Estimation of Periodic Water Balance Components
and
Generation of Geo-Spatial Hydrological Products at Uniform Grid-Wise at National Scale

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14	Abstract (with Keywords) : This document presents the details work carried out for development of national level hydrological modelling framework for estimating in-season hydrological fluxes. The document describes methodology adopted, data sets used, validation and outputs derived from the modelling framework. The geo-spatial products of hydrological fluxes (Surface Runoff, Soil Moisture, and Evapotranspiration) are published through Bhuvan Web-Portal. Keywords: VIC, Hydrology, Water Balance Components				

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1 INTRODUCTION

Description of terrestrial water flux components in terms of their geographical distribution and chronological variation is useful for water resources assessment, management and climate related research. Water resources availability and its controlling parameters are spatially distributed and show significant temporal variability. Hydrological response has a functional dependency of many dynamic and stationary parameters. Spatial heterogeneity and time variant behavior of these parameters are critical inputs into Hydrological models. Earth Observation (EO) data from multitude platforms providing enormous contribution for the creation of spatially distributed parameters relevant for hydrological budgeting and modeling. Repeatability of observations allows the generation of a time-series account of dynamic terrain parameters and provides capability to quantify and forecast the hydrological variables and water balance components.

The EOAM study being executed under Earth Observation Application Mission (EOAM) programme of ISRO. The objective is to establish a national level hybrid modelling framework, where the major hydrological processes are modeled through integration of geo-spatial data sets with hydro-meteorological data. The diverse modules are based on conceptual, empirical and process based approaches. The focus is on quantifying the spatial and temporal distribution of water balance components and to provide orderly description hydrological fluxes through geo-spatial products at regular periodicity. The model derived fluxes are useful for quantifying spatial and temporal variation in basin/sub-basin scale water resources, periodical water budgeting and form vital inputs for studies on topics ranging from water resources management to land-atmosphere interactions including climate change.

2 STUDY OBJECTIVES

The scope of the study is to generate grid-wise periodic water balance components at using distributed hydrological modelling using geo-spatial and hydro-meteorological data.

The specific objectives are

I. To develop and setup frame work for generation of grid-wise, water balance components covering all the river basins of the country using geo-spatial and hydro-meteorological data sets using macro-scale hydrological model

II. To conduct field experimentation for calibration and validation of model outputs

III. To generate periodic geo-spatial products describing grid-wise water balance components for the entire country

3 HYDROLOGICAL MODEL

Among the many hydrological models developed world wide, Variable Infiltration Capacity (VIC) model is extensively used by earth observation scientific fraternity for its methodical rationale, inclusion of bio-physical processes that govern water-energy exchanges and adoptability to different regions. VIC model is extensively used in studies on topics ranging from water resources management to land-atmosphere interactions and climate change.

3.1 VIC Land Surface Model

The Variable Infiltration Capacity (VIC), a semi distributed & physically based hydrological model that solves both the water balance and the energy balance (Figure 1). VIC is an open source research model, its various forms has been applied to many watersheds including the Fraser River, Columbia River, the Ohio River, the Arkansas-Red Rivers, and the Upper Mississippi Rivers. Employing the infiltration and surface runoff scheme in Xianjiang model (Zhao, 1980), VIC was first described as a single soil layer model by (Wood, 1992) and implemented in the GFDL and Max-Planck-Institute (MPI) GCMs.

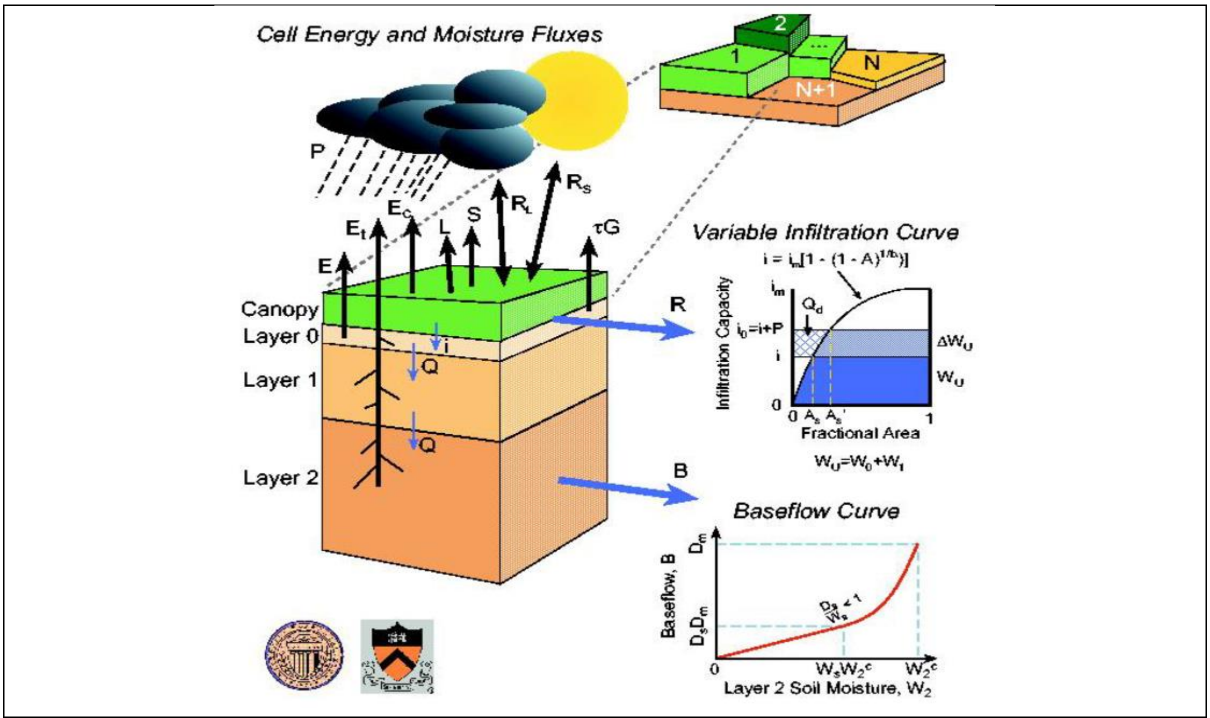


Figure 1: Schematic representation of VIC hydrological model

VIC is capable of partitioning 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. It utilizes a soil–vegetation–atmosphere transfer scheme that accounts for the influence of vegetation and soil moisture on land–atmosphere interactions. The model handles the subsurface into multiple soil layers. Each layer characterizes soil hydrological response such as bulk density, infiltration capacity, saturated hydraulic conductivity, soil layer depths, and soil moisture diffusion parameters.

VIC explicitly represents sub-grid heterogeneity in land cover classes taking their phenological changes into account such as their leaf area index (LAI), albedo, canopy resistance, and relative fraction of roots in each of the soil layers. The evapotranspiration from each land cover type is simulated using vegetation-class specific potential evapotranspiration, canopy resistance, aerodynamic resistance to the transport of water, and architectural resistance coefficients as defined in Penman-Monteith equation. In this model, the ET includes evaporation from the canopy layer of each vegetation class, transpiration from each vegetation class, and evaporation from bare soil. Total evapotranspiration ET over each grid cell is calculated as the area weighted sum of these three components. VIC uses the infiltration mechanism used in Xinanjang model (Zhao, 1992) to generate runoff from precipitation in excess of available infiltration capacity and base flow is computed using Arno model conceptualization (Todini, 1996).

In the model, soil moisture distribution, infiltration, drainage between soil layers, surface runoff, and subsurface runoff are all calculated for each land cover tile at each time step. Then for each grid cell, the total heat fluxes (latent heat, sensible heat, and ground heat), effective surface temperature, and the total surface and subsurface runoff are obtained by summing over all the land cover tiles weighted by fractional coverage.

Routing Model

In the VIC model, each grid cell is modeled independently without horizontal water flow. The grid-based VIC model simulates the time series of runoff only for each grid cell, which is non-uniformly distributed within the cell. In the routing model, water is never allowed to flow from the channel back into the grid cell. Once it reaches the channel, it is no longer part of the water budget. A linear transfer function model characterized by its internal impulse response function is used to calculate the within-cell routing. Then by assuming all runoff exits a cell in a single flow direction, a channel routing based on the linearized Saint-Venant equation is used to simulate the discharge at the basin outlet (Figure 2). The routing model is described in detail by Lohmann et al. (1996, 1998a).

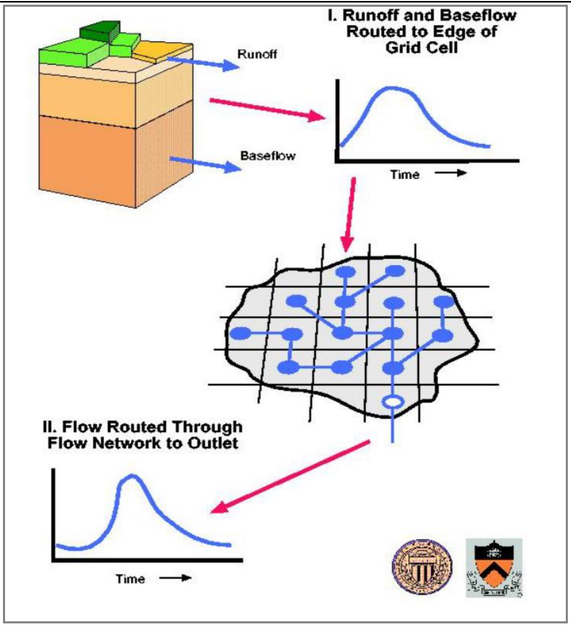


Figure 2: Schematic representation of VIC Routing model

4 MODEL INPUTS

The VIC model requires several sets of input data and are broadly categorized into:

1. Meteorological Forcing Files: VIC can take daily or sub-daily time-series of meteorological variables as inputs for each grid separately
2. Soil Parameter File: The soil parameter predominantly defines the grid-wise, layer-wise soil hydraulic particulars and along with model control parameters. The soil hydraulic parameters include saturated hydraulic conductivity, density, maximum soil moisture holding capacity, etc.
3. Vegetation Parameter & Library File: Land cover types, fractional areas, rooting depths, and seasonal LAIs of the various land cover tiles within each grid cell.
4. Global Parameter File: This is the main input file for VIC. It points VIC to the locations of the other input/output files and sets parameters that govern the simulation and model run
5. Routing Parameter File: Grid-wise elevation, direction of flow, slope, catchment fraction, diffusion

Using the various geo-spatial data sources (Table 1), model specific inputs have been prepared for the entire country and are detailed in the Methodology section.

Table 1 Data sets are used for generating the model specific inputs

S. No.	Parameter	Data sources
1	Terrain	• Carosat-1 DEM • Aster DEM • SRTM DEM
2	Soil	• NBSS & LUP Soil Map of India (1:500,000 scale) • FAO Soil data series (5 Million scale) • Field data / Literature / Experimentation
3	Vegetation Library	• LAI, Albedo (MODIS / NPOESS / JPSS) • Physical parameters (Field data / Literature / Experimentation)
4	Vegetation cover	• LULC (NRC-250k)
5	Irrigation	• Irrigation command maps (India-WRIS)
6	Meteorological data	• IMD surface / Gridded data (historic, Real-time, and forecast) • IMD / ISRO AWS • Satellite meteorological products (TRMM, CPC, MOSDAC, ...)
7	River discharge	• CWC River discharge data (Historic/real-time)
8	Reservoir data	• Storage, Rating curves, Releases

5 METHODOLOGY

Brief methodological steps (Figure 3) involved are as under:

- Geographical framework setup at 9min (~16.5km) grid level
- Catchment delineation for CWC Discharge sites using DEM
- Preparation Routing Parameters file (grid-wise fraction, flow direction)
- Preparation of model specific parameters on Soil, Vegetation and Routing using geo-spatial data sets (DEM, Land Use/Land Cover, Soil, Albedo, LAI, etc.)
- Preparation Soil Parameter file for each catchment (soil type, layer-wise depth, hydraulic properties)
- Preparation of vegetation parameter (Vegetation type, fraction)
- Preparation of Vegetation library (Monthly LAI, Albedo, Canopy resistance factors, Displacement height)
- Meteorological forcing data preparation and generation grid-wise forcing data Ascii files
- VIC Model setup and Run

- Routing Model Run
- Calibration of simulated discharge with observed discharge for selected historic years
- Model computations with calibrated parameterization using historic climate data and in-season climate data
- Generation of grid-wise daily water balance components
- Integration and Conversion of grid-wise VIC outputs into geo-spatial data sets / products and web publishing

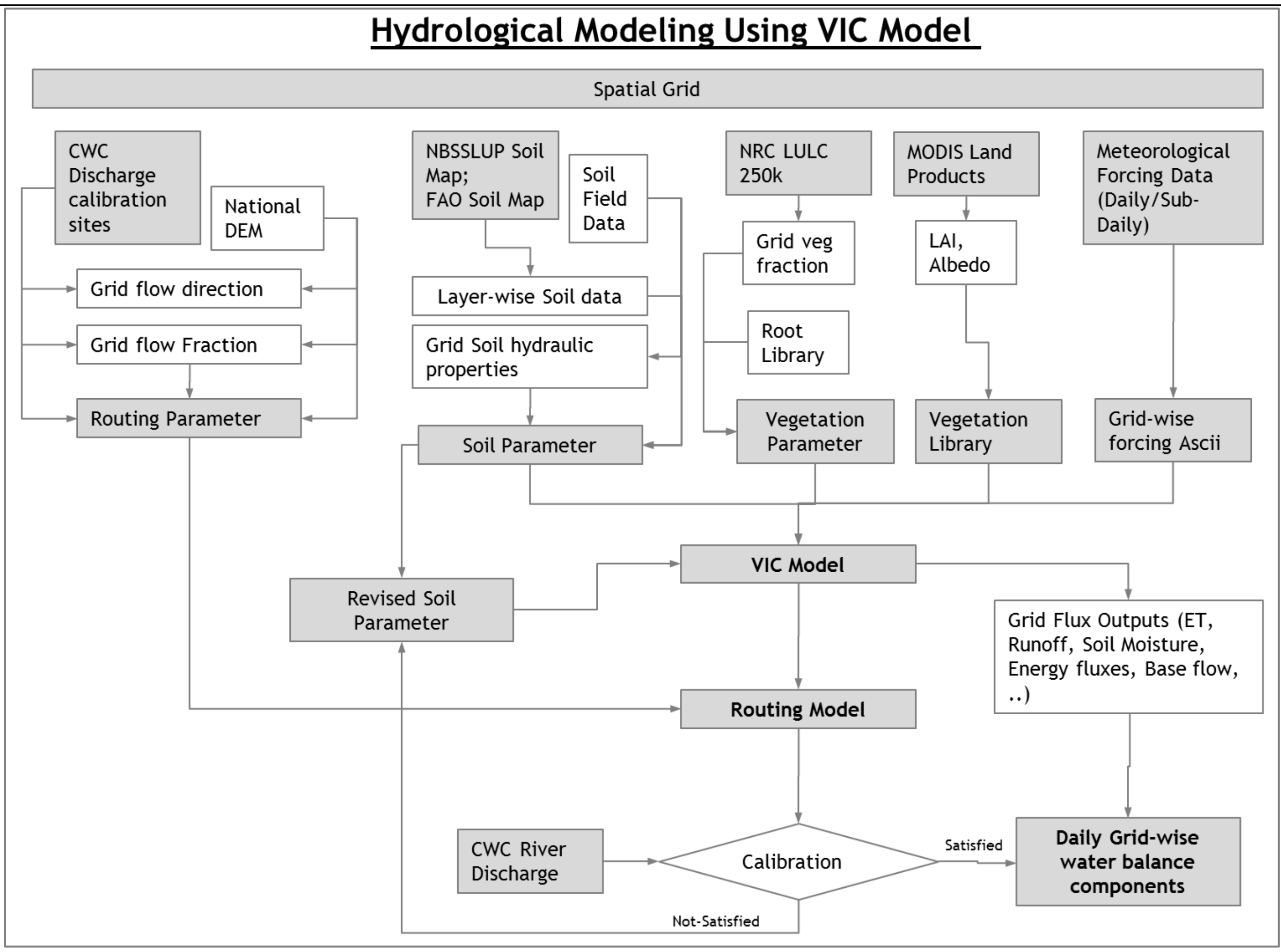


Figure 3: Methodological framework of VIC Hydrological modelling

5.1 National Geographic Framework Grid

The entire VIC model operations are grid-centric, with each grid is independently handled for water/energy balance computations. The various parameters (soil, vegetation, meteorological, routing) are indexed through grid unique numbering and sub-routines perform the required computations through reading various parameter files.

To achieve this, a national geographic frame work is prepared at 9min x 9min (~16.5 km x 16.5 km) grid size for the entire country, comprising 13709 spatial grids (Figure 4). These grids are sequentially numbered increasing linearly from west-east and north-south.

All the data parameterization has been prepared using the above grid framework.

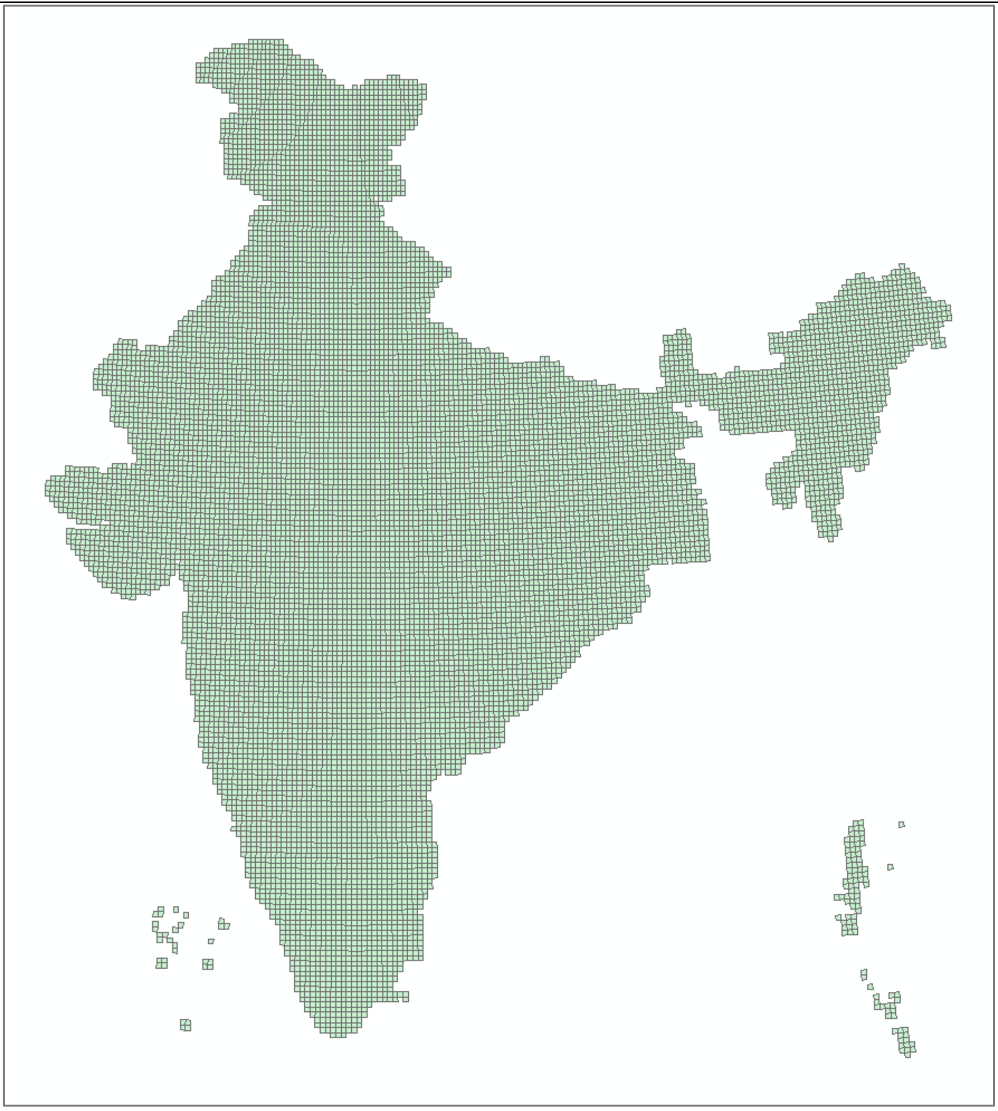


Figure 4: 9min x 9min Grid Framework for India (13709 grids)

5.2 Basin/ Catchment Routing Parameter

Using CWC gauge & discharge data obtained from India-WRIS, basin and catchment sites have been identified. Using digital surface elevation data (Cartosat-1/SRTM/Aster) catchment boundaries have been delineated and routing parameter files were prepared (Figure 5). Field recorded river discharge data at this location is used to compare and calibrate the model derived runoff.

