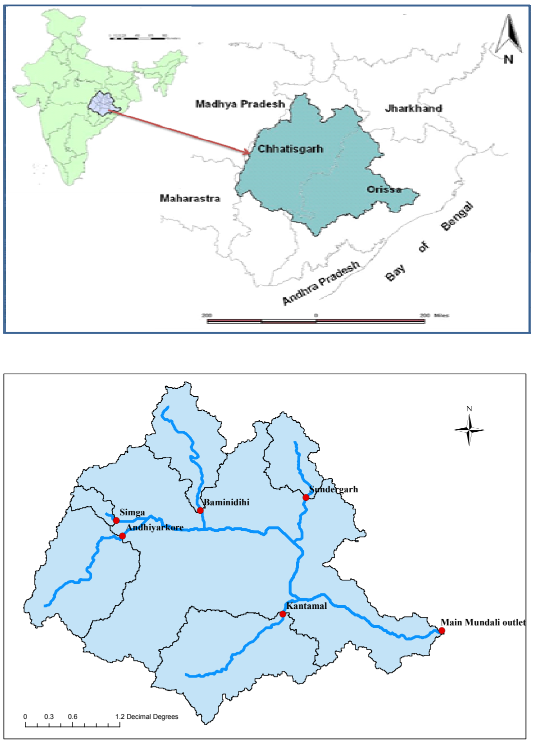


Fig. 1. Location of Study Area (Mahanadi river basin)

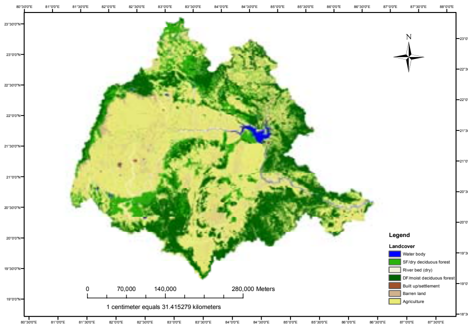
Mahanadi basin enjoys a tropical monsoon type of climate like most other parts of the country. The maximum precipitation is usually observed in the month of July, August and first half of September. Normal annual rainfall of the basin is 1360 mm (16% CV) of which about 86% i.e. 1170 mm occurs during the monsoon season (15% CV) from June to September (Rao, 1993). The river passes through tropical zone and is subjected to cyclonic storms and seasonal rainfall. In the winter the mean daily minimum temperature varies from 4°C to 12°C. The month of May is the hottest month, in which the mean daily maximum temperature varies from 42°C to 45.5°C.

3. METHODOLOGY

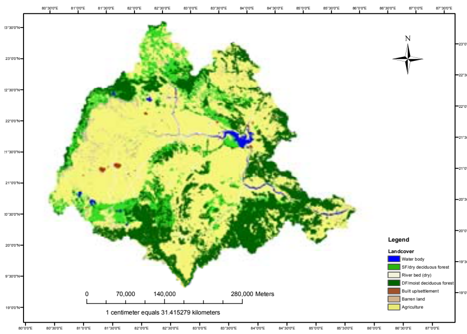
Basin boundary and drainage characteristics of the watershed were derived in HEC -GeoHMS module in ArcView 3.2a software using 1 km resolution GTopo30 USGS Digital elevation model (DEM) as major input. A fill grid map was generated after correcting the DEM for sinks. Flow direction map was derived from this fill sink map and subsequently a flow accumulation map was derived from it. Stream definition was derived from this flow accumulation by specifying the maximum threshold area for delineating drainages. A sub-basin for each delineated stream is then extracted. To extract the basin boundary, an outlet at Mundali station in the Mahanadi river basin was defined. Finally, a basin for the defined outlet was delineated along with the river network. It was further subdivided into desired number of sub-basins by specifying various outlets where the gauging station exists along the extracted drainage. A square grid of area 25 x 25 km^2 was generated over the study region. There were in all 267 such grids falling in the basin. This extracted grid network for the basin was used to overlay with the other thematic layers and hence define the distribution of various parameters and properties in the basin. VIC model requires the definition of input parameters for each grid distributed uniformly over the area.

