WATER BUDGET COMPONENTS ESTIMATION USING SATELLITE DATA AND HYDROLOGICAL MODEL

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CERTIFICATE

This is to certify that this thesis work entitled "***Water Budget Components Estimation Using Satellite Data and Hydrological Model***" is submitted by Ms. Tarul Umakant Sharma in partial fulfillment of the requirement for the award of ***Master of Technology in Remote Sensing and GIS*** by the Andhra University. The research work presented here in this thesis is an original work of the candidate and has been carried out in Water Resources Department under the guidance of Dr. Praveen Kumar Thakur, Scientist/Engineer 'SE' and Dr. Bhaskar R. Nikam, Scientist/Engineer 'SD' at Indian Institute of Remote Sensing, ISRO, Dehradun, India.

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Dedicated

to

Mummy & Papa

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ABSTRACT

Water budgeting is necessary to study the hydrological cycle. Out of many hydrological components; major are precipitation, change in Terrestrial Water Storage (ΔTWS, which include both surface and sub-surface water storage), Evapo-Transpiration (ET), surface runoff and baseflow. Precipitation is the main input in the hydrological cycle and it plays an important role in defining further simulations of the cycle. Water budgeting also helps to understand the direct and indirect factors affecting the changes in ground water storage.

Objective of this study is to estimate water budget components using different satellite data and Variable Infiltration Capacity (VIC) hydrological model after incorporating scaling issues for the Ganga basin. Water balance has been closed first by using satellite derived components and then by combining it with hydrological model derived components i.e. ET, runoff and baseflow. Satellite derived components include precipitation from National Centre for Atmospheric Research (NCEP) reanalysis data, ET from Moderate Resolution Imaging Spectroradiometer (MODIS) using Surface Energy Balance approach and ΔTWS from Gravity Recovery And Climate Experiment (GRACE) satellite mission.

Estimated ET shows an average value of 430.342 mm for year 2004 and 501.586 mm for year 2008, over whole basin. GRACE derived ΔTWS is available at coarser resolution and hence its statistical downscaling has been done by first using Central Ground Water Board's groundwater level data and secondly by using water balance derived change in groundwater storage as dependent variable. Results show a mean relative error of 0.04 cm for various locations when water level data was used and an error of 0.721 cm when water balance derived ground water storage change was used over whole basin. Annual water balance derived by integrating satellite and model derived components (-17.725mm) gave more accurate results as compared to water balance derived by using only satellite data (72.13mm using VIC runoff and 220.158mm using GRDC data). Assuming that satellite derived precipitation and ΔTWS contain less error, imbalance occurred in collective response of satellite and model derived water balance has been incorporated in ET. With this assumption, water balance has been obtained from year 2004 to 2008 by increasing ET ranging from 0.81% in year 2008 upto 13% in year 2004.

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
ET	Evapotranspiration
ΔTWS	Change in Terrestrial Water Storage
LAI	Leaf Area Index
DEM	Digital Elevation Model
SEBS	Surface Energy Balance System
LST	Land Surface Temperature
NDVI	Normalize Difference Vegetation Index
VIC	Variable infiltration Capacity
SWAT	Soil and Water Assessment Tool
GRACE	Gravity Recovery And Climate Experiment
MODIS	MODerate resolution Imaging Spectroradiometer
LULC	Land Use/Land Cover
NCAR	National Centre for Atmospheric Research
NCEP	National Centre for Environmental Prediction
GLDAS	Global Land Data Assimilation System
SEBAL	Surface Energy Balance Algorithm for Land
AVHRR	Advanced Very High Resolution Radiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ILWIS	Integrated Land and Water Information System
TRMM	Tropical Rainfall Measuring Mission
NBSSLUP	National Bureau of Soil Survey and Land Use Planning
FAO	Food and Agriculture Organization
IMD	India Meteorology Department
CGWB	Central Ground Water Board
GRDC	Global Runoff Data Centre

CHAPTER 1

INTRODUCTION

1.1 General

Hydrology is the science which deals with the study of occurrence, circulation, distribution and the removal of water on the earth, including that in the atmosphere and below the surface of the earth. This branch is concerned with the water in streams and lakes, rainfall and snowfall, i.e. on land, and water below the earth surface in the pores of soil and rock. Hydrology is important in water resources to study various aspects such as estimation of water resource potential and river basin, analysis of problems of flood and there pattern and magnitude, estimation of dependable yield for irrigation and hydro-electric power generation, determination of maximum flood and discharge flood volume expected to enter a reservoir, formation of flood and its control measures, maintenance and operation of river, erosion control to prolong life of a reservoir and control the pollution of river, municipal and industrial water supply and stream flow forecasting, and also flood forecasting with the help of precipitation and other hydro-meteorological data (Bonacci, 2004).