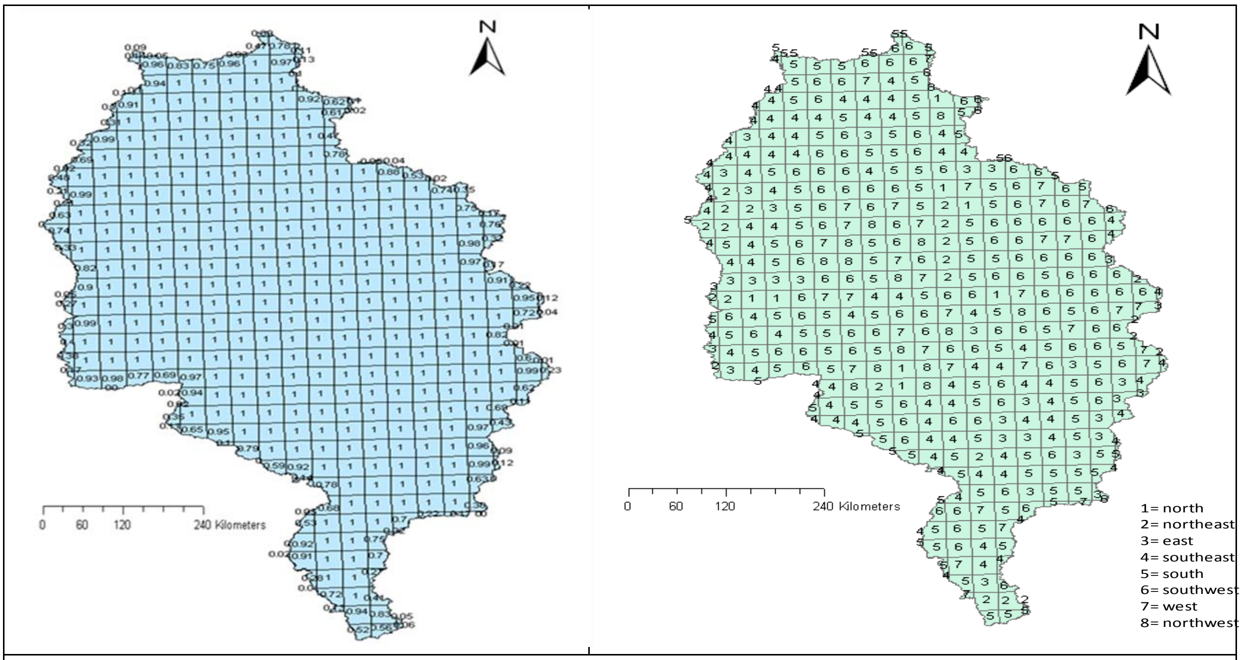
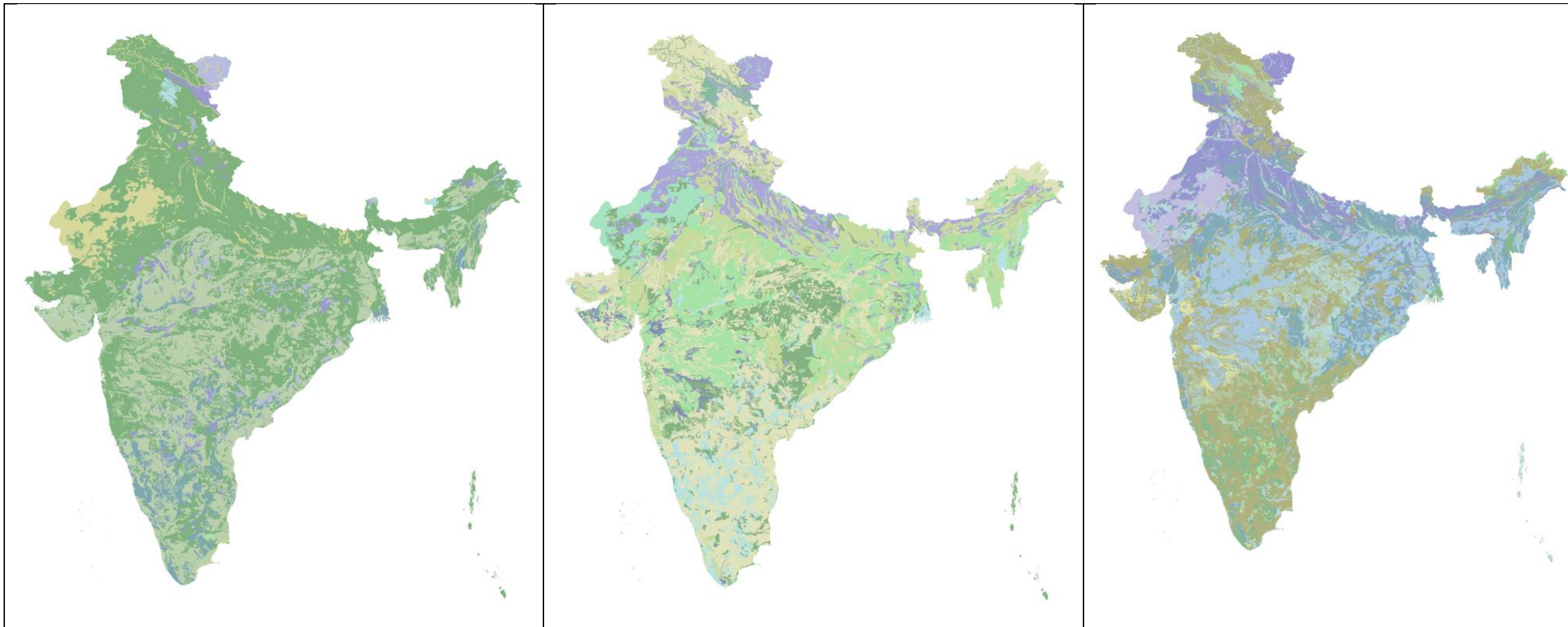


Figure 5: Area fraction and flow direction matrix of a typical sub-catchment for flow routing

5.3 Soil Parameter

The key feature of VIC hydrological model is its ability to handle soil as multiple layers and variability in soil-vegetation-water interactions across the soil column. The soil parameter file defines the layer-wise soil physical and hydraulic properties for each grid and serves as key database link for entire VIC operations. The soil parameters are supplied to VIC model as a single ASCII file, with a separate row for each grid cell, with each field containing a different parameter value.

NBSS&LUP Soil map and FAO HWSD Soil map were used to define soil texture information across space for the entire country. Using surface texture, particle size and soil depth information, the NBSS&LUP soil map has been categorized into various USDA equivalent textural classes with three soil layers as 0.15 m, 0.35 m and 1 m, respectively (Figure 6).



Layer 1 (0-15 cm)	Layer 2 (15-50 cm)	Layer 3 (50-150 cm)

Figure 6: Soil Textural Map (USDA Class) used for the Study

The soil parameters (Table 2) generally fall into two categories. The first category of soil parameters are determined from the pedo-transfer-functions and are not altered during subsequent process. These parameters include porosity (m^3m-^{3}), saturated soil potential (m), saturated hydraulic conductivity (ms-1), and the exponent B for unsaturated flow (Cosby et al., 1984). Next category of soil parameters are adjusted during calibration based on the agreement between simulated and observed hydrographs. Parameters in this category include the thickness of each soil layer, di; the exponent of the infiltration capacity curve, bi; and the three parameters in the base flow scheme: Dm, Ds, and Ws.

Table 2: Contents of VIC Soil parameter file

Column	Variable Name	Units
1	run_cell	N/A
2	gridcel	N/A
3	lat	degrees
4	lon	degrees
5	b_{infilt} , Variable infiltration curve parameter	N/A
6	Ds Fraction of Dsmax where non-linear baseflow begins	fraction
7	Dsmax , Maximum velocity of baseflow	mm/day
8	Ws, Fraction of maximum soil moisture where non-linear baseflow occurs	fraction
9	C, Exponent used in baseflow curve	N/A
10	Exponent *n* for hydraulic conductivity	N/A
11-13	Ksat, Saturated hydrologic conductivity	mm/day
13-15	phi_s, Soil moisture diffusion parameter	mm/mm
15-17	init_moist, Initial layer moisture content	mm
18	Average elevation of grid cell	m
19-21	depth, Thickness of each soil moisture layer	m
22	avg_T , Average soil temperature	C
23	dp, Soil thermal damping depth	m
24	bubble, Bubbling pressure of soil	cm
25-27	Quartz, Quartz content of soil	fraction
28-30	bulk_density	kg/m^3
31-33	soil_density	kg/m^3
34	off_gmt	hours
35-37	Wcr_FRACT, Fractional soil moisture content at the critical point	fraction
38-40	Wpwp_FRACT	fraction
41	rough, Surface roughness of bare soil	m
42	snow_rough, Surface roughness of snowpack	m
43	annual_prec, Average annual precipitation	mm
44	resid_moist, Soil moisture layer residual moisture	fraction
45	fs_active, frozen soil	1 or 0
46	frost_slope, Slope of uniform distribution of soil temperature	C
47	depth_of full_snow_cover	mm
48	initial_ice_content	N/A
49	July_Tavg, Average July soil temperature	C

The area under each soil textural class is converted into corresponding soil property and grid-wise representative value for each soil property is estimated through area weighted average.

The hydraulic properties of different soil texture classes used in preparation of soil parameter are given in the Table 3 and sample extract presented in Figure 7.

Table 3: Hydraulic properties of the various soil types used in the study

Property	Soil Texture											
	clay-heavy	silty-clay	clay-light	silty-clay-loam	silt	silt-loam	sandy-clay	loam	sandy-clay-loam	sandy-loam	loamy-sand	sand
k_sat	0.11	0.37	0.11	0.57	2.20	1.61	0.14	1.55	1.13	5.03	9.67	10.81
bulk density	1.42	1.37	1.42	1.40	1.29	1.45	1.58	1.53	1.64	1.61	1.56	1.53
bubbling	37.30	34.19	37.30	32.56	37.30	20.76	29.17	11.15	28.08	14.66	8.69	7.26
field capacity	0.88	0.79	0.88	0.75	0.63	0.65	0.82	0.61	0.63	0.40	0.26	0.22
wilting point	0.60	0.519	0.60	0.431	0.125	0.229	0.568	0.304	0.395	0.178	0.109	0.109
quartz content	0.25	0.08	0.25	0.09	0.05	0.19	0.50	0.41	0.61	0.69	0.85	0.95
Slope of retention curve ‘b’	12.28	9.76	12.28	7.48	3.05	3.79	1.19	5.30	8.66	4.84	3.99	4.10
Max. Soil Moisture (%v)	0.50	0.52	0.50	0.51	0.48	0.48	0.44	0.46	0.43	0.45	0.46	0.46

Source: (www.hydro.washington.edu/Lettenmaier/Models/VIC/Overview)

#run_cell	grid_cell	lat	long	infilt	Ds	Dsmax	Ws	c	expt-Layer	expt-Layer	expt-Layer	Ksat-Layer	Ksat-Layer	Ksat-Layer	phi_s	phi_s	phi_s
1	1	37.025	74.325	0.300	0.000	0.309	0.000	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	2	37.025	74.475	0.275	0.573	0.309	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	3	37.025	74.625	0.275	0.573	0.312	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	4	37.025	74.775	0.275	0.563	0.781	0.804	2	13.54	13.54	5.52	428.98	428.98	92.25	-999	-999	-999
1	5	37.025	74.925	0.275	0.573	0.326	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	6	37.025	75.075	0.275	0.573	0.326	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	7	37.025	75.225	0.275	0.573	0.308	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	8	37.025	75.375	0.275	0.573	0.295	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	9	36.875	73.725	0.275	0.573	0.318	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999
1	10	36.875	73.875	0.275	0.573	0.336	0.818	2	13.60	13.60	5.38	372.00	372.00	33.60	-999	-999	-999

init_moist	init_moist	init_moist	elev	depth	depth	depth	avg_T	dp	bubble	bubble	bubble	quartz	quartz	quartz	bulk_densi
40.31	79.69	2.19	4833.45	0.15	0.35	1	29.42	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
40.11	79.32	2.16	5111.93	0.15	0.35	1	29.42	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
40.33	79.82	2.50	4976.31	0.15	0.35	1	29.42	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
39.33	79.17	1.60	4920.28	0.15	0.35	1	29.42	4	11.05	11.05	28.64	0.42	0.42	0.512	1530
40.54	81.65	4.93	4760.28	0.15	0.35	1	29.42	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
40.69	82.10	5.01	4924.90	0.15	0.35	1	28.86	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
40.19	80.84	3.40	5046.75	0.15	0.35	1	28.86	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
40.39	81.77	3.86	4745.54	0.15	0.35	1	28.86	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
0.02	75.97	3.79	4761.78	0.15	0.35	1	29.42	4	11.15	11.15	29.17	0.41	0.41	0.503	1530
0.03	76.33	2.89	4630.72	0.15	0.35	1	29.42	4	11.15	11.15	29.17	0.41	0.41	0.503	1530

bulk_densi	bulk_densi	soil_densit	soil_densit	soil_densit	off_gmt	Wcr_FRAC	Wcr_FRAC	Wcr_FRAC	Wpwp_FR.	Wpwp_FR.	Wpwp_FR.	rough	snow_roug	annual_pr	resid_mois	resid_mois	resid_mois
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	637.70	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	763.58	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	763.58	0	0	0
1530	1583	2685	2685	2685	+5.5	0.419	0.419	0.563	0.299	0.299	0.556	0.001	0.0005	763.58	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	763.58	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	851.30	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	851.30	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	851.30	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	390.33	0	0	0
1530	1584	2685	2685	2685	+5.5	0.426	0.426	0.573	0.304	0.304	0.568	0.001	0.0005	637.70	0	0	0

Figure 7: Soil Parameter (extract) prepared for the model

5.4 Vegetation Parameter and Vegetation Library

VIC explicitly represents sub-grid heterogeneity in land cover classes taking their phenological changes into account such as their leaf area index (LAI), albedo, canopy resistance, and relative fraction of roots in each of the soil layers. Therefore, proper representation of sub-grid heterogeneity through various vegetation (land use /land cover) categories is critical for accurate/correct simulation of the hydrological water balance at the grid level.

The vegetation parameterization is represented in two inputs files, namely: vegetation parameter and vegetation library. Vegetation parameter file describes the vegetative (land use/land cover) composition of each grid cell (Table 4). Vegetation library file (Table 5) describes the vegetation type-wise phenological variations in terms of LAI, Albedo, height, resistance, roughness length, etc.

Table 4: Contents of Vegetation Parameter file

Variable Name	*Units*	*Description*
veg_class	N/A	Vegetation class identification number (reference index to vegetation library)
Land cover fraction (Cv)	fraction	Fraction of grid cell covered by vegetation type
root_depth	m	Root zone thickness (sum of depths is total depth of root penetration)
root_fract	fraction	Fraction of root in the current root zone.

Repeats for each vegetation tile and defined root zone, within the vegetation tile

Land use/Land cover data generated under Natural Resources Census (NRC) at 56m spatial resolution (NRSC, 2015) for the year 2007-08 is used for vegetation parameter file preparation (Figure 8).

The LULC map represents agricultural cultivated areas as season specific classes, namely: kharif only, rabi only, zaid only and double/triple cropped areas. As VIC model needs vegetation specific parameterization, such as, monthly LAI, Albedo, root depth, monthly height, the agricultural classes need to be associated with region specific crop categories. Further, a single seasonal agricultural class (e.g., kharif only), can be different crop categories across regions (rice, cotton, maize, jowar, etc.). Similarly, two seasonal agricultural classes can have two different set of crops grown among different regions (rice-rice, rice-wheat, rice-pulses, etc.). Therefore, agricultural classes under NRC LULC data need to be transformed into spatially varying classes represented by dominant crop(s)/crop group.

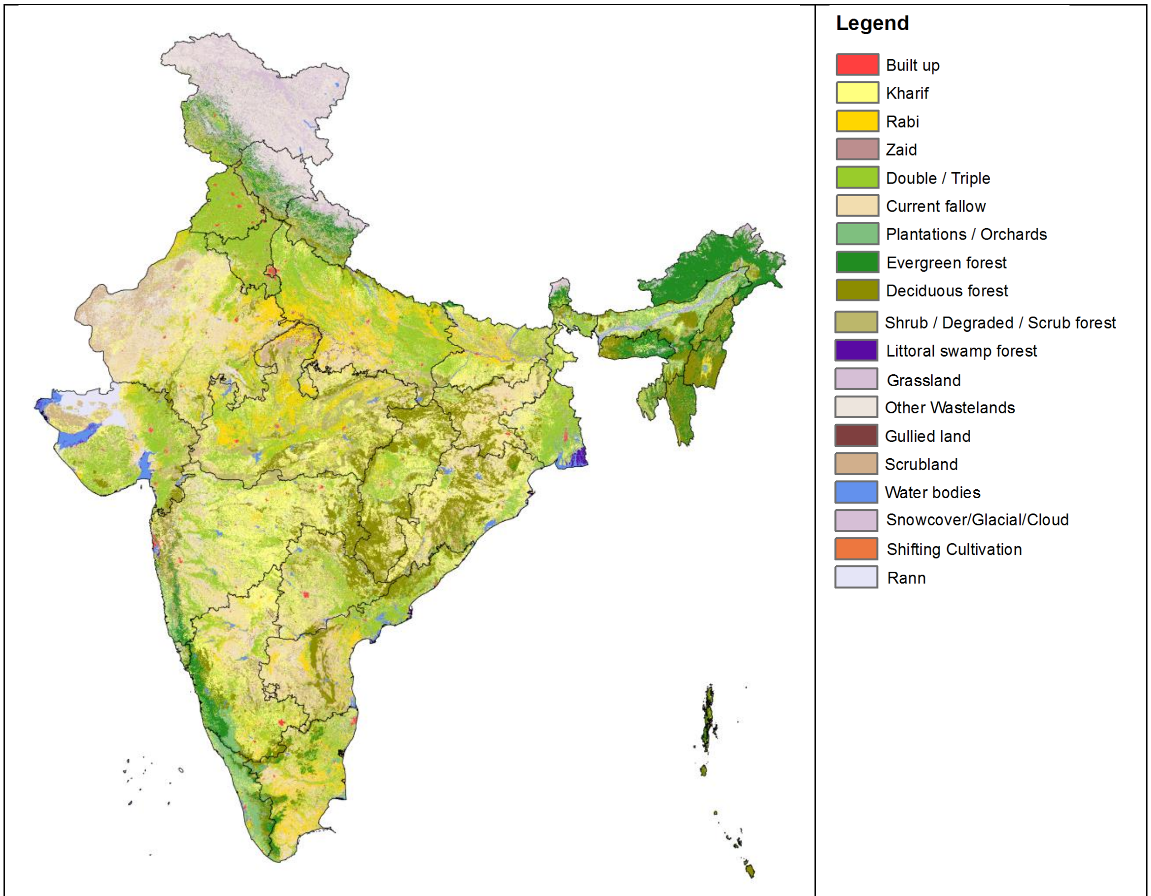


Figure 8: Land use/Land cover map – Year 2007-08
(source: NRSC)

Leaf area index (LAI) is dimensionless and is defined as the one sided green leaf area per unit ground area. Vegetation, specifically agricultural crops, exhibit significant seasonal and intra-seasonal variation in LAI resulting from type, growth stage and seasonal variations. Son et. al. (2014) demonstrated the usefulness of phenology-based classification approach to derive information of rice growing areas. Global products of vegetation green Leaf Area Index (LAI) are being operationally produced from Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) at 1-km resolution and eight-day frequency (MOD15A2; www.modisland.gsfc.nasa.gov)

2007-08 year 8-day LAI data were downloaded for Indian region and time-series stacked image was prepared. Using the agricultural mask from LULC map, the time-series LAI stacked image was categorized into multiple classes representing spatially and temporally varying LAI profiles using iso-data clustering technique. By comparing with field district/state agricultural statistics, LAI classes were related with agricultural crop dominant areas and entire agricultural area has been converted into major/dominant crop type map. The schematic representation of the above approach is presented Figure 9.