Remote sensing based satellite images being most reliable and offering synoptic views of large areas were the viable option to study landcover dynamics on a regional scale. LANDSAT MSS images of 1972-73 were downloaded, preprocessed and mosaiced to create a seemless image of the whole basin. Since the individual images were of different dates, classifying the mosaic into landcover types was not feasible. So, the individual images were classified using unsupervised classification (Isodata clustering) technique into several classes (200) and they were merged based on their spectral signatures into 7 landcover types namely Water body, DF/moist deciduous forest, SF/dry deciduous forest, Agriculture, Built up/settlement, Barren land and River bed (dry). The preliminary classified layer was then improved using visual interpretation approach. Thus, an integrated digital and visual classification was attempted to map landcover since a single technique would not have been feasible for regional mapping. The individual classified images were then mosaiced and clipped by the basin boundary. Landcover mapping for 1985 was done using NOAA AVHRR images (1 km resolution) whereas AWiFs (56 m resolution) was used to prepare for the year 2003. The same approach of unsupervised classification and visual interpretation technique was followed to perform the task. The landuse/ landcover maps of Mahanadi basin for 1972, 1985 and 2003 are shown in Fig. 2. GCP's (ground control points) were used to improve and validate classification scheme. Classification accuracy of more than 70% was achieved using this approach.

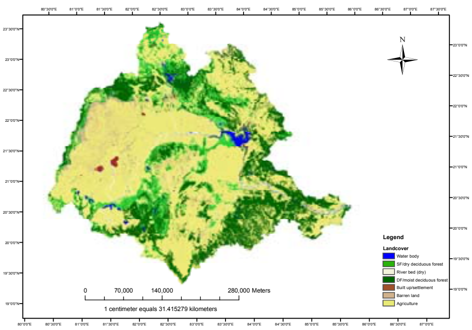
Four major input files are required to make the VIC model input database. They are Vegetation parameter file, Vegetation Library file, Soil parameter file and Forcing files. The data in these files were stored in the ASCII format. A soil parameter file describes the characteristics of each soil layer for each grid cell. This is also where other basic grid cell information is defined like grid cell no., lat-long of the grids (which serves as a link to other parameter files), mean elevation etc. Mean elevation values for each grid were derived from Digital elevation model. The primary data source to prepare this input was digital soil texture map prepared from NBSS & LUP (National Bureau of Soil Survey and Landuse Planning, Nagpur) soil maps (scale-1:50,000). Soil texture map was rasterised and overlaid with the grid map to extract dominant soil type in each grid. The second soil layer was taken as FAO global soil map of the world. All other parameters except c, elev, depth, off_gmt, rough, and annual prec are a function of soil texture and were derived using soil hydraulic properties index defined in VIC model documentation.



a. Landuse/Landcover Map of 1972



b. Landuse/Landcover Map of 1985



c. Landuse/Landcover Map of 2003

Fig. 2 Landuse/landuse Map of 1972, 1985 & 2003

Table 1.LULC statistics of 1972,1985 & 2003

	Water body (%)	DF/Moist Decid (%)	SF/Dry decid (%)	Agriculture (%)	Built up (%)	Barren land (%)	River bed (%)
1972	1.16	27.23	11.96	54.08	0.08	4.15	1.34
1985	1.19	26.64	10.92	56.41	0.22	3.83	1.35
2003	1.62	23.52	9.96	59.63	0.31	3.51	1.46

The vegetation parameter file describes the vegetative composition of each grid cell, and uses the same grid cell numbering as the soil file (latitudes and longitudes are not included in the file). This file cross-indexes each vegetation class (from any land-cover classification scheme) to the classes listed in the vegetation library. To prepare this file, landuse map was overlaid on the grid map and the no. of vegetation classes as well as fraction of grid covered by those classes was extracted. A small code in C language was used to read this information from crossed map and arrange it in the format specified by the model. Root depths for landcover types were accepted as recommended by Canadell et. al. (1996). It was assumed that the specified root zone contains all of the roots of a landcover type. For the selected land cover classification of the study area, a vegetation library file was set up. This describes the static (varying by month, but the same values year-to-year) parameters associated with each land cover class.

LAI defines an important structural property of a plant canopy as the one sided leaf area per unit ground area. For derivation of LAI, MODIS LAI maps (MOD 15A02 product) were downloaded from NASA's GSFC website (www.modis-land.gsfc.nasa.gov). For each landuse class, sufficient number of cloud free points were chosen and their LAI profile on the stacked image was drawn. An average monthly value of those points was taken as the LAI value in each month for that landuse class. Albedo was also derived from MODIS BRDF/ Albedo product in the same way. Other variables like roughness length, displacement height, overstory, architectural resistance, minimum stomatal resistance were derived from LDAS 8^{th} database (http://ldas.gsfc.nasa.gov/LDAS8th/MAPPED.VEG/ web. veg.monthly.table.html) and MM5 terrain dataset.