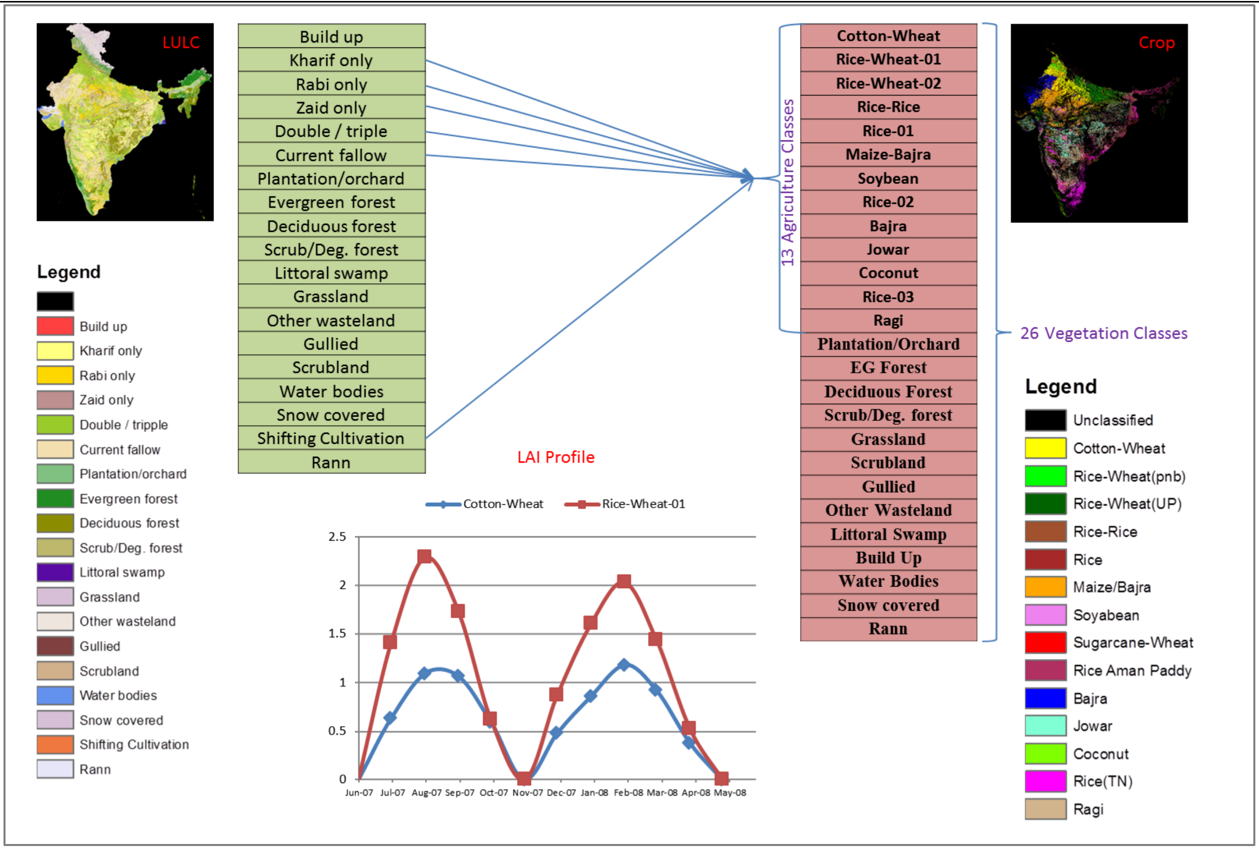


Figure 9: Reclassification of LULC agricultural area into crop specific dominant areas using time-series LAI data

The other land use/land cover classes (forest, water bodies, urban, etc.) were adopted directly from LULC map and an integrated vegetation map has been prepared for 2007-08 year (Figure 10). This exercise enabled improved definition of vegetation parameterization for entire India, incorporating the region specific crop parameterization.

Using 9min grid shape file and vegetation map, 9min grid-wise vegetation composition is extracted to arrive at model specific vegetation parameter file (Figure 11).

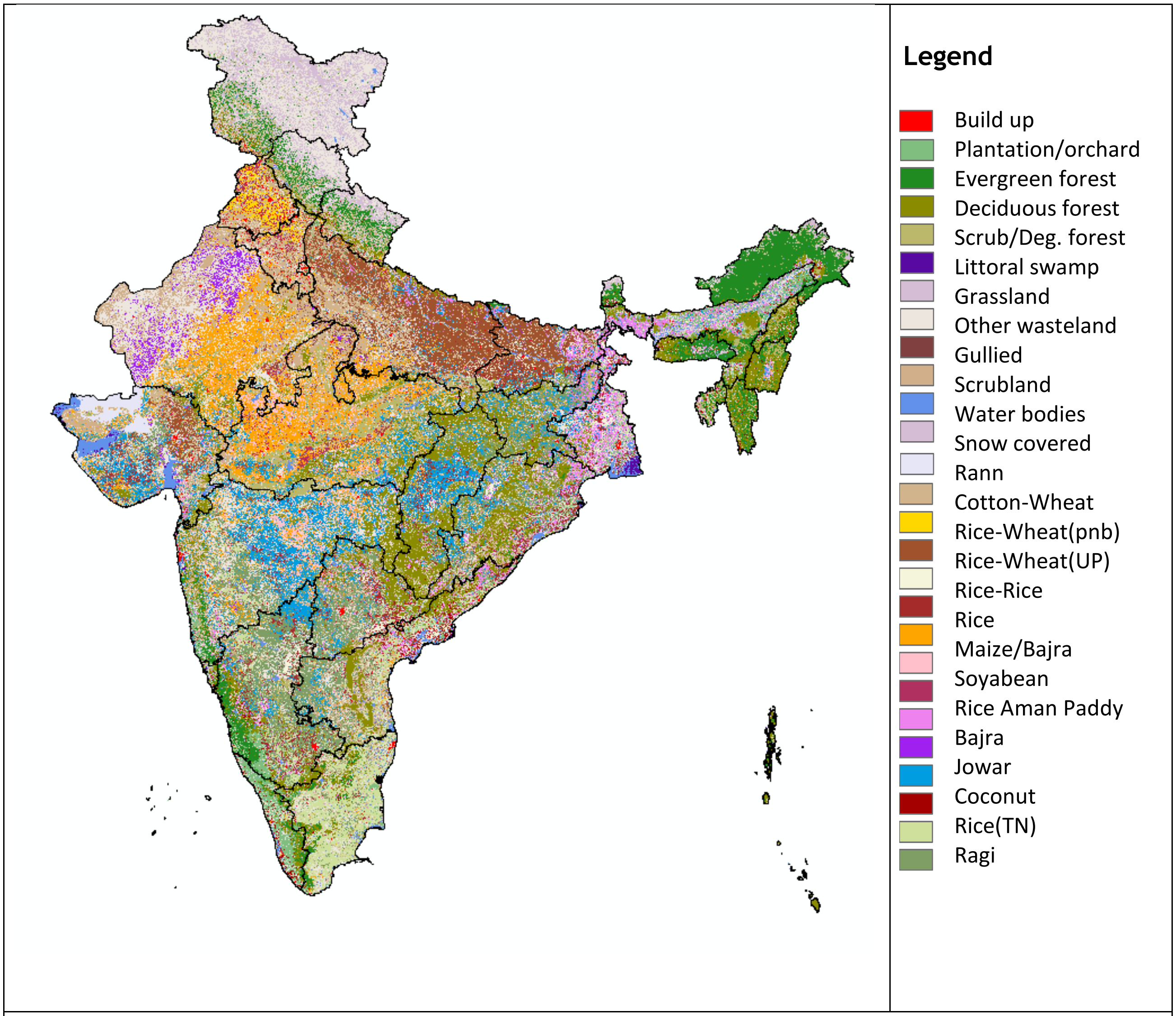


Figure 10: Integrated vegetation (LULC and Crop Type) – Year 2007-08

```
1   4
1   0.5915 0.150 0.250 0.350 0.650 1.000 0.100
13   0.0628 0.150 0.200 0.350 0.600 1.000 0.200
16   0.0693 0.150 0.600 0.350 0.400 1.000 0.000
19   0.2763 0.150 0.400 0.350 0.500 1.000 0.100
2   4
1   0.2787 0.150 0.250 0.350 0.650 1.000 0.100
4   0.1519 0.150 0.600 0.350 0.300 1.000 0.100
5   0.0730 0.150 0.600 0.350 0.300 1.000 0.100
19   0.4964 0.150 0.400 0.350 0.500 1.000 0.100
3   4
1   0.3496 0.150 0.250 0.350 0.650 1.000 0.100
3   0.0563 0.150 0.250 0.350 0.600 1.000 0.150
4   0.0617 0.150 0.600 0.350 0.300 1.000 0.100
19   0.5325 0.150 0.400 0.350 0.500 1.000 0.100
4   4
1   0.2072 0.150 0.250 0.350 0.650 1.000 0.100
16   0.1126 0.150 0.600 0.350 0.400 1.000 0.000
18   0.0797 0.150 0.200 0.350 0.600 1.000 0.200
19   0.6004 0.150 0.400 0.350 0.500 1.000 0.100
5   5
1   0.0901 0.150 0.250 0.350 0.650 1.000 0.100
4   0.0691 0.150 0.600 0.350 0.300 1.000 0.100
16   0.1874 0.150 0.600 0.350 0.400 1.000 0.000
18   0.3194 0.150 0.200 0.350 0.600 1.000 0.200
19   0.3340 0.150 0.400 0.350 0.500 1.000 0.100
6   4
1   0.0826 0.150 0.250 0.350 0.650 1.000 0.100
5   0.1127 0.150 0.600 0.350 0.300 1.000 0.100
18   0.6545 0.150 0.200 0.350 0.600 1.000 0.200
19   0.1502 0.150 0.400 0.350 0.500 1.000 0.100
7   2
1   0.7626 0.150 0.250 0.350 0.650 1.000 0.100
16   0.2374 0.150 0.600 0.350 0.400 1.000 0.000
8   4
1   0.6209 0.150 0.250 0.350 0.650 1.000 0.100
4   0.0527 0.150 0.600 0.350 0.300 1.000 0.100
16   0.0981 0.150 0.600 0.350 0.400 1.000 0.000
19   0.2283 0.150 0.400 0.350 0.500 1.000 0.100
9   3
1   0.6153 0.150 0.250 0.350 0.650 1.000 0.100
16   0.0776 0.150 0.600 0.350 0.400 1.000 0.000
19   0.3071 0.150 0.400 0.350 0.500 1.000 0.100
10   3
1   0.2677 0.150 0.250 0.350 0.650 1.000 0.100
16   0.2306 0.150 0.600 0.350 0.400 1.000 0.000
19   0.5017 0.150 0.400 0.350 0.500 1.000 0.100
```

Figure 11: Extract of Vegetation Parameter file prepared for the model

The vegetation library file defines the monthly lai, albedo, height and other related vegetation parameters (Table 5). Albedo was also derived from MODIS BRDF/Albedo product in the similar way. MODIS BRDF/Albedo at 1-km resolution at 16-day frequency (MCD43B3; www.modisland.gsfc.nasa.gov) were used.

Table 5: Contents of Vegetation Library file

Variable Name	*Units*	*Description*
veg_class	N/A	Vegetation class identification
overstory	N/A	Flag to indicate whether or not the current vegetation type has an overstory
rarc	s/m	Architectural resistance of vegetation type (~2 s/m)
rmin	s/m	Minimum stomatal resistance of vegetation type (~100 s/m)
LAI		Leaf-area index of vegetation type
albedo	fraction	Shortwave albedo for vegetation type
rough	M	Vegetation roughness length (typically 0.123 * vegetation height)
displacement	M	Vegetation displacement height (typically 0.67 * vegetation height)
wind_h	M	Height at which wind speed is measured.
RGL	W/m^2	Minimum incoming shortwave radiation at which there will be transpiration.
rad_atten	fract	Radiation attenuation factor. Normally set to 0.5, though may need to be adjusted for high latitudes.
wind_atten	fract	Wind speed attenuation through the overstory.
trunk_ratio	fract	Ratio of total tree height that is trunk (no branches).

Using vegetation (land use/land cover) map, training areas have been created for each class. Integrating with temporal stacked MODIS LAI and albedo image data, 8/16 day temporal profiles have been extracted for LAI and Albedo. Training areas have been carefully demarcated avoiding cloud covered regions during the monsoon season. Using curve smoothening techniques, monthly LAI and Albedo values have been derived for each class. Other variables like monthly height, roughness length, displacement height, over story, architectural resistance, and minimum stomatal resistance were assigned using reference/literature data (http://ldas.gsfc.nasa.gov).

Vegetation library created for 9min grid data base shown in Table 6.

Table 6: Vegetation Library file prepared for the model

#Class	OvrStry	Rarc	Rmin	JAN-LAI	FEB-LAI	MAR-LAI	APR-LAI	MAY-LAI	JUN-LAI	JUL-LAI	AUG-LAI	SEP-LAI	OCT-LAI	NOV-LAI	DEC-LAI	JAN-ALB	FEB_ALB	MAR-ALB	APR-ALB	MAY-ALB	JUN-ALB
1	0	25	80	0.00	0.00	0.00	0.00	0.00	0.00	0.65	2.45	3.10	1.35	0.60	0.20	0.160	0.160	0.160	0.160	0.160	0.139
2	0	25	80	0.00	0.00	0.00	0.00	0.00	0.27	0.60	3.01	2.26	1.05	0.86	0.00	0.142	0.141	0.140	0.140	0.140	0.120
3	0	25	80	0.00	0.00	0.00	0.00	0.00	0.27	0.55	1.10	2.09	2.29	1.15	0.23	0.152	0.148	0.148	0.148	0.148	0.118
4	0	25	80	0.00	0.00	0.00	0.00	0.00	0.38	0.60	1.25	2.94	3.02	1.20	0.00	0.145	0.141	0.141	0.145	0.145	0.130
5	0	25	80	0.00	0.00	0.00	0.00	0.00	0.61	0.95	2.00	3.51	3.15	1.70	0.00	0.137	0.137	0.137	0.137	0.144	0.130
6	0	25	80	0.00	0.00	0.00	0.00	0.00	0.37	0.60	1.80	2.45	2.90	1.70	0.90	0.159	0.150	0.149	0.150	0.150	0.135
7	0	25	80	0.00	0.00	0.00	0.00	0.00	0.34	0.90	1.75	2.25	2.50	0.85	0.60	0.151	0.150	0.150	0.150	0.150	0.130
8	0	25	80	0.00	0.00	0.70	1.20	1.50	0.30	0.70	1.70	2.50	2.75	1.15	0.80	0.150	0.140	0.135	0.130	0.130	0.130
9	0	25	80	0.00	0.00	0.00	0.00	0.00	0.30	1.49	1.80	2.30	2.40	1.94	1.10	0.143	0.143	0.145	0.145	0.145	0.130
10	1	60	100	1.44	1.35	1.35	1.30	1.28	1.18	2.30	2.95	3.60	4.46	3.20	1.90	0.130	0.130	0.130	0.130	0.132	0.130
11	1	60	100	2.50	1.80	1.50	1.70	2.55	2.82	3.00	3.50	4.00	4.40	4.00	3.00	0.120	0.120	0.120	0.120	0.115	0.110
12	1	60	100	4.80	4.05	3.75	3.20	3.10	3.20	4.05	6.05	6.35	6.20	5.70	5.30	0.115	0.115	0.115	0.115	0.115	0.110
13	0	25	80	1.10	1.50	2.20	0.50	0.00	0.00	1.00	2.50	3.50	3.00	2.00	1.50	0.130	0.125	0.125	0.135	0.130	0.130
14	0	25	80	0.90	3.50	3.66	1.30	0.00	0.00	1.20	2.20	3.17	2.65	1.20	0.00	0.135	0.110	0.110	0.125	0.140	0.140
15	1	60	100	5.70	6.10	6.40	5.40	5.43	5.53	5.53	5.94	6.20	6.55	5.98	5.70	0.130	0.125	0.125	0.125	0.125	0.120
16	0	25	80	0.00	0.00	0.00	0.00	0.00	0.00	0.80	1.20	1.60	1.20	0.00	0.00	0.160	0.160	0.160	0.160	0.160	0.150
17	1	60	120	3.40	3.40	3.30	3.20	3.00	3.00	3.50	4.50	5.20	4.80	4.20	3.50	0.125	0.125	0.125	0.125	0.125	0.123
18	1	50	120	2.50	2.20	1.80	1.20	1.20	1.76	2.65	3.20	4.20	4.00	3.50	3.20	0.135	0.135	0.140	0.140	0.150	0.150
19	0	50	120	0.00	0.00	0.00	0.00	0.00	1.10	1.65	2.50	2.75	2.50	2.10	1.50	0.140	0.140	0.150	0.150	0.150	0.140
20	0	25	80	1.25	1.00	1.00	1.00	1.00	1.00	1.50	2.50	2.75	2.75	2.50	1.50	0.130	0.130	0.130	0.130	0.130	0.120
21	0	0	150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.230	0.230	0.240	0.250	0.250	0.250
22	0	0	175	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.025	0.025	0.025	0.025	0.025	0.025
23	0	0	175	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.025	0.025	0.025	0.025	0.025	0.025
24	0	0	150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.140	0.140	0.140	0.140	0.140	0.140

JUL-ALB	AUG-ALB	SEP-ALB	OCT-ALB	NOV-ALB	DEC-ALB	JAN-ROU	FEB-ROU	MAR-ROU	APR-ROU	MAY-ROU	JUN-ROU	JUL-ROU	AUG-ROU	SEP-ROU	OCT-ROU	NOV-ROU	DEC-ROU	JAN-DIS	FEB-DIS	MAR-DIS	APR-DIS
0.128	0.125	0.124	0.136	0.148	0.160	0.000	0.000	0.000	0.000	0.000	0.000	0.052	0.194	0.246	0.246	0.048	0.016	0.000	0.000	0.000	0.000
0.115	0.115	0.122	0.135	0.135	0.140	0.000	0.000	0.000	0.000	0.000	0.022	0.049	0.246	0.246	0.086	0.070	0.000	0.000	0.000	0.000	0.000
0.115	0.115	0.115	0.130	0.139	0.145	0.000	0.000	0.000	0.000	0.000	0.029	0.059	0.118	0.246	0.246	0.049	0.025	0.000	0.000	0.000	0.000
0.110	0.110	0.110	0.120	0.130	0.143	0.000	0.000	0.000	0.000	0.000	0.017	0.027	0.056	0.132	0.135	0.054	0.000	0.000	0.000	0.000	0.000
0.105	0.100	0.100	0.110	0.135	0.137	0.000	0.000	0.000	0.000	0.000	0.024	0.025	0.077	0.135	0.135	0.065	0.000	0.000	0.000	0.000	0.000
0.125	0.120	0.120	0.120	0.140	0.158	0.000	0.000	0.000	0.000	0.000	0.022	0.036	0.107	0.172	0.172	0.101	0.053	0.000	0.000	0.000	0.000
0.120	0.120	0.120	0.120	0.147	0.151	0.000	0.000	0.000	0.000	0.000	0.023	0.062	0.121	0.172	0.172	0.059	0.041	0.000	0.000	0.000	0.000
0.125	0.110	0.110	0.125	0.147	0.149	0.000	0.000	0.034	0.059	0.074	0.015	0.034	0.084	0.135	0.135	0.057	0.039	0.000	0.000	0.188	0.322
0.125	0.125	0.125	0.125	0.135	0.143	0.000	0.000	0.000	0.000	0.000	0.017	0.084	0.101	0.130	0.130	0.109	0.062	0.000	0.000	0.000	0.000
0.125	0.120	0.115	0.115	0.125	0.130	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	5.360	5.360	5.360	5.360
0.105	0.105	0.105	0.105	0.112	0.118	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	6.700	6.700	6.700	6.700
0.105	0.105	0.105	0.105	0.110	0.115	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	6.700	6.700	6.700	6.700
0.120	0.105	0.105	0.115	0.120	0.130	0.148	0.148	0.108	0.025	0.000	0.000	0.049	0.123	0.172	0.172	0.111	0.111	0.804	0.804	0.590	0.134
0.125	0.110	0.110	0.125	0.140	0.145	0.012	0.086	0.135	0.135	0.000	0.000	0.025	0.081	0.135	0.135	0.044	0.000	0.067	0.469	0.737	0.737
0.120	0.120	0.120	0.120	0.125	0.130	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	1.230	6.700	6.700	6.700	6.700
0.140	0.130	0.130	0.144	0.154	0.165	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.009	0.012	0.009	0.000	0.000	0.000	0.000	0.000	0.000
0.120	0.120	0.120	0.125	0.125	0.125	1.476	1.476	1.476	1.476	1.476	1.476	1.476	1.476	1.476	1.476	1.476	1.476	8.040	8.040	8.040	8.040
0.135	0.125	0.125	0.125	0.130	0.135	0.861	0.861	0.861	0.861	0.861	1.230	1.230	1.230	1.230	1.171	1.230	0.984	4.690	4.690	4.690	4.690
0.135	0.130	0.125	0.130	0.135	0.140	0.000	0.000	0.000	0.000	0.000	0.074	0.111	0.168	0.185	0.168	0.141	0.101	0.000	0.000	0.000	0.000
0.120	0.120	0.120	0.120	0.125	0.130	0.034	0.027	0.027	0.027	0.027	0.027	0.040	0.067	0.074	0.074	0.067	0.040	0.183	0.146	0.146	0.146
0.200	0.200	0.200	0.200	0.220	0.230	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.025	0.025	0.025	0.025	0.025	0.025	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.025	0.025	0.025	0.025	0.025	0.025	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.140	0.140	0.140	0.140	0.140	0.140	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 6 (contd.): Vegetation Library file prepared for the model

MAY-DIS	JUN-DIS	JUL-DIS	AUG-DIS	SEP-DIS	OCT-DIS	NOV-DIS	DEC-DIS	WIND_H	RGL	rad_atten	wind_atte	truck_ratio
0.000	0.000	0.281	1.059	1.340	1.340	0.259	0.086	4	100	0.5	0.5	0.2
0.000	0.121	0.267	1.340	1.340	0.468	0.382	0.000	4	100	0.5	0.5	0.2
0.000	0.157	0.322	0.644	1.340	1.340	0.268	0.135	4	100	0.5	0.5	0.2
0.000	0.093	0.147	0.305	0.718	0.737	0.293	0.000	3.1	100	0.5	0.5	0.2
0.000	0.129	0.134	0.419	0.737	0.737	0.357	0.000	3.1	100	0.5	0.5	0.2
0.000	0.120	0.194	0.582	0.938	0.938	0.550	0.291	3.4	100	0.5	0.5	0.2
0.000	0.127	0.338	0.657	0.938	0.938	0.319	0.225	3.4	100	0.5	0.5	0.2
0.402	0.080	0.188	0.456	0.737	0.737	0.308	0.214	3.1	100	0.5	0.5	0.2
0.000	0.092	0.457	0.553	0.706	0.706	0.595	0.338	3.1	100	0.5	0.5	0.2
5.360	5.360	5.360	5.360	5.360	5.360	5.360	5.360	10	50	0.5	0.5	0.2
6.700	6.700	6.700	6.700	6.700	6.700	6.700	6.700	12	50	0.5	0.5	0.2
6.700	6.700	6.700	6.700	6.700	6.700	6.700	6.700	12	50	0.5	0.5	0.2
0.000	0.000	0.268	0.670	0.938	0.938	0.603	0.603	3.4	100	0.5	0.5	0.2
0.000	0.000	0.134	0.443	0.737	0.737	0.242	0.000	3.1	100	0.5	0.5	0.2
6.700	6.700	6.700	6.700	6.700	6.700	6.700	6.700	12	50	0.5	0.5	0.2
0.000	0.000	0.034	0.050	0.067	0.050	0.000	0.000	2.1	75	0.5	0.5	0.2
8.040	8.040	8.040	8.040	8.040	8.040	8.040	8.040	14	30	0.5	0.5	0.2
4.690	6.700	6.700	6.700	6.700	6.381	6.700	5.360	12	30	0.5	0.5	0.2
0.000	0.402	0.603	0.914	1.005	0.914	0.767	0.548	3.5	75	0.5	0.5	0.2
0.146	0.146	0.219	0.365	0.402	0.402	0.365	0.219	2.6	30	0.5	0.5	0.2
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2	75	0.5	0.5	0.2
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2	30	0.5	0.5	0.2
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2	30	0.5	0.5	0.2
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2	50	0.5	0.5	0.2

5.5 Meteorological Forcing

VIC meteorological forcing data includes daily maximum temperature (C), minimum temperature, precipitation (mm), wind speed (m/s) and optional parameters : surface albedo (fraction), atmospheric density (kg/m3), atmospheric pressure (kPa), shortwave radiation (W/m2), (C), atmospheric vapor pressure (kPa),.

The model prescribes specific file structure for the meteorological data inputs. A separate file for each grid needs to be generated in ascii/binary format, with columns representing each parameter and rows representing the time-step (daily/sub-daily). The file name for each grid is to be suffixed with grid center lat-long coordinates in degree-decimals. Accordingly a software tool has been written, which creates the requisite forcing data files using meteorological data in netcdf format and grid lat-long ascii data (Figure 11 & Figure 12).

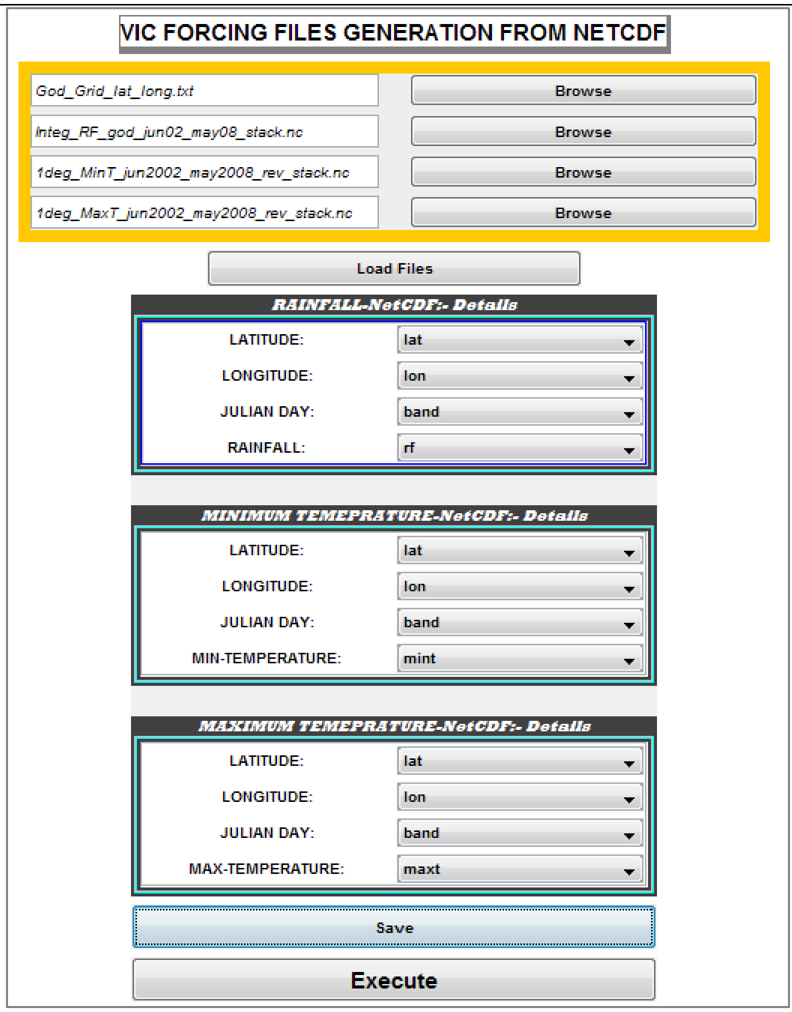


Figure 12: Software tool for generating VIC model specific meteorological forcing data files

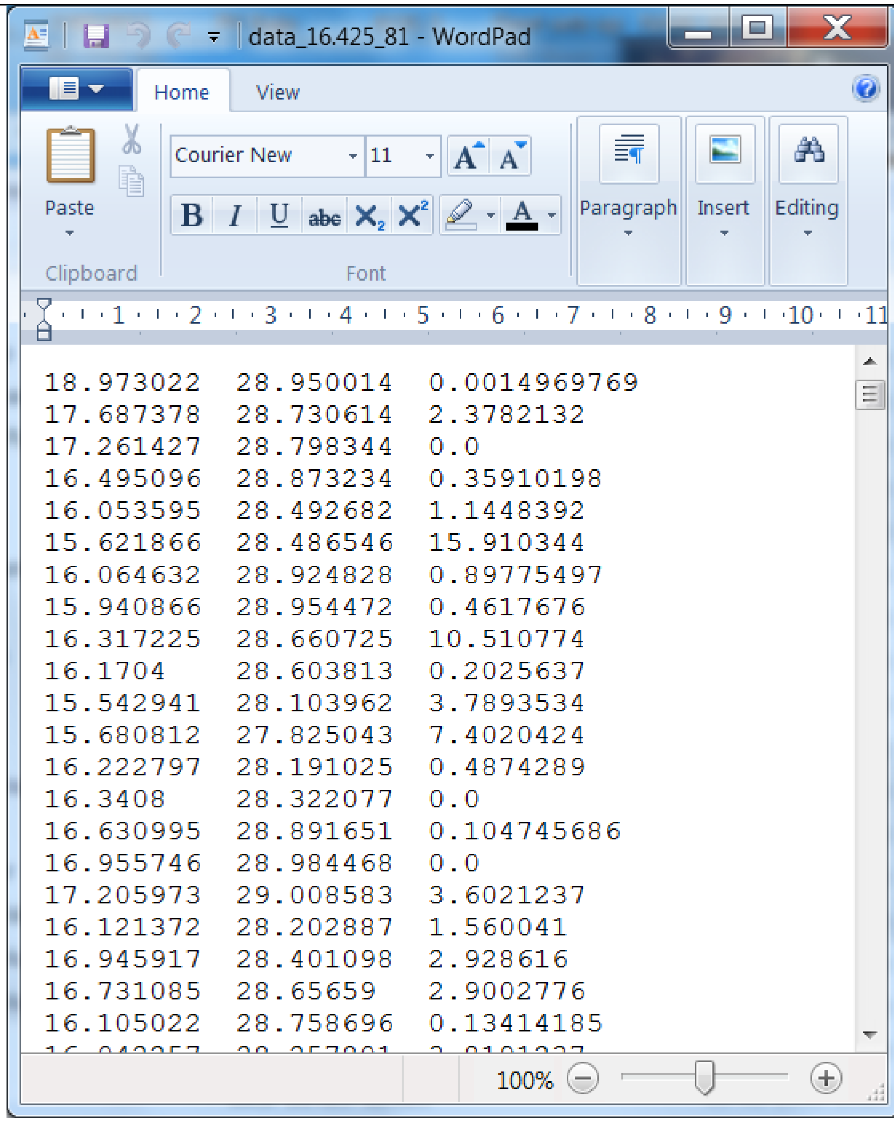


Figure 13: Typical forcing data ASCII file

Various sources are used for meteorological data (Table 7) for the preparation of forcing parameterization.

- Historical data sets (2001-2013) data were used for model development, calibration and validation.
- Long-term data (1951-2013) are used to generate historical mean/max/min state of water balance components.
- Since 01 Jan 2014, near-real-time data (TRMM/CPC/IMD-AWS/GEFS(R) are being used for in-season model computations.

- GEFS(R) Five day forecast and WRF three day forecast (IMD/SAC/NARL) is used to forecast hydrological components

Table 7: Meteorological data used

S. No.	Source	Data specifications	Time period
1	IMD	0.25 Degree gridded daily rainfall	1901-2013
		1 Degree gridded daily Max/Min Temperature	1971-2008
		http://www.imd.gov.in	
2	CPC	0.1 Degree gridded daily rainfall	01 Jan 2014 – till date
		http://www.cpc.ncep.noaa.gov	
3	TRMM	0.25 Degree gridded daily rainfall	01 Jan 2014 – 31 Mar 2015
		http://mirador.gsfc.nasa.gov	
4	GEFS (R)	0.5 Degree gridded daily rainfall, Max/Min Temperature, Wind speed	01 Jan 1985 – till date and +3 days forecast
		http://www.esrl.noaa.gov/psd/forecasts/reforecast2/download.html	
5	VIC	0.5 Degree gridded daily rainfall, Max/Min Temperature, Wind speed	1948-2007
		http://vic.readthedocs.org/en/master/Datasets/Datasets	

5.6 Model Development, Calibration and Validation

VIC model version 4.1 (VIC-3L) has been installed and configured in Linux environment. Global parameter is the main input/control file for VIC operations. It points VIC to the locations of the other input/output files and sets parameters that govern the simulation (e.g., start/end dates, modes of operation). Figure 13 provides the extract of Global parameter file created.

Using the soil parameter file, vegetation parameter file, vegetation library file and meteorological forcing data, the model computations were carried out in water balance mode at daily time-step. VIC computations are grid-centric and each grid is independently handled with grid to grid interactions. The outputs from model are independent for each grid in ASCII format and include: surface runoff, evapotranspiration, base flow, and layer-wise soil moisture and energy fluxes. Typical VIC output file for grid is presented in Figure 14.

Software tools have been written to convert independent grid-wise fluxes into geo-spatial format to represent spatial patterns of fluxes (ET, Runoff, Soil moisture). Routing model has been used to compute stream flow at basin outlet at daily time-step.

```
#######################################################################
# VIC Model Parameters - 4.1.1
#######################################################################
# $Id: global.param.Godavari_2007,Trial_ECV_SM 2012/10/03 $
#######################################################################
# Simulation Parameters
#######################################################################
NLAYER     3     # number of soil layers
NODES      1     # number of soil thermal nodes
TIME_STEP  24    # model time step in hours (set to 24 if FULL_ENERGY = FALSE, set to < 24 if FULL_ENERGY = TRUE)
SNOW_STEP  1     # time step in hours for which to solve the snow model (should = TIME_STEP if TIME_STEP < 24)
STARTYEAR  2002 # year model simulation starts
STARTMONTH 06    # month model simulation starts
STARTDAY   01    # day model simulation starts
STARTHOUR  00    # hour model simulation starts
ENDYEAR    2008 # year model simulation ends
ENDMONTH   05    # month model simulation ends
ENDDAY           31    # day model simulation ends
FULL_ENERGY      FALSE # TRUE = calculate full energy balance; FALSE = compute water balance only
FROZEN_SOIL      FALSE # TRUE = calculate frozen soils
QUICK_FLUX TRUE  # TRUE = use simplified ground heat flux method of Liang et al (1999); FALSE = use finite element method of Cherkauer et al (1999)
QUICK_SOLVE      FALSE # TRUE = Use Liang et al., 1999 formulation for iteration, but explicit finite difference method for final step.
NO_FLUX          FALSE # TRUE = use no flux lower boundary for ground heat flux computation; FALSE = use constant flux lower boundary condition.  If NO
IMPLICIT    TRUE  # TRUE = use implicit solution for soil heat flux equation of Cherkauer et al (1999), otherwise uses original explicit solution.
EXP_TRANS   FALSE # TRUE = exponentially distributes the thermal nodes in the Cherkauer et al. (1999) finite difference algorithm, otherwise uses linea
SNOW_ALBEDO      USACE # USACE = use traditional VIC algorithm based on US Army Corps of Engineers empirical snow albedo decay curves, using hard-coded
SNOW_DENSITY     DENS_BRAS  # DENS_BRAS = use traditional VIC algorithm taken from Bras, 1990; DENS_SNTHRM = use algorithm taken from SNTHRM model.
BLOWING          FALSE # TRUE = compute evaporative fluxes due to blowing snow

DIST_PRCP   FALSE # TRUE = use distributed precipitation
PREC_EXPT   0.6   # exponent for use in distributed precipitation eqn (only used if DIST_PRCP is TRUE)
CORRPREC    FALSE # TRUE = correct precipitation for gauge undercatch
MIN_WIND_SPEED   0.1   # minimum allowable wind speed (m/s)
MAX_SNOW_TEMP    0.5   # maximum temperature (C) at which snow can fall
MIN_RAIN_TEMP    -0.5 # minimum temperature (C) at which rain can fall
CONTINUEONERROR TRUE     # TRUE = if simulation aborts on one grid cell, continue to next grid cell; TFALLBACK = when energy balance fails to converge,
COMPUTE_TREELINE FALSE # Can be either FALSE or the id number of an understory veg class; FALSE = turn treeline computation off; VEG_CLASS_ID = replace
EQUAL_AREA FALSE # TRUE = grid cells are from an equal-area projection; FALSE = grid cells are on a regular lat-lon grid
RESOLUTION 0.05 # Grid cell resolution (degrees if EQUAL_AREA is FALSE, km^2 if EQUAL_AREA is TRUE); ignored if LAKES is FALSE
AERO_RESIST_CANSNOW   AR_406_FULL      # Options for aerodynamic resistance in snow-filled canopy:
                 # AR_406   = multiply by 10 for latent heat but do NOT multiply by 10 for sensible heat and do NOT apply stability correction (as in V
                 # AR_406_LS      = multiply by 10 for latent heat AND sensible heat and do NOT apply stability correction; when no snow in canopy, use
                 # AR_406_FULL    = multiply by 10 for latent heat AND sensible heat and do NOT apply stability correction; additionally, always use ove
                 # AR_410   = apply stability correction but do NOT multiply by 10 (as in VIC 4.1.0); additionally, always use overstory aero_resist fo
                 # AR_COMBO       = multiply by 10 AND apply stability correction; additionally, always use overstory aero_resist for ET (as in 4.1.0).
                 # Default  = AR_406_FULL
GRND_FLUX_TYPE   GF_FULL     # Options for ground flux:
                 # GF_406 = use (flawed) formulas for ground flux, deltaH, and fusion from VIC 4.0.6 and earlier;
                 # GF_410 = use formulas from VIC 4.1.0 (ground flux is correct, but deltaH and fusion ignore surf_atten);
                 # GF_FULL = use correct ground flux formula from VIC 4.1.0 and also take surf_atten into account in deltaH and fusion
                 # Default  = GF_FULL
PLAPSE           TRUE  # This controls how VIC computes air pressure when air pressure is not supplied as an input forcing: TRUE = set air pressure to s

#######################################################################
# State Files and  Parameters
#######################################################################
#INIT_STATE      /home/pvraju/Godavari/God_0208   # Initial state path/file

#STATENAME /home/pvraju/Godavari/God_0208   # Output state file path/prefix.  The date (STATEYEAR,STATEMONTH,STATEDAY) will be appended to the prefix a
#STATEYEAR 2008 # year to save model state
#STATEMONTH      05    # month to save model state
#STATEDAY  31    # day to save model state
#BINARY_STATE_FILE       FALSE   # TRUE if state file should be binary format; FALSE if ascii

#######################################################################
# Forcing Files and Parameters
#
#       All FORCING filenames are actually the pathname, and prefix
#               for gridded data types: ex. DATA/forcing_
#               Latitude and longitude index suffix is added by VIC
#
#     There must be 1 FORCE_TYPE entry for each variable (column) in the forcing file
#
#     If FORCE_TYPE is BINARY, each FORCE_TYPE must be followed by:
#               SIGNED/UNSIGNED SCALE_FACTOR
#          For example (BINARY):
#               FORCE_TYPE PREC UNSIGNED   40
#          or (ASCII):
#               FORCE_TYPE PREC
#######################################################################
FORCING1   /home/pvraju/Godavari/God_0208/God_2002_08_forcing_data_cpc_aws_merg_RF_1deg_temp/data_     # Forcing file path and prefix, ending in "_"
FORCE_FORMAT     ASCII # BINARY or ASCII
FORCE_ENDIAN     LITTLE     # LITTLE (PC/Linux) or BIG (SUN)
N_TYPES          3     # Number of variables (columns)
FORCE_TYPE TMIN
FORCE_TYPE TMAX
```