The Meteorological forcing file contains meteorological variables required to force the VIC model like daily precipitation, daily maximum and minimum air temperature. Forcing data files play big role in the model input to produce all the outputs in both water balance and full energy balance modes of the model. Accurate streamflow simulation requires forcing input of high accuracy as it is the most influential variable generating runoff and driving hydrological cycle. Precipitation input was prepared using India Meteorological Department's 1^oX1^o gridded rainfall dataset. Daily rainfall values for each 1 degree grid falling in the basin were extracted for 365 days in the year 2003. Rainfall grids were then overlaid with the basin grids to extract precipitation in each basin grid. VIC model requires one forcing file for each grid having 365 rows and 3 columns in ASCII format. Temperature data from NCDC (National Climatic Data Centre, NOAA) is available for some selected stations in the study area. This point temperature data was used to derive maximum and minimum temperature of each basin grid using nearest neigbour and lapse rate method since it is assumed that temperature varies with the altitude. The following relation was applied in MS Excel spreadsheet:

$$T_{grid} = T_{nearest\ point} + 5.5/1000*(elevation_{nearest\ point} - grid\ elevation) \quad (1)$$

A Global control file where the necessary information to specify various user preferences and parameters was prepared. It contains information like N-layers, Time step, start time, end time, Wind_H, snow temp, rain temp., Location of the input output files, modes which are to be activated etc. The VIC 4.0.5 was compiled using gcc complier on Linux operating system. The code was compiled using the make file included in the archive, by typing 'make'. The compiled code creates an executable entitled 'vicNl'. To begin running the model, 'vicNl -g (global control file name)' was written at the command prompt. Global control parameters were modified according to the input characteristics and to activate the ware balance. In addition to that input and output path were specified. VIC source code was executed in the LINUX environment to generate the flux files for each basin grid. These flux files contain fluxes of surface runoff, evapotranspiration, baseflow, soil moisture etc. produced at that location. In order to simulate streamflow at an outlet, routing of runoff component was done using a routing model developed by Lohmann et. al (1998). Routing was done for 6 sub-basins namely Mundali (main outlet), Kantamal, Andhiyarkore, Simga, Baminidihi and Sundergarh. Daily and monthly streamflows in Cusec and mm for each outlet location was obtained as the output.

Calibration of a hydrological model is an iterative process which involves changing the values of sensitive model parameters to obtain best possible match between the observed and simulated values. In general, before conducting numerical simulations, six model parameters of the VIC-2L model need to be calibrated because they cannot be determined well based on the available soil information (Yuan, 2004). These six model parameters are the depths of the upper and lower soil layers (*di*, *i* = 2, 3); the exponent (*B*) of the VIC-2L soil moisture capacity curve, which describes the spatial variability of the soil moisture capacity; and the three subsurface flow parameters (i.e., *D*m, *D*s, and *W*s, where *D*m is the maximum velocity of base flow, *D*s is the fraction of *D*m, and *W*s is the fraction of maximum soil moisture). Three criteria were selected for model calibration: (i) Relative error (*Er* in percent), (ii) The Nash–Sutcliffe coefficient (*Ce*) (Nash and Sutcliffe, 1970), and (iii) Coefficient of Determination, (R^2).

4. RESULTS AND DISCUSSION

This study attempts to model the hydrology of Mahanadi river basin and assess landcover change impacts on streamflows at various locations along the river in the basin. For this purpose, mapping of landuse/ landcover was carried out in detail to represent the present and historical landcover conditions and changes that have taken place over whole of the basin in a span of three decades. Analysing landuse changes from 1972 to 2003, it may be concluded that the total forest cover has declined by 5.71% of the total area of the basin. A reduction in barren land (0.64%) is followed by increase in areas of surface water bodies (0.47%), built up land (0.22%), river bed (0.11%) and most prominently agriculture (5.55%). This implies that the total forest cover and barren land has declined at the expense of increase in water body, river bed, agriculture and built up land in a span of 30 years.The simulation results obtained while calibrating and validating the VIC land surface hydrologic model were analysed and simulated streamflows were compared with the observed discharge at outlet station to look for the model efficiency in representing hydrological conditions accurately.