Figure 14: Extract of Global Parameter file

```
FORCE_TYPE PREC
FORCE_DT   24    # Forcing time step length (hours)
FORCEYEAR  2002 # Year of first forcing record
FORCEMONTH 06   # Month of first forcing record
FORCEDAY   01   # Day of first forcing record
FORCEHOUR  00   # Hour of first forcing record
GRID_DECIMAL    3    # Number of digits after decimal point in forcing file names
WIND_H          10    # height of wind speed measurement (m)
MEASURE_H       2.0     # height of humidity measurement (m)
ALMA_INPUT FALSE # TRUE = ALMA-compliant input variable units; FALSE = standard VIC units

########################################################################
# Land Surface Files and Parameters
########################################################################
SOIL            /home/pvraju/Godavari/God_0208/God0208_soil_sm31may02.txt  # Soil parameter path/file
ARC_SOIL        FALSE   # TRUE = read soil parameters from ARC/INFO ASCII grids
#SOIL_DIR        (soil param directory)   # Directory containing ARC/INFO ASCII grids of soil parameters - only valid if ARC_SOIL is TRUE
BASEFLOW   ARNO # ARNO = columns 5-8 are the standard VIC baseflow parameters; NIJSSEN2001 = columns 5-8 of soil file are baseflow parameters from Nijs
JULY_TAVG_SUPPLIED    FALSE # TRUE = final column of the soil parameter file will contain average July air temperature, for computing treeline; this wil
VEGPARAM        /home/pvraju/Godavari/God_0208/God0208_vegparam.txt   # Veg parameter path/file
GLOBAL_LAI      FALSE    # TRUE = read LAI from veg param file; FALSE = read LAI from veg library file
ROOT_ZONES      3     # Number of root zones (must match format of veg param file)
VEGLIB             /home/pvraju/Godavari/God_0208/God0208_veg_library.txt  # Veg library path/file
SNOW_BAND  1          # Number of snow bands; if number of snow bands > 1, you must insert the snow band path/file after the number of bands (e.g. SNOW
#LAKES          (put lake parameter path/file here)   # Lake parameter path/file
#LAKE_PROFILE   FALSE # TRUE = User-specified depth-area parameters in lake parameter file; FALSE = VIC computes a parabolic depth-area profile

########################################################################
# Output Files and Parameters
########################################################################
RESULT_DIR      /home/pvraju/Godavari/God_0208/God0208_flux_cpc_aws_merge_1deg_temp   # Results directory path
OUT_STEP        0       # Output interval (hours); if 0, OUT_STEP = TIME_STEP
SKIPYEAR   0    # Number of years of output to omit from the output files
COMPRESS   FALSE # TRUE = compress input and output files when done
BINARY_OUTPUT   FALSE # TRUE = binary output files
ALMA_OUTPUT     FALSE # TRUE = ALMA-format output files; FALSE = standard VIC units
MOISTFRACT      FALSE # TRUE = output soil moisture as volumetric fraction; FALSE = standard VIC units
PRT_HEADER TRUE   # TRUE = insert a header at the beginning of each output file; FALSE = no header
PRT_SNOW_BAND   FALSE   # TRUE = write a "snowband" output file, containing band-specific values of snow variables; NOTE: this is ignored if N_OUTFILES

########################################################################
#
# Output File Contents
#
# As of VIC 4.0.6 and 4.1.0, you can specify your output file names and
# contents # in the global param file (see the README.txt file for more
# information).
#
# If you do not specify file names and contents in the global param
# file, VIC will produce the same set of output files that it has
# produced in earlier versions, namely "fluxes" and "snow" files, plus
# "fdepth" files if FROZEN_SOIL is TRUE and "snowband" files if
# PRT_SNOW_BAND is TRUE.  These files will have the same contents and
# format as in earlier versions.
#
# The OPTIMIZE and LDAS_OUTPUT options have been removed.  These
# output configurations can be selected with the proper set of
# instructions in the global param file.  (see the output.*.template
# files included in this distribution for more information.)
#
# If you do specify the file names and contents in the global param file,
# PRT_SNOW_BAND will have no effect.
#
# Format:
#
#   N_OUTFILES    <n_outfiles>
#
#   OUTFILE       <prefix>        <nvars>
#   OUTVAR        <varname>       [<format>       <type>  <multiplier>]
#   OUTVAR        <varname>       [<format>       <type>  <multiplier>]
#   OUTVAR        <varname>       [<format>       <type>  <multiplier>]
#
#   OUTFILE       <prefix>        <nvars>
#   OUTVAR        <varname>       [<format>       <type>  <multiplier>]
#   OUTVAR        <varname>       [<format>       <type>  <multiplier>]
#   OUTVAR        <varname>       [<format>       <type>  <multiplier>]
#
#
# where
#   <n_outfiles> = number of output files
#   <prefix>     = name of the output file, NOT including latitude
#                  and longitude
#   <nvars>      = number of variables in the output file
#   <varname>    = name of the variable (this must be one of the
#                  output variable names listed in vicNl_def.h.)
#   <format>     = (for ascii output files) fprintf format string,
#                  e.g.
#                    %.4f = floating point with 4 decimal places
#                    %.7e = scientific notation w/ 7 decimal places
#                    *    = use the default format for this variable
#
#   <format>, <type>, and <multiplier> are optional.  For a given
#   variable, you can specify either NONE of these, or ALL of
#   these.  If these are omitted, the default values will be used.
#
```

Figure 14 (Contd.): Extract of Global Parameter file

```
# NRECS: 2192
# DT: 24
# STARTDATE: 2002-06-01 00:00:00
# ALMA_OUTPUT: 0
# NVARS: 23
# YEAR    MONTH DAY  OUT_PREC    OUT_EVAP    OUT_RUNOFF     OUT_BASEFLOW    OUT_WDEW    OUT_SOIL_LIQ_0    OUT_SOIL_LIQ_1    OUT_SOIL_LIQ_2
2002  06   01   0.0000      0.2209      0.0000     0.0284     0.0000     50.2177    71.5444    109.0916   33.3741    17.0995    0.0000
2002  06   02   1.6440      0.1109      0.0691     0.0284     0.0000     50.8401    71.5322    109.0781   3.9285     -10.7159   0.0000
2002  06   03   0.0150      0.1109      0.0000     0.0284     0.0000     50.8369    71.5204    109.0646   3.9282     -10.7162   0.0000
2002  06   04   0.4372      0.1109      0.0079     0.0284     0.0000     50.9043    71.5088    109.0511   3.9277     -10.7167   0.0000
2002  06   05   0.4297      0.0080      0.0016     0.0284     0.0000     50.9155    71.4973    109.0375   3.9272     -6.3253    0.0000
2002  06   06   19.9231     0.1017      0.5955     0.0284     0.0000     56.0835    71.4987    109.0240   3.9268     -10.7175   0.0000
2002  06   07   1.0929      0.0119      0.0000     0.0284     0.0000     56.0358    71.5314    109.0104   3.9262     -6.8980    0.0000
2002  06   08   0.5076      -0.0190     0.0000     0.0284     0.0000     55.9893    71.5630    108.9970   3.9259     -5.0669    0.0000
2002  06   09   10.2129     0.0967      0.0538     0.0284     0.0000     56.3906    71.5985    108.9837   3.9254     -10.5389   0.0000
2002  06   10   0.1889      0.0147      0.0000     0.0284     0.0000     56.3353    71.6386    108.9705   3.9249     -6.9665    0.0000
2002  06   11   2.3658      0.0067      0.0000     0.0284     0.0000     56.2815    71.6771    108.9574   3.9246     -6.7285    0.0000
2002  06   12   2.7495      0.0153      0.0000     0.0284     0.0000     56.2290    71.7142    108.9444   3.9241     -7.2564    0.0000
2002  06   13   0.3077      -0.0202     0.0000     0.0284     0.0000     56.1779    71.7498    108.9316   3.9239     -5.1518    0.0000
2002  06   14   0.0000      -0.0125     0.0000     0.0284     0.0000     56.1280    71.7840    108.9188   6.4581     -3.8827    0.0000
2002  06   15   0.0914      -0.0270     0.0000     0.0284     0.0000     56.0793    71.8169    108.9061   3.9232     -4.4774    0.0000
2002  06   16   0.0000      -0.0128     0.0000     0.0284     0.0000     56.0318    71.8487    108.8936   6.4565     -3.8497    0.0000
2002  06   17   3.4493      0.0219      0.0000     0.0284     0.0000     55.9853    71.8792    108.8811   3.9225     -7.4621    0.0000
2002  06   18   1.5320      -0.0021     0.0000     0.0284     0.0000     55.9399    71.9086    108.8688   3.9224     -6.3690    0.0000
2002  06   19   0.0000      -0.0115     0.0000     0.0284     0.0000     55.8954    71.9369    108.8565   6.4557     -4.1323    0.0000
2002  06   20   3.5520      0.0227      0.0000     0.0284     0.0000     55.8520    71.9642    108.8443   3.9220     -7.5080    0.0000
2002  06   21   0.1771      -0.0204     0.0000     0.0284     0.0000     55.8094    71.9905    108.8322   3.9218     -5.2134    0.0000
2002  06   22   3.7654      0.0271      0.0000     0.0284     0.0000     55.7677    72.0158    108.8202   3.9217     -7.7567    0.0000


OUT_NET_SHORT   OUT_R_NET  OUT_EVAP_CANOP  OUT_TRANSP_VEG  OUT_EVAP_BARE   OUT_SUB_CANOP   OUT_SUB_SNOW    OUT_AERO_RESIST OUT_SURF_TE
0.2209     0.0000     0.0000     0.0000     313.6477   0.0000     0.0446     92.6366    299.3400   0.0000     1.5000
0.0000     0.0000     0.0000     0.1109     286.9016   0.0000     0.8500     93.0284    300.9703   0.0000     1.5000
0.0000     0.0000     0.0000     0.1109     286.9016   0.0000     0.8500     93.0285    300.9703   0.0000     1.5000
0.0000     0.0000     0.0000     0.1109     286.9016   0.0000     0.8500     93.0286    300.9703   0.0000     1.5000
0.0000     0.0000     0.0000     0.0080     286.9016   -1.7569    0.8500     93.0288    300.9704   0.0000     1.5000
0.0000     0.0000     0.0000     0.1017     286.9016   0.0000     0.8500     93.0289    300.9704   0.0000     1.5000
0.0000     0.0000     0.0000     0.0119     286.9016   -1.5350    0.8500     93.0291    300.9704   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0190    286.9016   -1.6985    0.8500     93.0291    300.9704   0.0000     1.5000
0.0000     0.0000     0.0000     0.0967     286.9016   0.0000     0.8500     93.0293    300.9704   0.0000     1.5000
0.0000     0.0000     0.0000     0.0147     286.9016   -1.7285    0.8500     93.0294    300.9704   0.0000     1.5000
0.0000     0.0000     0.0000     0.0067     286.9016   -1.1723    0.8500     93.0295    300.9704   0.0000     1.5000
0.0000     0.0000     0.0000     0.0153     286.9016   -1.0789    0.8500     93.0297    300.9705   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0202    286.9016   -1.6572    0.8500     93.0298    300.9705   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0125    286.9016   -1.9322    0.8164     92.6388    299.3403   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0270    286.9016   -1.7156    0.8500     93.0300    300.9705   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0128    286.9016   -1.9310    0.8164     92.6391    299.3403   0.0000     1.5000
0.0000     0.0000     0.0000     0.0219     286.9016   -0.9231    0.8500     93.0302    300.9705   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0021    286.9016   -1.3225    0.8500     93.0302    300.9705   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0115    286.9016   -1.8701    0.8164     92.6393    299.3404   0.0000     1.5000
0.0000     0.0000     0.0000     0.0227     286.9016   -0.8860    0.8500     93.0303    300.9705   0.0000     1.5000
0.0000     0.0000     0.0000     -0.0204    286.9016   -1.6310    0.8500     93.0304    300.9705   0.0000     1.5000
0.0000     0.0000     0.0000     0.0271     286.9016   -0.8327    0.8500     93.0304    300.9705   0.0000     1.5000
```

Figure 15: Typical VIC output file for a grid

Like most physically based hydrologic models, the VIC model has many parameters to be optimized for obtaining best agreement between modeled and field observed. However, most of the parameters can be derived from in situ measurement and remote sensing observation. The main calibration parameters are:

a) b_i, the infiltration parameter, which controls the partitioning of rainfall (or snowmelt) into infiltration and direct runoff
b) Ds_{max}, the maximum baseflow velocity
c) *Ds*, the fraction of maximum baseflow velocity
d) *Ws*, the fraction of maximum soil moisture content of the third soil layer at which non-linear baseflow occurs
e) Second and third soil layer thicknesses

Few general guidelines to VIC model calibration:

1. Ds - [>0 to 1] this is the fraction of Ds_{max} where non-linear (rapidly increasing) baseflow begins. With a higher value of Ds, the baseflow will be higher at lower water content in the lowest soil layer.
2. Ds_{max} - [>0 to ~30, depends on hydraulic conductivity] this is the maximum baseflow that can occur from the lowest soil layer (in mm/day).
3. Ws - [>0 to 1] this is the fraction of the maximum soil moisture (of the lowest soil layer) where non-linear baseflow occurs. This is analogous to Ds. A higher value of Ws will raise the water content required for rapidly increasing, non-linear baseflow, which will tend to delay runoff peaks.
4. b_i - [>0 to ~0.4] This parameter defines the shape of the Variable Infiltration Capacity curve. It describes the amount of available infiltration capacity as a function of relative saturated grid cell area. A higher value of b_i gives lower infiltration and yields higher surface runoff.

Basin wise model is calibrated for the water years between 1976 and 1985 and validation conducted for the water years between 1986 and 2005 using the observed stream flow data of CWC at the selected basins outlet. Calibration of a hydrological model is an iterative process which involves changing the values of model parameters to obtain best fit between the observed and simulated values. Nash-Sutcliffe efficiency (NSE), performance measuring criteria was considered for calibration purposes. The model parameters were optimized till best fit between observed and modeled is obtained. Figure 15 shows the comparison river discharge hydrograph estimated from VIC model and its comparison with field observed for Godavari and Mahanadi river basins.

The values of performance of the model for the daily stream flow simulation based on performance measuring criteria is tabulated for calibration periods in Table 8, which satisfy the recommended values suggested in literature.

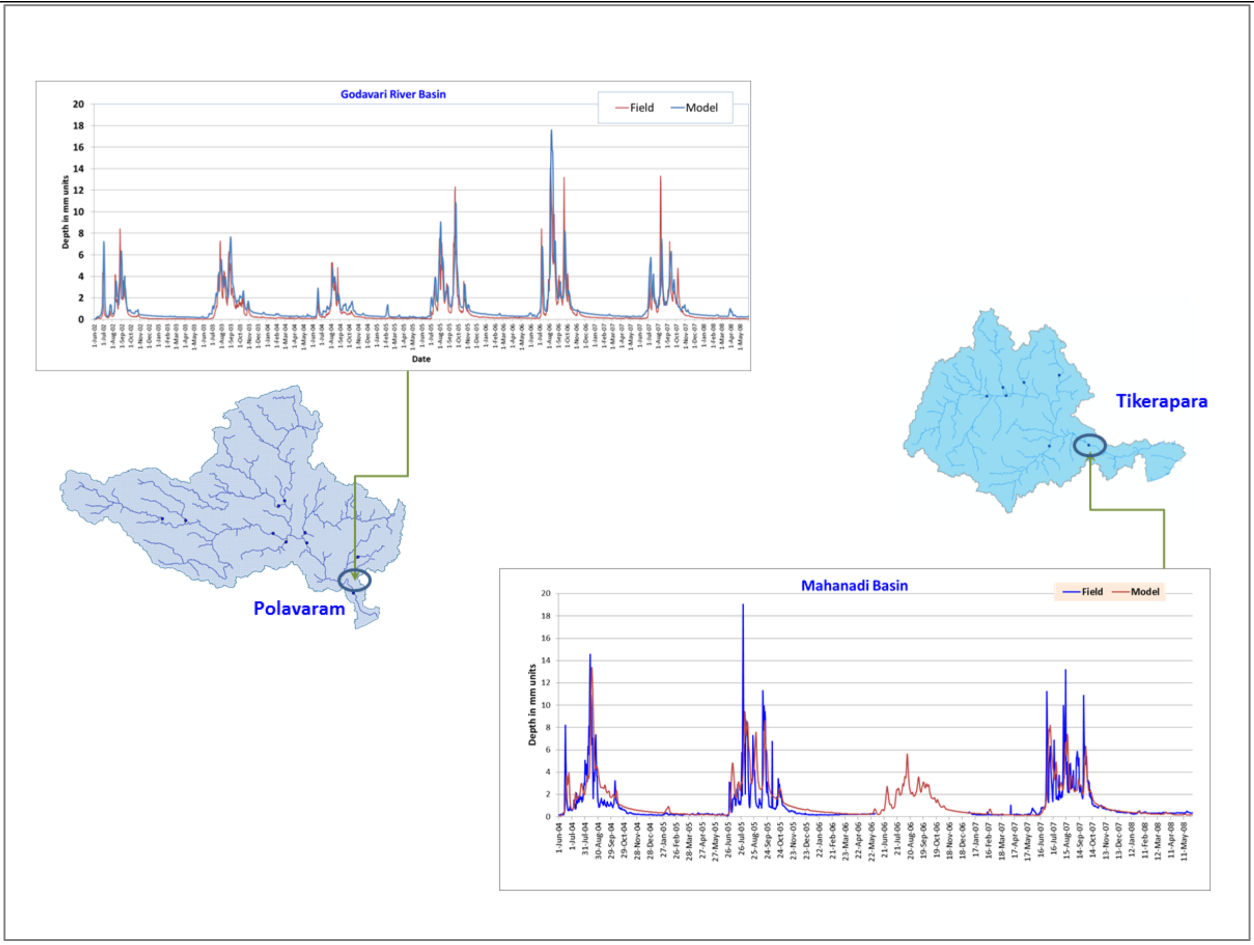


Figure 16: Comparison of model derived river discharge with field observed for Godavari and Mahanadi river basins.

Table 8: NSE Coefficients for different basins

S.no	River Basin	Gauge Site	NSE
1	Godavari	Polavaram	0.73
2	Mahanadi	Tikarapara	0.64
3	Krishna	Vijayawada	0.59
4	Narmada	Gurudeshwar	0.77
5	Subarnarekha	Ghatsila	0.68

Model derived ET estimates have been compared with MODIS spatial ET estimates during the year 2013 (Figure 16). MODIS (MOD16) global evapotranspiration (ET)/latent heat flux (LE)/potential ET (PET)/potential LE (PLE) datasets are produced at 1km spatial resolution over global vegetated land areas at 8-day, monthly and annual intervals (http://www.ntsg.umt.edu/project/mod16).

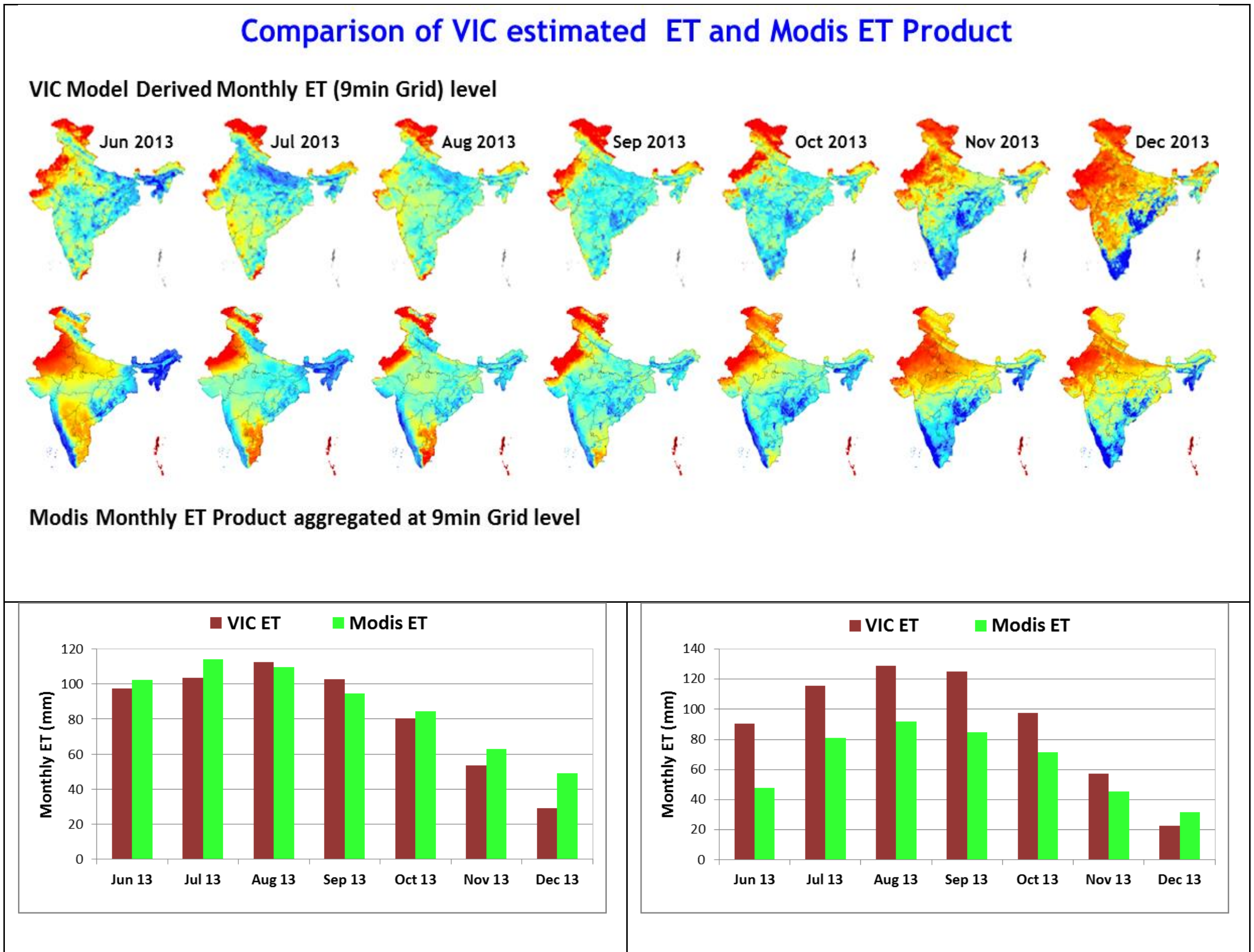


Figure 17: Comparison VIC model derived ET with MODIS ET (MOD16) estimate

Model derived Soil Moisture estimates have been compared with CTCZ SM measure during the year 2013. CTCZ data for 70 locations, uniformly distributed over space, were compared with the model estimated soil moisture, for top layer (0- 150mm), second layer (150mm -500mm) and for the entire column (500mm) of soil for selected days. Figures 17(a), 17(b) and 17(c), illustrates the scatterplot which depicts the measure of performance.

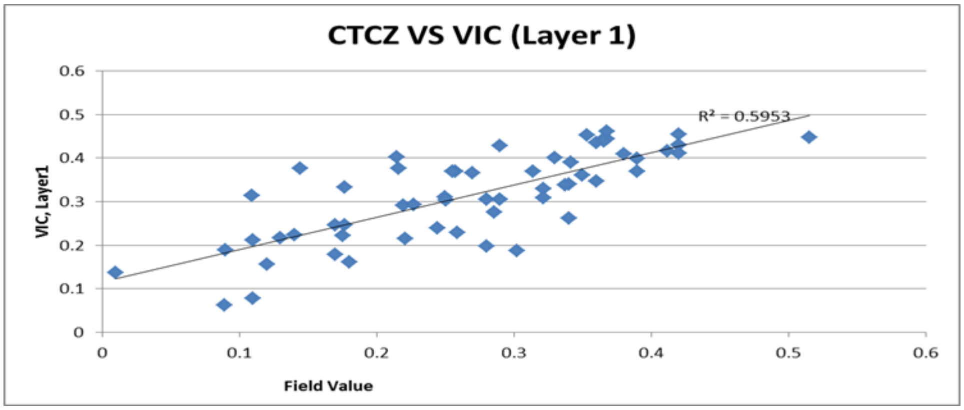


Figure 18(a): Comparison of is Field observed field SM with VIC modeled SM for layer 1 on a day with rainfall distributed uniformly over space

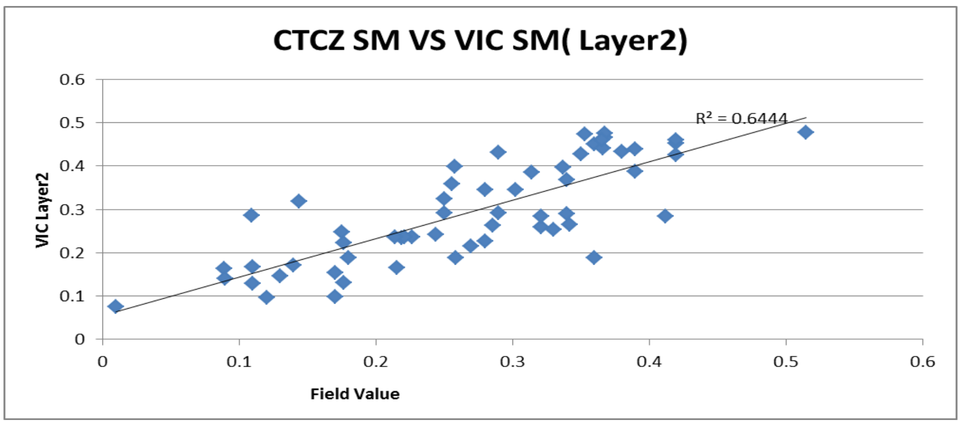


Figure 18(b): Comparison of is Field observed field SM with VIC modeled SM for layer 2 on a day with rainfall distributed uniformly over space

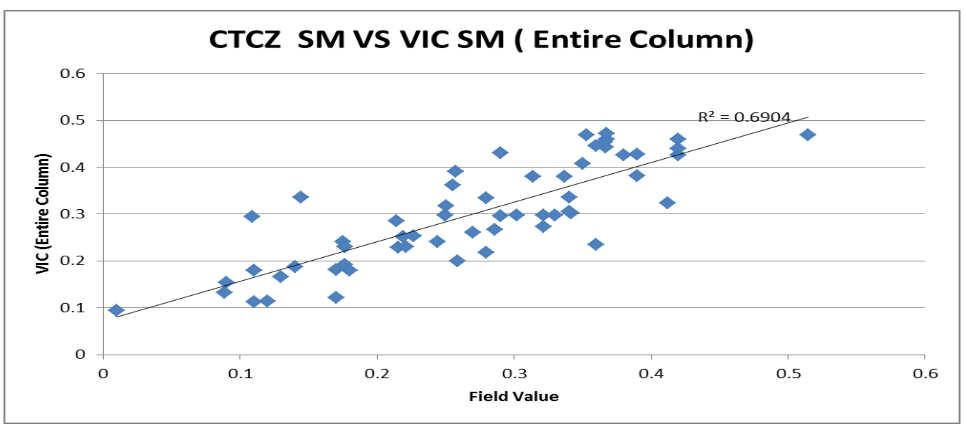


Figure 18(c): Comparison of is Field observed field SM with VIC modeled SM for entire column on a day with rainfall distributed uniformly over space

It can be seen that, the model generated SM value is in good match with the field observed values with a regression value of approximately 0.6 in all the layers. It was also seen that, on comparison of field observed values with model generated values for 70 locations on a day of

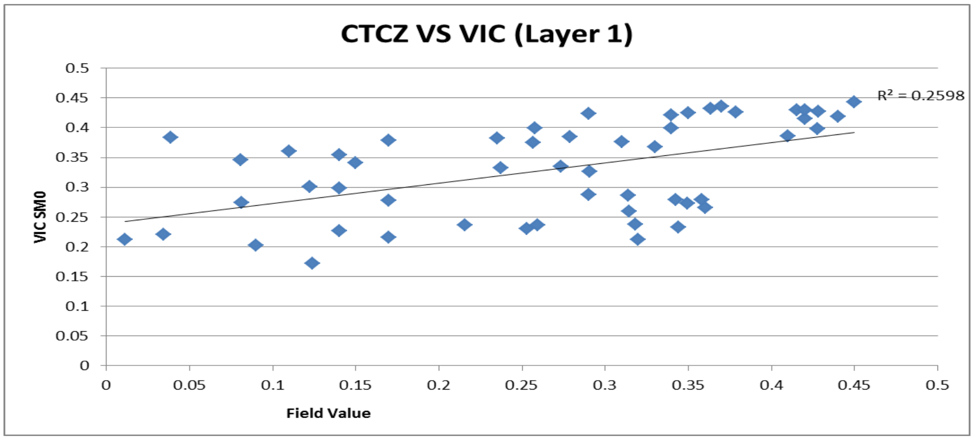


Figure 19(a): Comparison of is Field observed field SM with VIC modeled SM for layer 1 on a day with localized rainfall occurrences

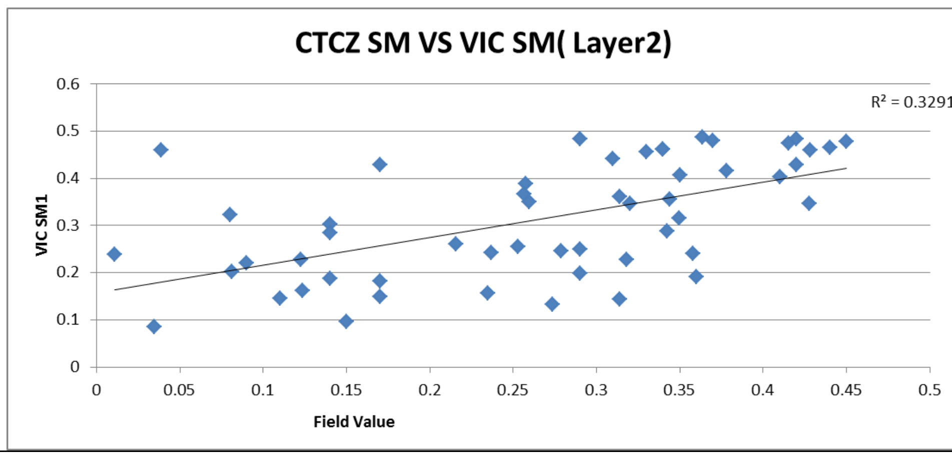


Figure 19(b): Comparison of is Field observed field SM with VIC modeled SM for layer 2 on a day with localized rainfall occurrences

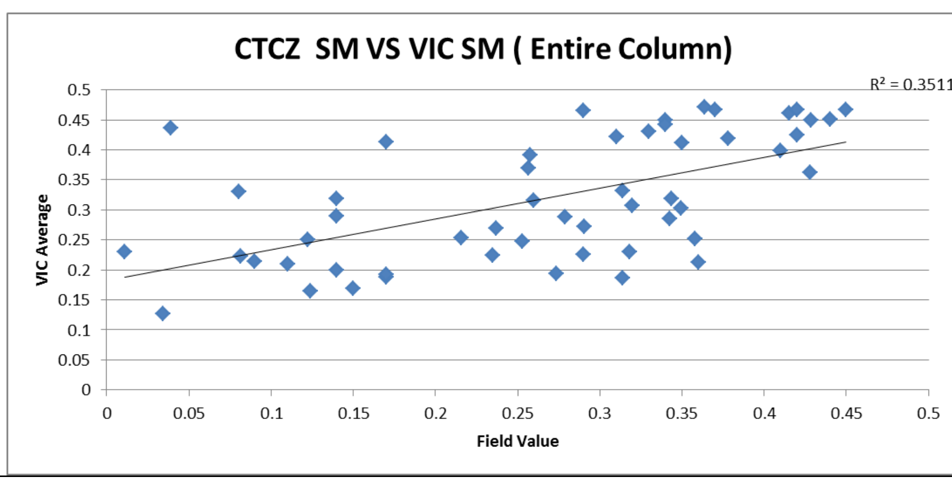


Figure 19(c): Comparison of is Field observed field SM with VIC modeled SM for entire column on a day with localized rainfall occurrences regionalized rainfall, the regression value in all the three cases was observed to be around 0.3, as demonstrated in Figure 18(a,b,c).

Figure 19 and Figure 20 demonstrates the trend in soil moisture variations at two station points. Station point 1 is located in a nonagricultural area and Station point 2 is located in an agriculture dominated area.

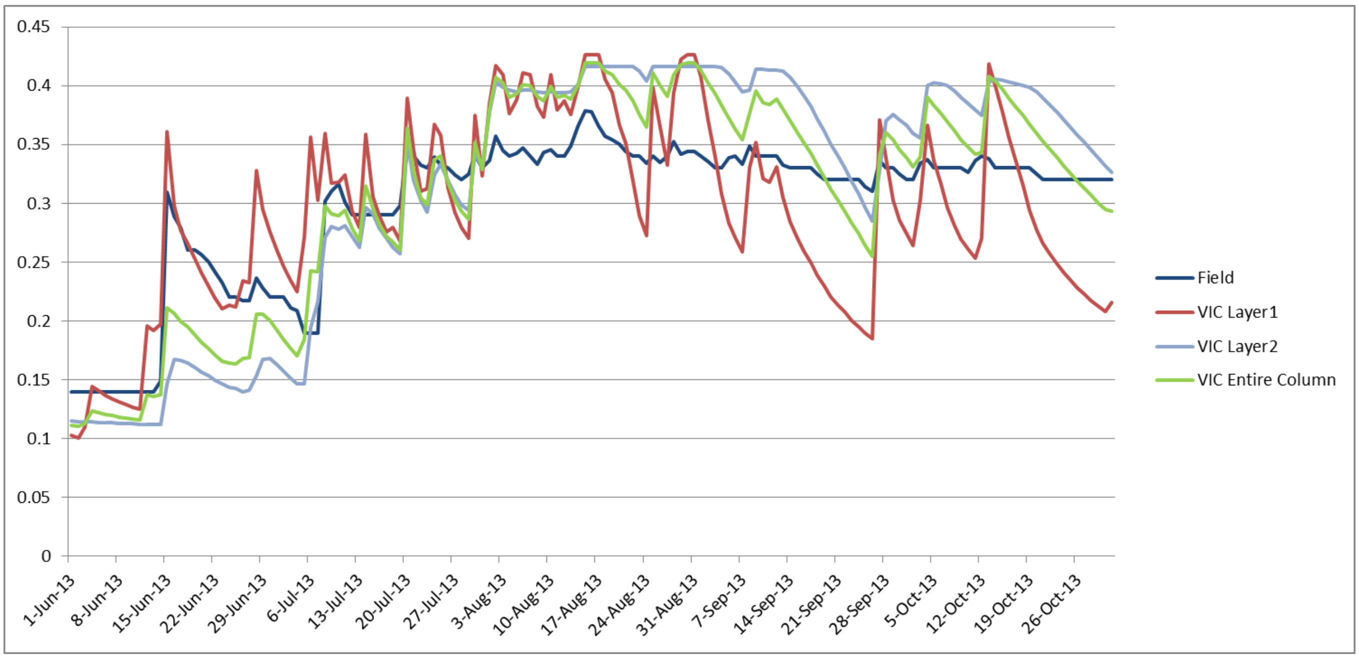


Figure 20: Comparison of trend in SM variation from June to October (Modeled and Field observed) in at Station 1

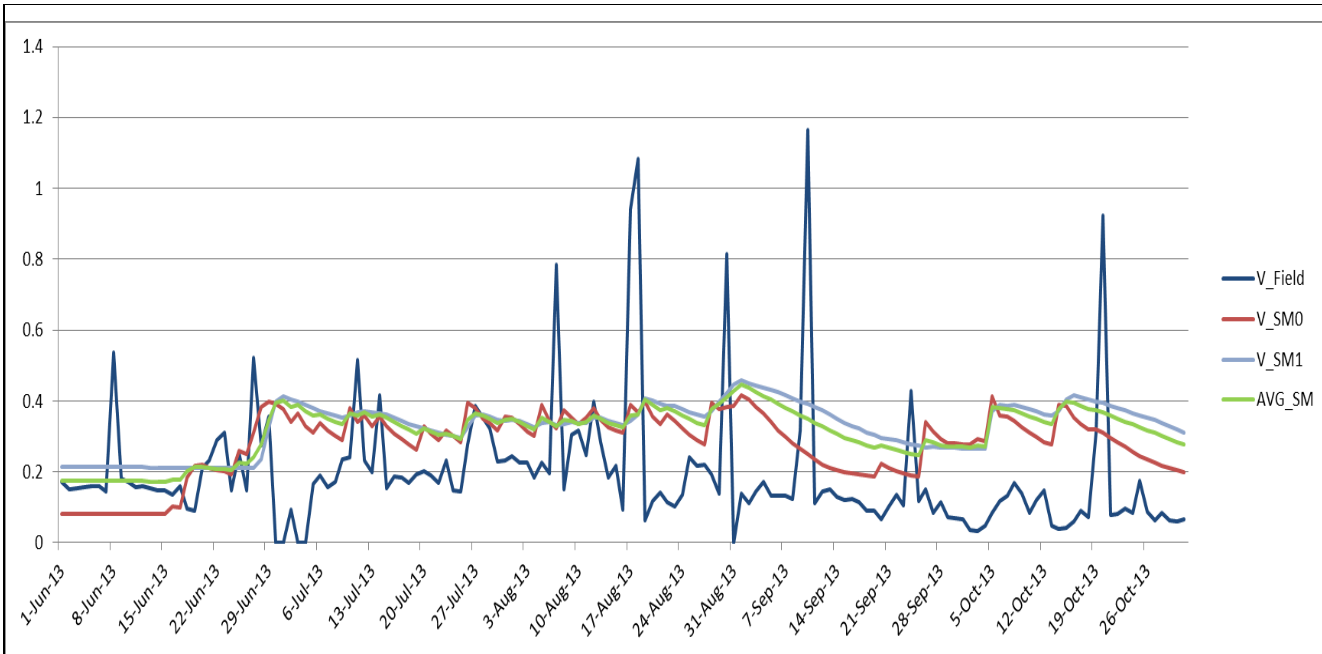


Figure 21: Comparison of trend in SM variation from June to October (Modeled and Field observed) in at Station 2

It can be observed from the above comparison that, in station 1, located in a non-agricultural area the model generated output captures the exact trend as that of field observed. The soil moisture in this location is due to the rainfall. But the at station point 2 the variation in field observed soil moisture shows a sudden increase on certain days as compared to the trend followed by model generated soil moisture values, this variation in trend can be attributed to the irrigation intervention which is not accounted in the model.

6 Current Status of 9 minute Hydrological modeling

- Hydrological modeling (Variable Infiltration Capacity Model) framework has been setup at 9min (~16.5km & 13709 grids) grid level for the entire country.
- Model specific input parameters (Soil, Vegetation, Routing) are prepared for the entire country at 9min grid level
- Historical meteorological data has been organized (1951-2013) from various sources and VIC model specific meteorological inputs are prepared
- The model performance has been optimized through calibration of model estimated runoff with measured stream discharge (CWC) using historic gridded meteorological products from IMD (1976-2005) for selected river basins.