4.1 Hydrological Modelling using VIC land surface model

4.1.1 *Pre-calibration simulation*:The vegetation, soil, and forcing (meteorological) data as described were applied to the VIC-2L model to simulate evapotranspiration, runoff, and soil moisture at each grid over the Mahanadi River basin for year 2003. To compare the VIC-2L model simulated runoff with the observed streamflow, the simulated runoff is routed through the river network using a simple routing model at the outlet Mundali as suggested by Lohmann et al, (1998). The routed daily and monthly runoff at these stations was compared with the daily and monthly observed streamflows, respectively as shown in Fig. 3. The R^2 showing agreement between the trends of simulated and observed streamflow records were found to be as 0.747, prior to calibration.

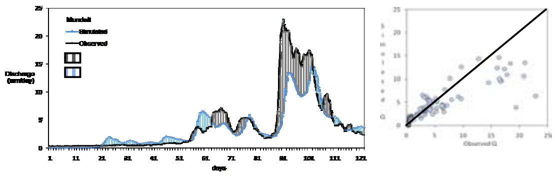


Fig 3. Pre-calibration Comparison b/w Observed & Simulated daily discharges

4.1.2 *Model Calibration and validation*:

Since streamflow can be measured with relatively high accuracy compared with other water fluxes in the watershed it is mostly used to calibrate model parameters. In general, before conducting numerical simulations, the six model parameters of the VIC-2L model were calibrated and assigned values as: B = 2.0, *D*m = 15.0, *D*s = 0.02, *W*s = 0.8 and *di* = 0.5 and 2.0 m for *i* = 2 and 3. The velocity parameter was also adjusted (increased to 2.3 m/s) since the simulated runoff was coming delayed. The stream discharge at Mundali outlet for a period of 6 months was considered as the reference for calibration.

Post calibration comparison of observed and simulated hydrograph at Mundali is shown in Fig 4. A good agreement between the observed and simulated values was found with an R^2 value of 0.836, *Ce* of 0.821 and *Er* of -8. 49 %. It can be seen that low flow simulations were overestimated and an underestimation was found during high flows.

VIC is a model primarily designed to assess and evaluate long term climate and landcover changes on basin hydrology. It therefore essentially ignores the effect due to human induced activities. VIC simulates naturalized flows without considering any effect of reservoirs, dams or any other structural intervention. The Mahanadi basin contains several storage reservoirs and diversion structures and the observed streamflows 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. 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.

Better simulation results were obtained for monthly time-step when compared with daily and good agreement at Mundali was found. Comparisons of observed versus simulated hydrographs during model validation (daily) are shown in Fig. 4. Monthly comparisons were found good (Fig. 5) with an R^2 value of 0.920, *Ce* of 0.890 and *Er* of -8.70%. The VIC model simulated runoff compares well with the daily observed streamflow in general, but significant overestimations of the streamflows are evident. This may be because of erratic spatial distribution of precipitation. Streamflows are most sensitive to vegetation and forcing input, thus near perfect simulations require accurate estimation of these parameters. In the present simulation, precipitation information has spatial resolution of 1 degree which is coarser, high resolution is therefore expected to improve simulation.

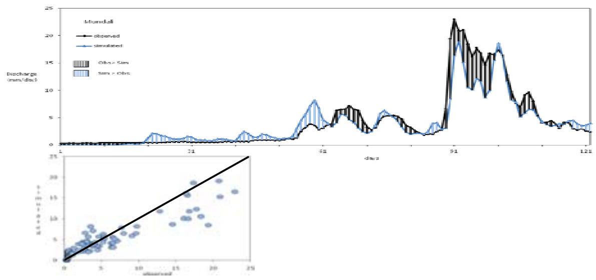


Fig. 4. Comparison of Hydrograph at main outlet (Mundali): Calibration period

Though the agreement between observed and simulated discharges is good, under-estimations and over-estimations are inherent in the simulation. This is because of the fact that VIC simulates naturalized flows and the observed discharge used for validation is biased and affected by human interventions. Model performance showed good agreement at Mundali inspite of a large reservoir since calibration was performed at this outlet. It may be seen from the simulation results that model has generally overestimated (S>O) during months of June, July and under-estimated during August and September. The possible reason may be initial reservoir storage in June-July due to which observed flows are less as compared to simulated whereas observed flow exceeds once the reservoir capacity is filled (in Aug, Sept.). It may be concluded that the agreement between and observed and simulated hydrological components is largely dependent on the hydrological and landcover conditions in the basin and model assumptions. The synoptic view and landuse/landcover conditions of various sub-basins are shown in the Figure 2. The landcover classes are same as shown for whole of the Mahanadi basin (Fig. 1) with Mundali as an outlet.