- Long-term (1951-2013) hydrological fluxes (Surface runoff, Evapotranspiration and Soil moisture) have been generated at 9min grid level for the entire country (Figure 21)
- Since 1st Jun 2014, near-real-time meteorological data (Rainfall, Temperature, etc.) are collected and processed on daily basis and model computations are being carried out at daily time-step.
- National scale, 9min grid-wise surface runoff, evapotranspiration, soil moisture are being estimated with two-day time lag since 01 Jan 2014 (Figure 22)
- Geo-spatial products of the daily water balance components are being published through NRSC/Bhuvan website (http://bhuvan.nrsc.gov.in/nices/) (Figure 23)
- Deviations of current seasonal conditions from historic mean conditions are being generated through Standardized Runoff Index (SRI) – Figure 24
- Weather forecast data are integrated into the hydrological modeling framework and advance forecast (T+3 days) of hydrological variables are being estimated
- Under Disaster events (Hudhud cyclone) forecast products are generated and published on Bhuvan portal (Annexure 1 and 2)

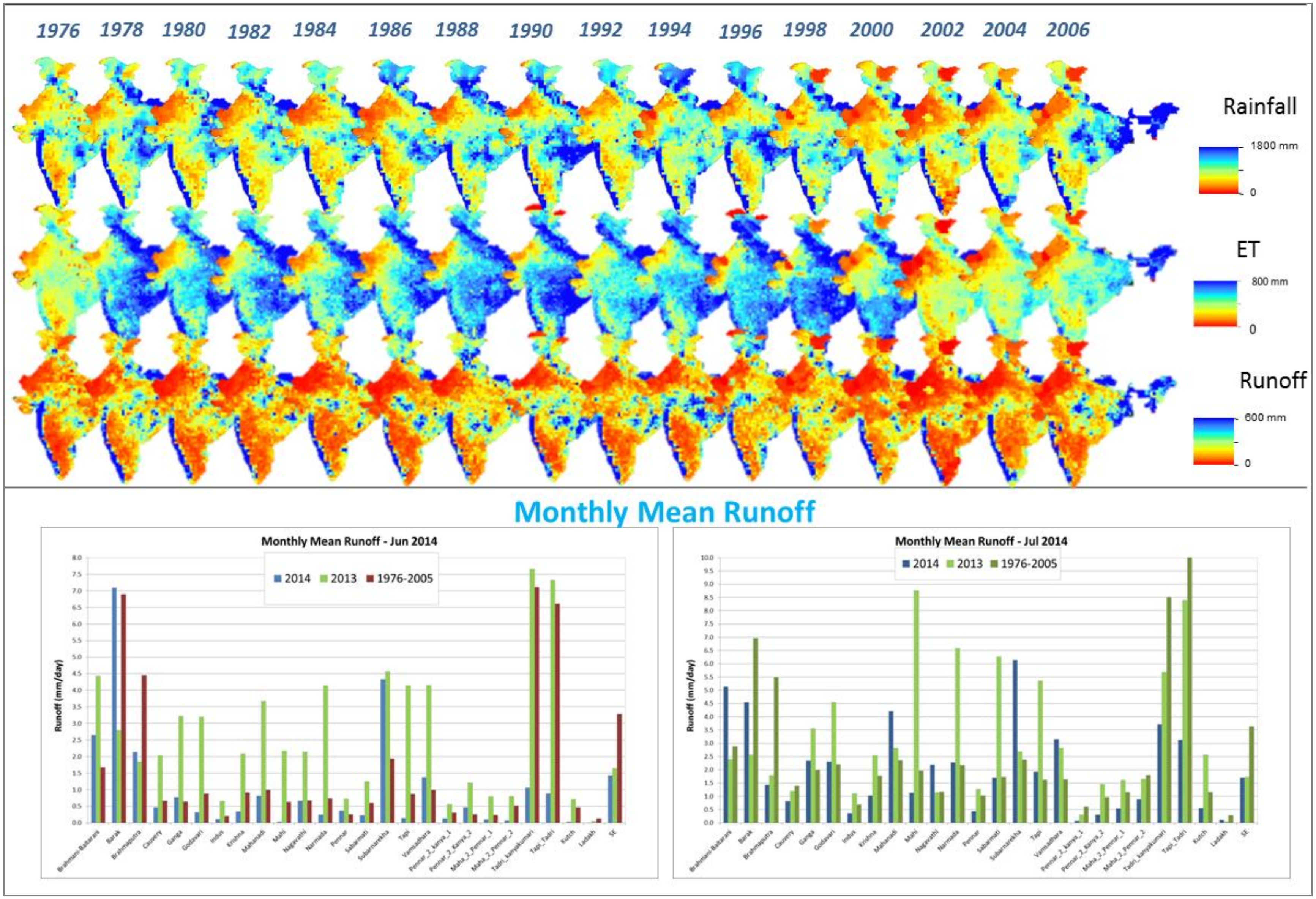


Figure 22: Long-term hydrological fluxes estimated at 9min grid level for the entire country

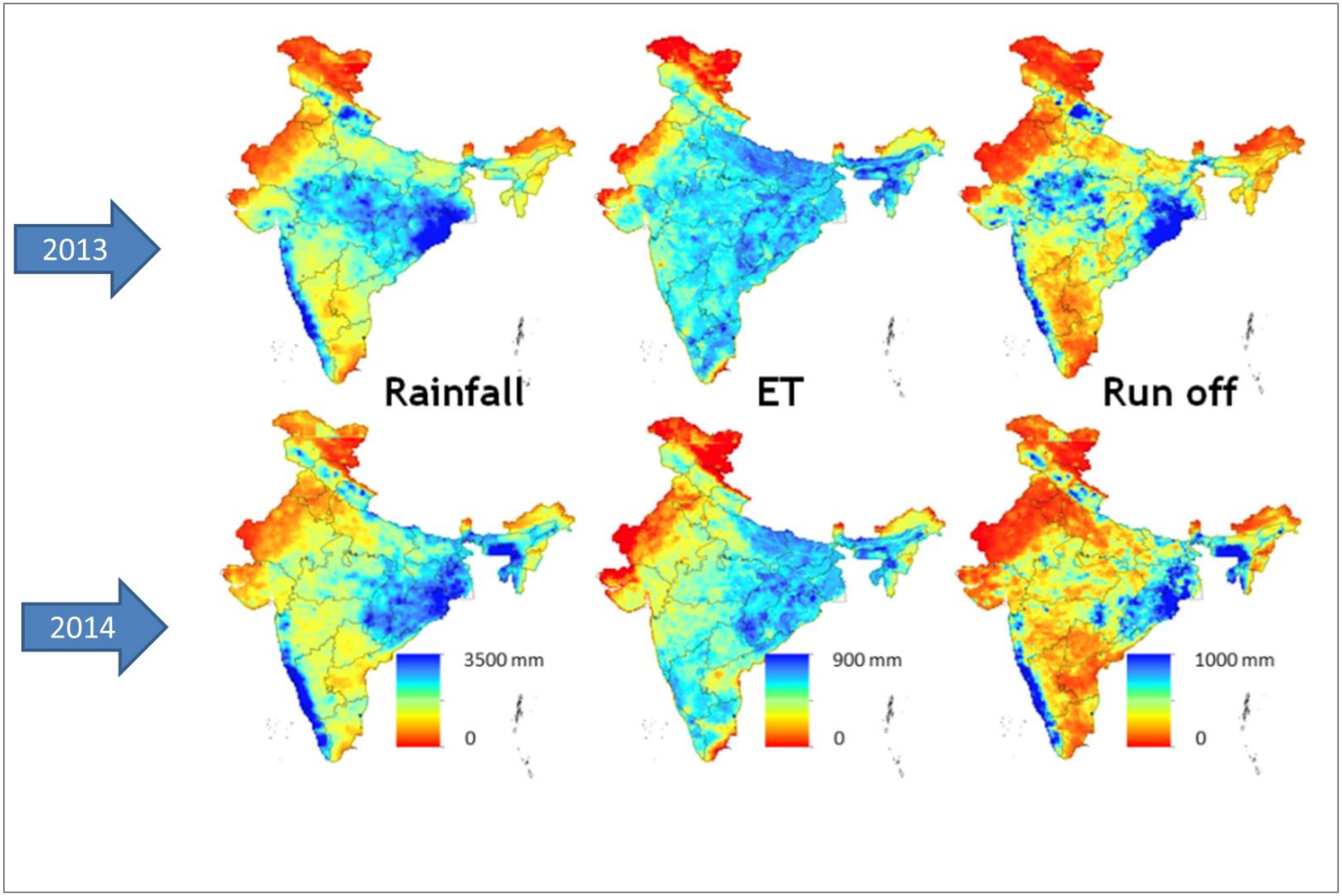


Figure 23: Seasonal water balance components (Jun-Oct) during 2013 and 2014 as estimated from hydrological modeling

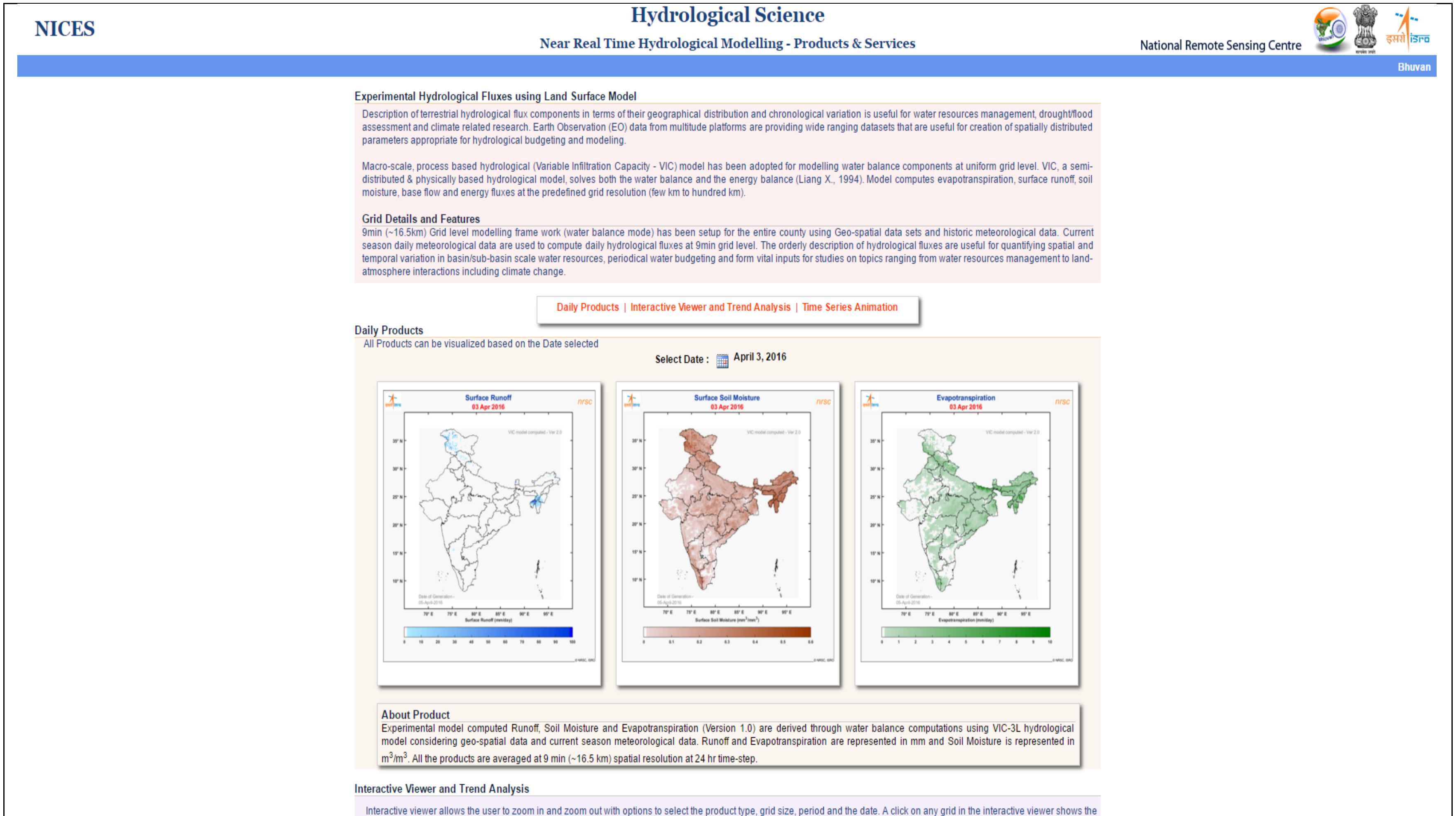


Figure 24: Daily water balance components published on Bhuvan web portal

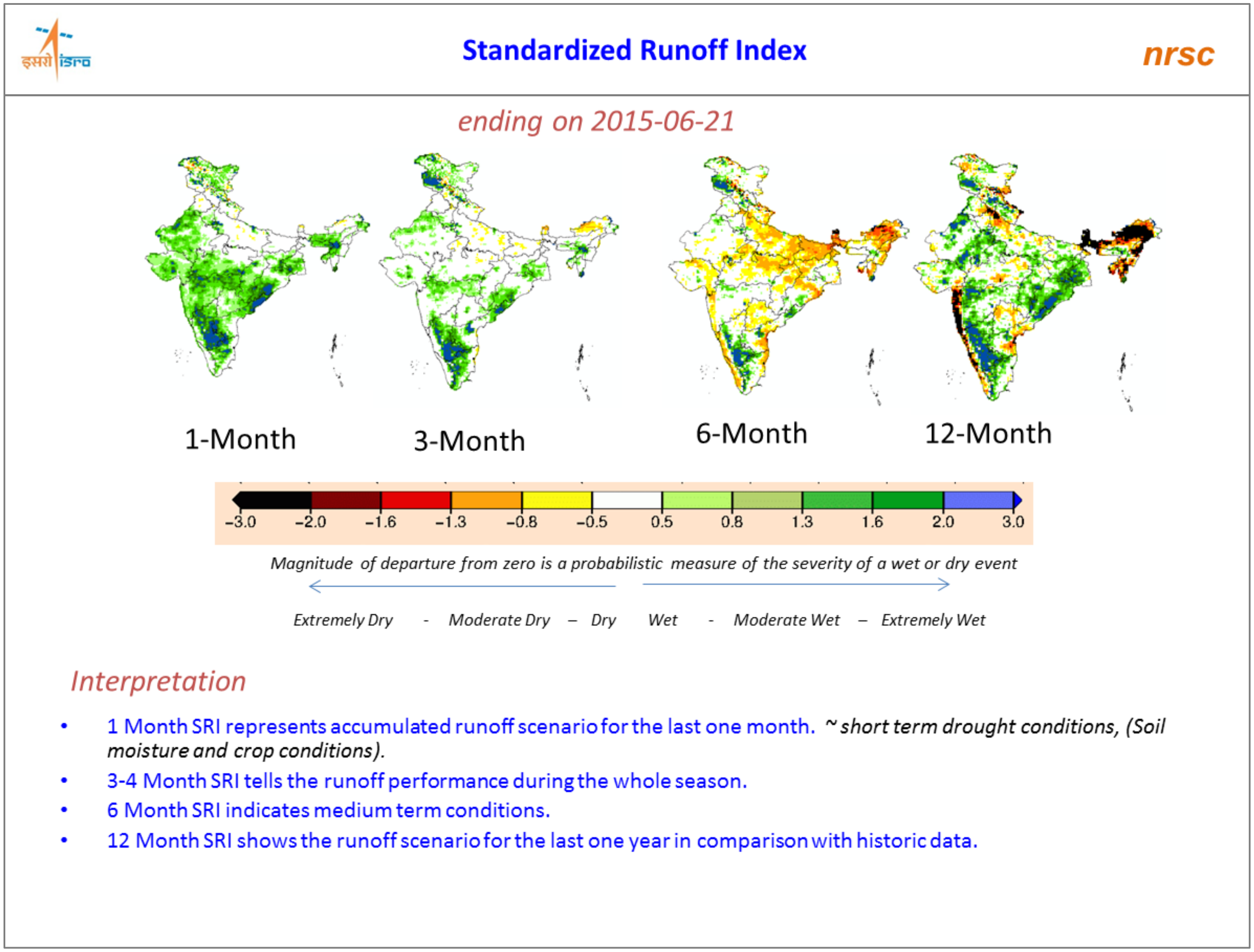
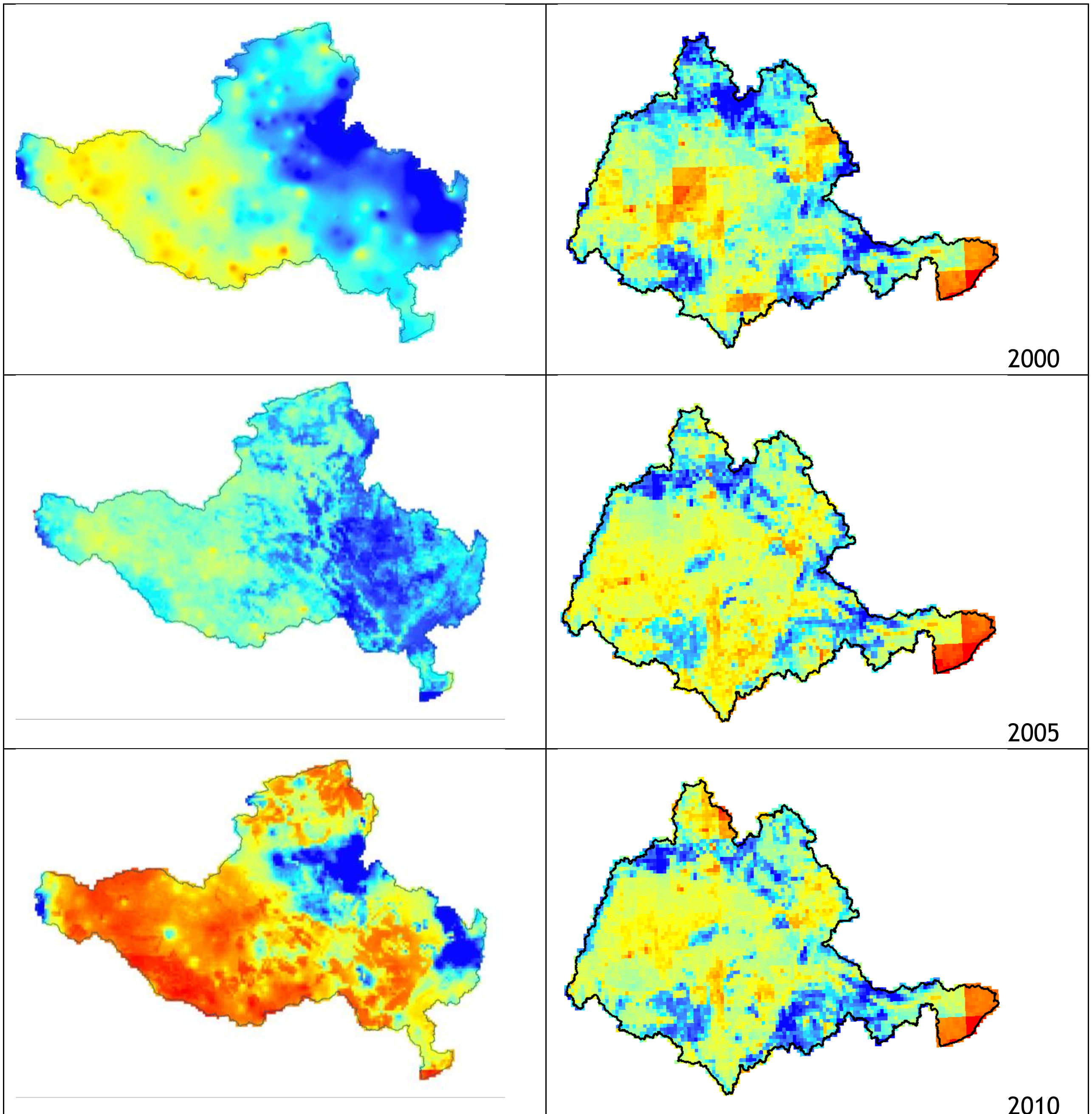


Figure 25: Standardized Runoff Index generated from the hydrological model outputs

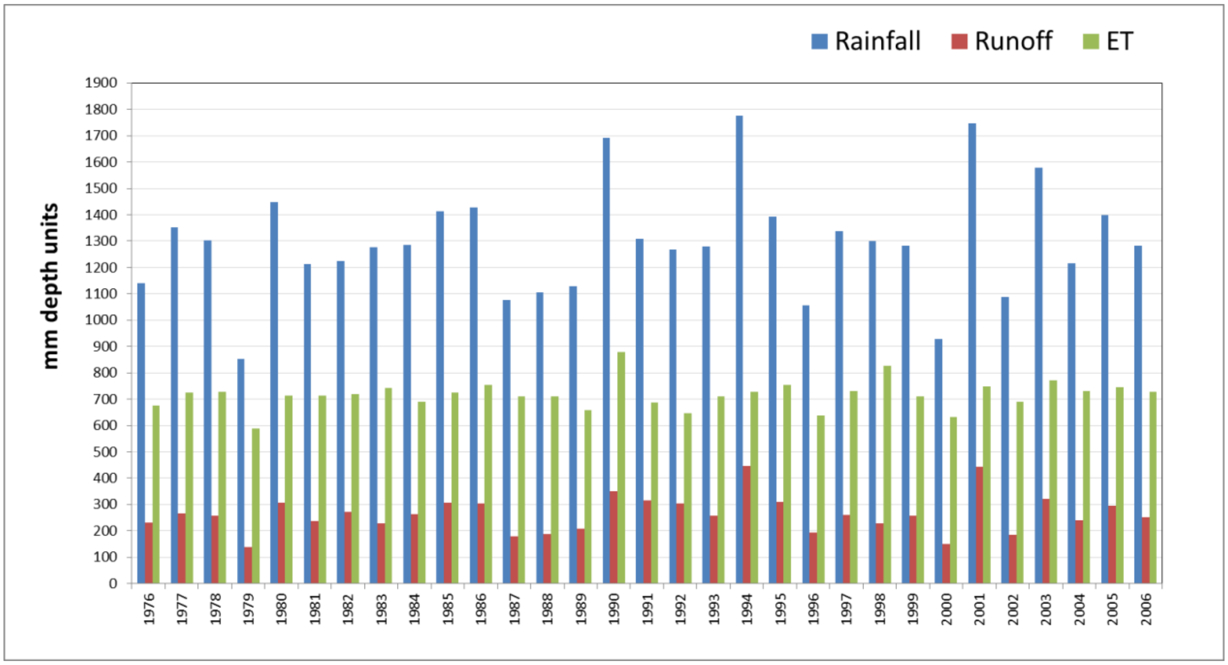
7. 3 minute Hydrological modeling setup

- Hydrological modeling (Variable Infiltration Capacity Model) framework has been setup at 3min (~5.5km) grid level for the Godavari, Mahanadi, Mahi and Lower Ganga basins.
- Model specific input parameters (Soil, Vegetation, Routing) are prepared for the above basins
- Historical meteorological data has been organized (2001-2013) from various sources and VIC model specific meteorological inputs are prepared
- The model performance has been optimized through calibration of model estimated runoff with measured stream discharge (CWC) using historic gridded meteorological products from IMD (2001-2013) for selected river basins.
- Long-term (1976-2013) hydrological fluxes (Surface runoff, Evapotranspiration and Soil moisture) have been generated at 3min grid level for the Godavari and Mahanadi river basins (Figures 25 & 26)