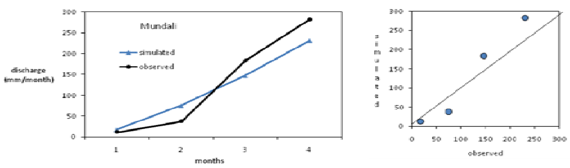


Fig. 5. Simulated and observed monthly hydrographs at outlet

4.2 Effect of landcover changes on streamflows

4.2.1 *Historical and current hydrological simulation using VIC model*: Simulation was done for year 1972 and 1985 after calibration and validation of the VIC model for 2003. Only the vegetation cover and related parameters were changed in the simulations; the model meteorological forcings and soil parameters were kept same for both the current and historical scenarios. In this way, the effects of vegetation change on basin hydrology were isolated from the effects of climate variability.

4.2.2 *Trend of changes in streamflows*: Streamflows for year 1972, 1985 and 2003 were compared to look for the changes that have taken place due to change in landcover in the Mahanadi river basin. Monthly discharges were found to be varying significantly as compared to daily flows. Fig 6 shows a scatter plot of monthly flows (mm) for 2003 and 1972, events above the slope line indicates an increase in river flow. A rise of 24.44 mm in the annual discharge is predicted at Mundali outlet of the Mahanadi basin from 1972 to 2003 (16.97 mm being in the period of 1972-85 and 7.47 mm in 1985-03) which is 4.53% of the flow in 1972. It may be concluded that a decrease in forest cover by 5.71% in the Mahanadi river basin has caused the river flow to increase by 4.53%. This is quite a significant amount in terms of volumetric rise (3514242122 m^3). Table 2 summarizes the predicted incremental changes in runoff (mm) at outlet by season (e.g. JFM refers to cumulative rise for January, February and March). In figure 7, monthly hydrographs for 1972 and 2003 are presented to see the changes that have taken place. A plot of relative percentage difference in runoff (from 1972 to 2003) over 1972 is also shown in the same figure. The rise in percent runoff was prominent during May, June, Oct and November months. The decrease in runoff from 1972 to 2003 may be due to reverse trend in landcover conversions and/or human activities.

In summary, a decrease in natural cover of forest over time has caused a significant rise in streamflows and particularly surface runoff. Removal of forest cover is known to increase streamflow as a result of reduced evapotranspiration. Base-flow is expected to decrease while surface runoff increases owing to the decrease in infiltration and hence groundwater recharge processes. Urban expansion and intensive cultivation will loosen the soil leading to soil loss (soil erosion) due to high flows. Urbanization also tends to decrease infiltration rates and increase extents of impervious surfaces, although the area over which such changes have occurred is a small fraction of the total basin area. The VIC model, being physically based, distributed, macroscale model is particularly suitable for studying climate and landcover change scenarios and their implications on hydrological processes at regional and global scale over long time frames.

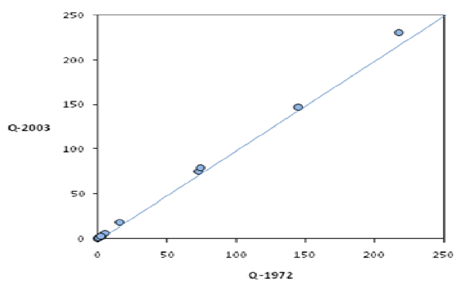


Fig.6. Comparison of streamflows for 1972-2003 at Mundali

Table 2. Changes in runoff by sub-basin and season (in mm)

Stations	JFM	AMJ	JAS	OND	Annual	% increase	Vol. Increase (m^3)
Mundali	0.027	1.79	16.97	5.64	24.44	4.53	3.51 x 10^6

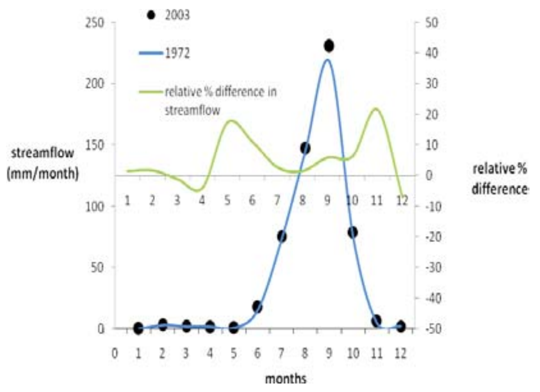


Fig. 7. Monthly hydrographs of historic (1972) and current (2003) naturalized Streamflow stations, and relative percentage difference of runoff

5. SUMMARY AND CONCLUSIONS

Land use and vegetative cover play an important role in watershed runoff and streamflow discharge patterns over time, including peak flows. Increased human interventions have caused rapid transitions in landcover, adversely affecting the watershed processes and hydrological cycle in the long run. Distributed hydrological modelling offers an efficient solution to evaluate the long term hydrological changes by allowing quantification of changes in streamflow patterns.The Mahanadi river basin covering major portions of Chattisgarh and Orissa (India) has been repetitively facing the adverse hydro-meteorological conditions such as floods, droughts and cyclones etc. in the recent times. Frequent occurrence of these events indicates a shift in the hydrological response of the basin attributed to landcover changes. This study attempts to model the hydrology of Mahanadi river basin using physically based, distributed VIC hydrological model and assess landcover change impacts on streamflows at various locations along the river.

A detailed remote sensing based landcover mapping of the basin for years 1972, 1985 and 2003 reveals following changes:

- Total forest cover area has been reduced by 5.71% of the total area of the basin from 1972 to 2003. A reduction in barren land (0.64%) is followed by an increase in areas of surface water bodies (0.47%), built up land (0.22%), river bed (0.11%) and most prominently agriculture (5.55%). This implies that the total forest cover and barren land has reduced at the expense of increase in water body, river bed, agriculture and built up land in a span of 30 years.

- Taking the internal conversion of various landcover classes into account, an overall trend from 1972 to 2003 was a change from forest and barren land to agriculture, built up and water bodies.

Performance of the VIC macroscale hydrological model to simulate streamflows during calibration and validation can be summarized as follows:

- Pre-calibration simulation and comparison of observed and simulated streamflow was done for year 2003. The coefficient of determination before calibration was found to be as 0.747, for Mundali.

- The calibration of the model at Mundali outlet was performed for year 2003. Streamflow was found sensitive to variables like upper and lower soil layer depth, velocity of flow and vegetation parameters. R^2 of 0.836, Ce of 0.821 and Er of 0.085 was obtained during daily simulation. The model performance was found better for monthly simulations with Ns of 0.89.

Streamflows were simulated using VIC model for the year 1972, 1985 and 2003. Following conclusions can be drawn from the analysis carried for predicting changes over years:

- An increase by 4.53% (24.44 mm) in the annual streamflow is predicted at Mundali outlet of the Mahanadi basin from 1972 to 2003. It may be concluded that a decrease in forest cover by 5.71% in the Mahanadi river basin has caused the river flow to increase by 4.53%. This is quite a significant amount in terms of volumetric rise (3514242122 m^3).

- The relative percentage increase in streamflow was found high in the months of May and November in all sub-basins. It may be concluded that the impact of landcover changes are most pronounced during low flows and that during high flows, role of landcover becomes comparatively less.

REFERENCES

Canadell, J., Jackson, R.B., Ehleringer, J.B. and Moorey, H.A., 1996. Maximum rooting depth of vegetation types at the global scale. *Oecologia*, 108(4), pp. 1432-1939.

Lettenmaier, D.P., 2001. Present and Future of Modeling Global Environmental Change: Toward Integrated Modeling,. In: T.M. Eds. and H. Kida (Editors), *Macroscale Hydrology: Challenges and Opportunities*, pp. 111-136.

Liang, X., 1994. A Two-Layer Variable Infiltration Capacity Land Surface Representation for General Circulation Models. *Water Resour. Series TR140*, Univ. of Washington, Seattle.

Liang, X., Lattenmaier, D.P., Wood, E.F. and Burgess, S.J., 1994. A simple hydrologically based model of land surface, water, and energy flux for general circulation models. *Journal of Geophysical Research*, 99(D7), pp. 14,415-14,428.

Liang, X., Lettenmaier, D.P. and Wood, E.F., 1996. One-dimensional Statistical Dynamic Representation of Subgrid Spatial Variability of Precipitation in the Two-Layer Variable Infiltration Capacity Model. *J. Geophys. Res.*, 101(D16), pp. 21,403-21,422.

Lohmann, D.E., Raschke, Nijssen, B. and Lettenmaier, D.P., 1998. Regional scale hydrology:II. Application of the VIC-2L model to the Weser river, Germany. *Hydrological Sciences*, 43(1), pp. 143-158.

Rao, P.G., 1993. Climatic changes and trends over a major river basin in India. *Climate Research*, 2, pp. 215-223.