Seasonal Evapotranspiration (Jun-Oct) at 3min grid level over Godavari river basin	Seasonal Evapotranspiration (Jun-Oct) at 3min grid level over Mahanadi river basin

Figure 26: 3min Grid level water balance components



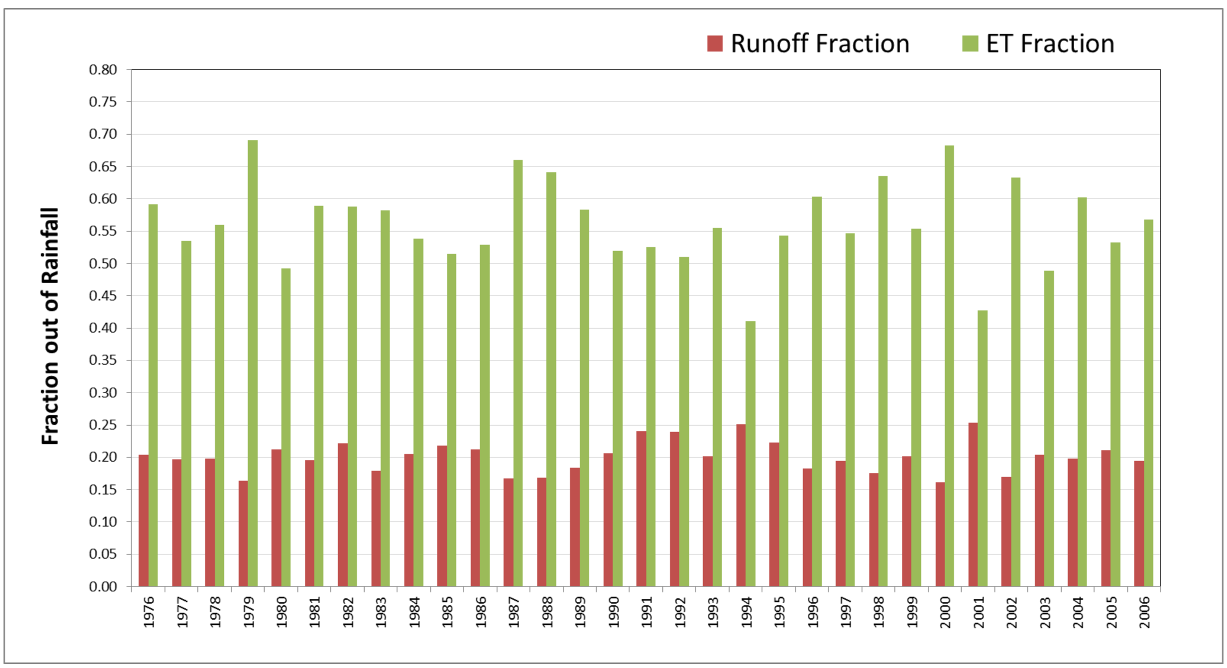


Figure 27: Hydrological model (3min) derivatives for Mahanadi river basin

8 FURTHER/ONGOING WORK

- To operationalize Web-enabled National level hydrological modeling for in season hydrological water balance components for the entire country at 3min grid level
- To incorporate in-season satellite data based vegetation/crop information for computing near-real-time fluxes
- To estimate interventional river discharge using reservoir storage information under WBIS
- To develop and establish a comprehensive field experimentation setup for calibration and validation of Soil Moisture, ET
- Operationalization of hydrological fluxes forecasting using IMD & SAC (WRF) forecast product
- Operationalization of early warning systems (Current season deviations/extremes)

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Annexure 1

Early Warning of High Surface/River Runoff – Hudhud Cyclone

Experimental Surface and River Runoff forecast for Cyclone Hudhud in Catchment areas of Nagavali and Vamsadhara rivers

As part of Operational Hydrological Products & Services, surface runoff conditions are predicted for next three days across the country using weather forecast data. Currently, NRSC uses NOAA Global Ensemble Forecast System Reforecast (GEFS/R) data, which provides weather forecast for next 8 days (3hr/6hr time-step) at 0.5deg resolution (ftp://ftp.cdc.noaa.gov/Projects/Reforecast2).

Surface Runoff Forecast

After tracking and assimilating the information on Hudhud cyclone as early as 08th Oct, 2014, using GEFS/R weather forecast data daily surface runoff was forecasted over AP and Orissa coast, where Cyclone was predicted to make landfall. The forecasted surface runoff conditions were hosted on Bhuvan web portal (Figure 1).

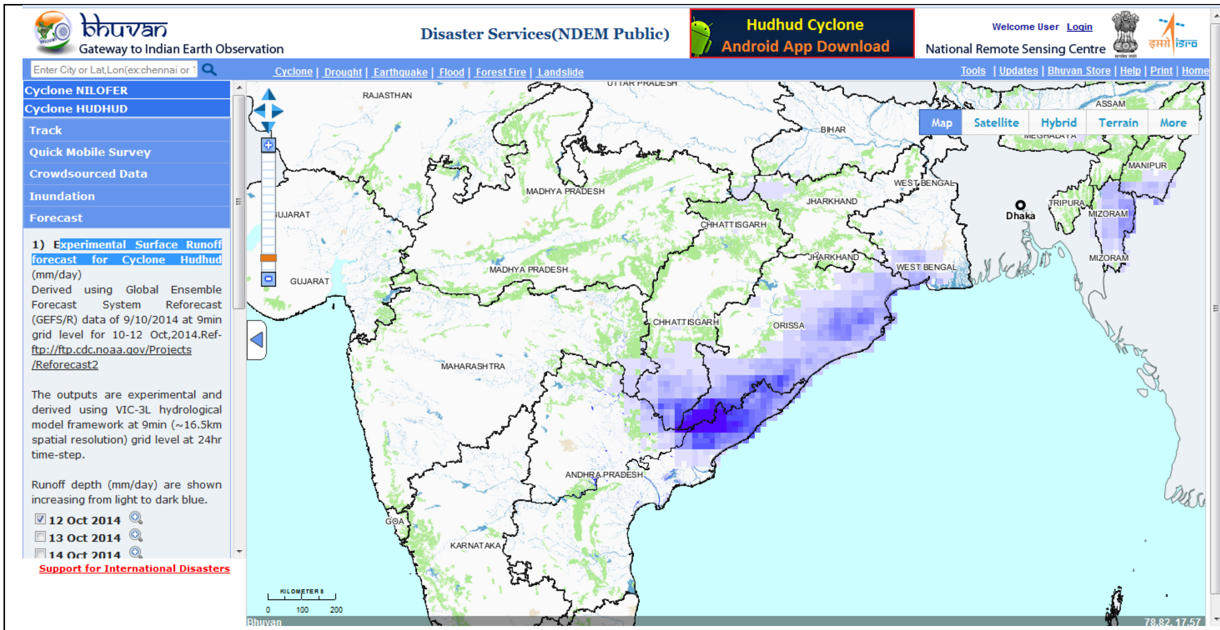

Figure 1: Bhuvan portal depicting the surface runoff forecast on 12 Oct, 2014 for Cyclone Hudhud using GEFS/R weather forecast data of 09 Oct, 2014

Using daily weather forecast from GEFS/R, the surface runoff forecast updated on daily basis (Figure 2).

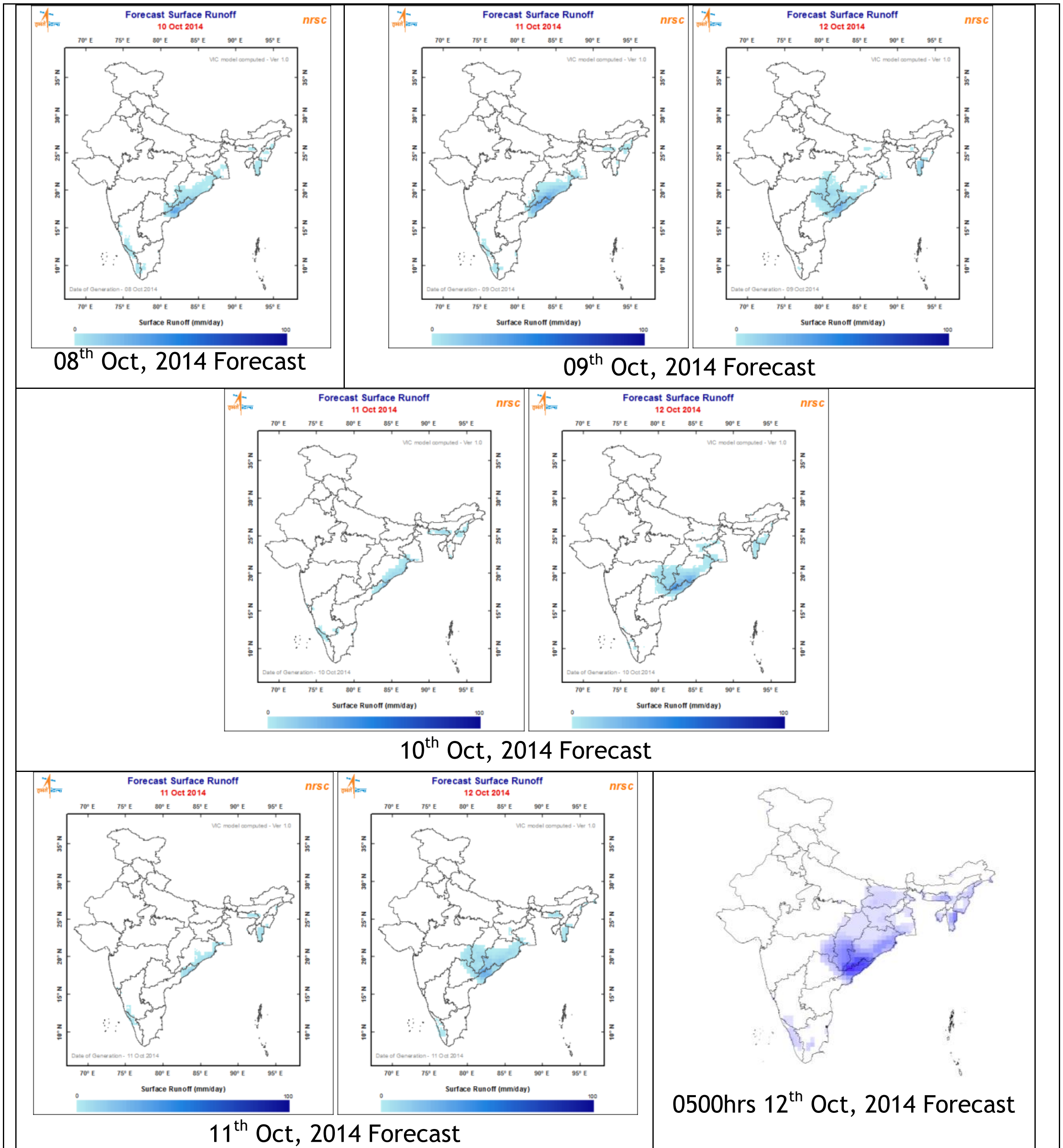

Figure 2: Daily Surface runoff forecast for Hudhud Cyclone using GEFS/R weather forecast

(Note: Date of forecast denotes the GEFS(R) forecast generation date)

Forecast of River Runoff in Nagavali and Vamsadhara catchments

The Cyclone Hudhud was predicted to make land fall in the catchment areas of Nagavali and Vamsadhara rivers located along Andhra Pradesh and Orissa coastline. Srikakulam and Kashi Nagar are the basin terminal discharge observations operated by CWC for Vamsdhara River and Nagavali river, respectively. The catchment area of Vamsadhara River up to Kashi Nagar is 7820 sq.km and catchment area of Nagavali River up to Srikakulam is 9500 sq.km. The maximum discharge observed at Srikakulam is 7669 cumecs (12 May, 1990) and at Kashi Nagar is 16790 cumecs (18 Sep, 1980) - *Source: Integrated Hydrological Data Book, 2012, CWC/MoWR)*.

The forecasted surface runoff was routed to generate daily runoff hydrographs at these river terminal sites and forwarded to the concerned department. Figure 3 shows the runoff forecast during Cyclone Hudhud in Nagavali and Vamsadhara river catchments (up to Srikakulam and Kashi Nagar, respectively).

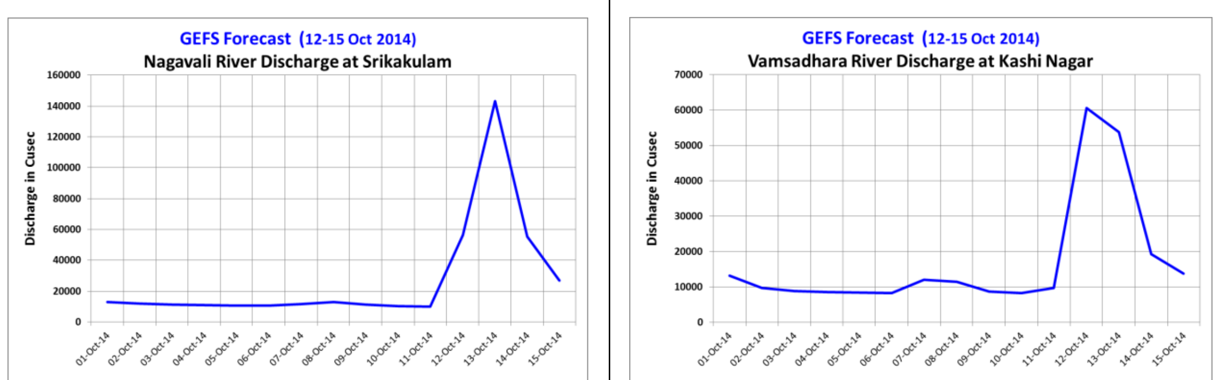

Figure 3: Forecasted runoff using GEFS/R weather forecast data during Hudhud cyclone (Forecasted on 11 Oct 2014)

It may be noted that runoff forecast are from Experimental model computations and are not fully calibrated. The estimates may vary by ± 20% with the actual.

Some media reported high inflows in Nagavali and Vamsadhara rivers during Hudhud cyclone is provided below in figure 4.

Post Hudhud, Nagavali flood threatens Srikakulam

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natural disasters
cyclones
flood

Srikakulam town is facing a major flood threat as river Nagavali received heavy inflows on Sunday evening. The gushing water has almost completely submerged the old bridge that leads to district headquarters. Nearly 100,000 cusecs of water is reaching the town.

The situation at Gotta barrage on Vamsadhara river at Hiramandalam is relatively better with nearly 53,000 cusecs of water flow being recorded on Monday morning.

Minister for Labour K. Atchan Naidu and District Collector Gaurav Uppal have evaluated the flood control measures in a meeting held at the latter's office and instructed the officials of all departments concerned to be on a high alert.

Low-lying areas like Housing Board Colony, P.N. Colony and Gujaratipeta in Srikakulam town were inundated and the rains inflicted a heavy damage on crops in about a lakh acres spread in Burja, Etcherla, Narasannapeta, Polaki, Sitampeta, Srikakulam and Itchapuram mandals.

Six teams of National Disaster Response Force and Army and Navy personnel helped in relief and rescue operations even as strong winds battered coastal areas under impact of the cyclone.

Burja, Sitampeta and Srikakulam town recorded 240 mm, 234 mm and 210 mm rainfall respectively in the last 24 hours, according to official sources.

Road transport continued to be hampered due to damages to highways and internal roads in towns. Besides, movement of trains has come to a complete halt. Most of the towns and villages are still without power as transmission lines were snapped.

Keywords: Cyclone Hudhud, Nagavali flood, Srikakulam district

Figure 4: Media report depicting high runoff inflow in Nagavali and Vamsadhara river during Hudhud cyclone.

Annexure 2

Retrospective Analysis of Kashmir Floods

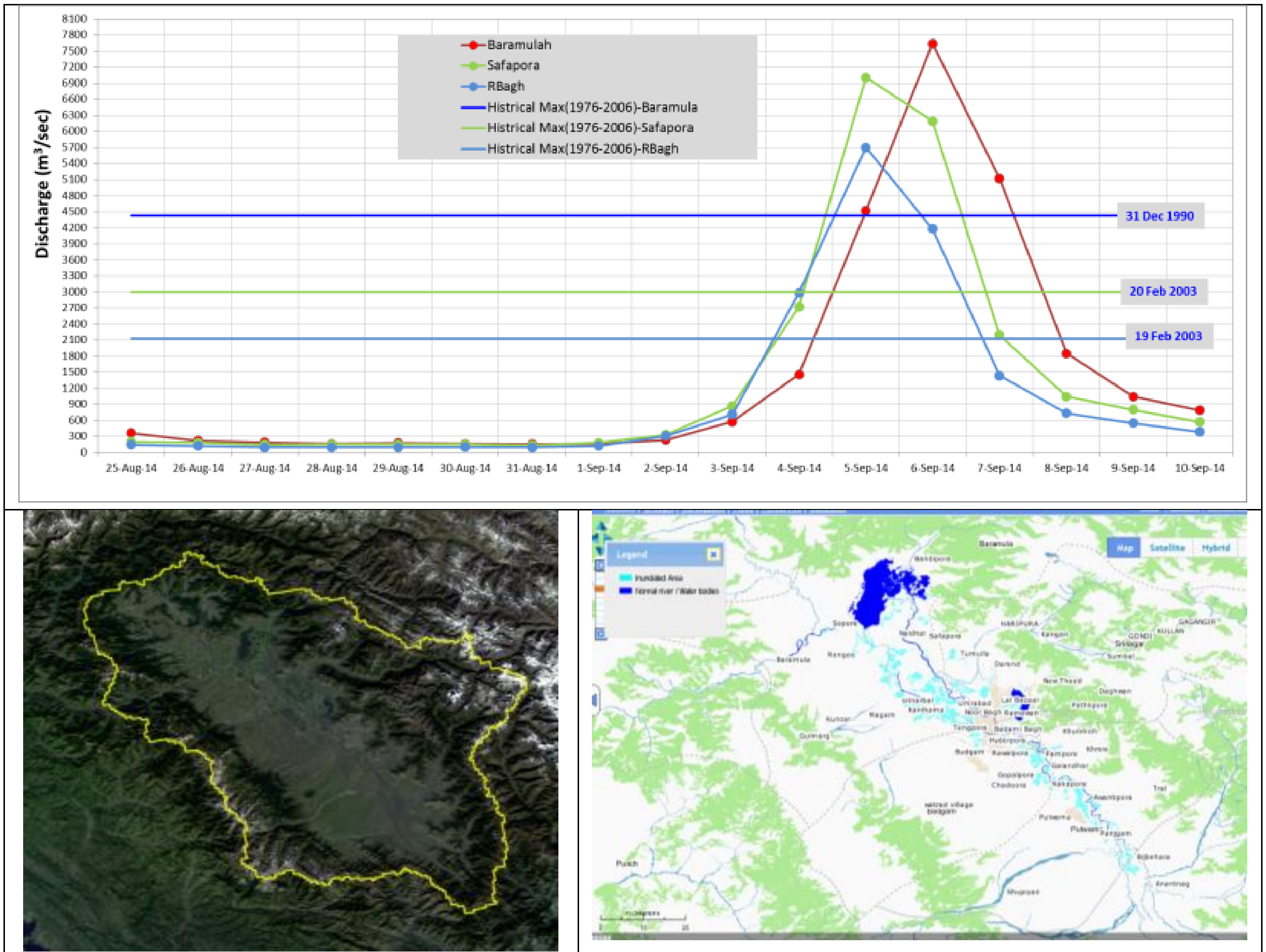

Figure 5: Daily Runoff Estimated along Jhelum River during Kashmir flood and comparison with historical conditions