Water is present in the atmosphere in the form of vapor, on the surface in the form of water, snow or ice and below the surface as ground water occupying all the voids within a geologic stratum. Total water supply of earth is in constant circulation from earth to atmosphere and back to earth, except for the deep ground water. This water circulatory system is known as hydrologic cycle. Hydrologic cycle is a very vast and complicated cycle in which there are a large number of paths of varying time scale. It is also continuous re-circulating cycle in the sense that there is neither beginning nor end. It is the process of transfer of moisture from the atmosphere to the earth in the form of precipitation, conveyance of the precipitated water by streams and rivers to ocean and lakes, etc. and evaporation of water back to the atmosphere. However, total water resources of the earth remains constant, sun being the source of energy in this and atmosphere is the main source of cycle for water storage as vapor after evaporation from different sources gets stored in the atmosphere (Punmia *et.al*, 2009).

1.2 Hydrological Cycle

Hydrologic or water cycle consists of following process: Evapotranspiration takes place from the surfaces of ocean, lakes and also from soil moisture. Also, branches of trees and all other types of vegetation produce water vapor in the form of Transpiration (Chang and Okimoto, 1970). This combined vapor, known as Evapotranspiration (ET) gets stored in the atmosphere, moves up and forms clouds. When clouds get much condensed, they fall back into ocean and land in either liquid or frozen form of water known as Precipitation. Different forms of precipitation include rainfall, snow, drizzle, glaze, hail, sleet, snowflakes, dew, fog, mist, frost, etc. which are recorded by different instruments such as rain gauge, snow gauge, evaporation, station, ground water level observation wells, etc. on ground. A part of this precipitation goes back to the atmosphere as vapor by the process of evaporation from interception and rest of it falls on the earth surface. From the water falling on the earth surface, a part of it enters into the soil as Infiltration and a part of it flows on surface which is known as Surface runoff (Kuchment, 2004). However, surface detention receives direct forms of precipitation whereas channel storage receives direct water as well as from surface runoff. From the water which is infiltrated, a part of it percolates down and gets stored as ground water which directly meets to the oceans and some of it is stored as moisture to the soil. Ultimately ground water storage and surface runoff, both meets the channel storage. However, if the channel is effluent channel i.e. if channel water level is lower than ground water level then because of hydraulic gradient, water flows from ground to stream. From the channel storage, runoff takes place till the ocean and forms ocean storage. Evaporation also takes place from channel as well as ocean storage because of large surface area. From soil moisture storage, water gets evaporated directly from soil and by transpiration from plant and goes back to the atmosphere, thus closing the Hydrologic cycle (Jain, 2012).

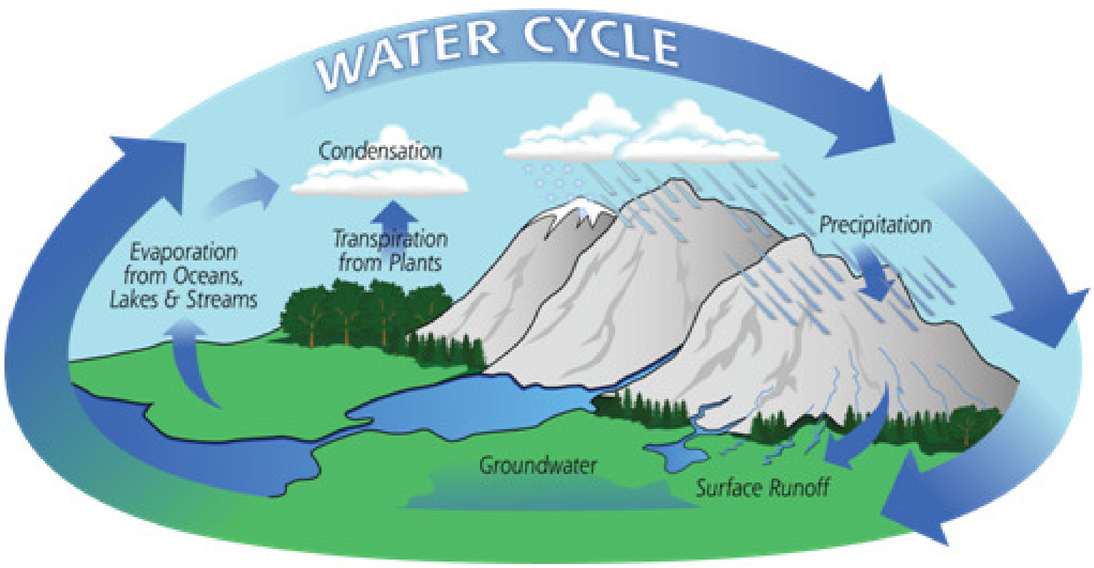


Figure 1.1: Water cycle (Source: gpm.nasa.gov)

The hydrology of a place mainly depends on climate, topography and geology. However, topography is influenced by geology of that place which also affects ground water availability. Climate depends mainly on the geographical location whereas topography affects precipitation and also occurrence of lakes as well as runoff rate. Climatic variables such as temperature, humidity, radiation, wind velocity, etc. mainly affect the hydrologic cycle in terms of occurrence of precipitation. Humidity depends upon the amount of water vapor present in the atmosphere. And hence, more the temperature more will be humidity. Water vapor present in the atmosphere is important as it is source of precipitation and also it controls the rate of evaporation from land and water surfaces. Radiation is the main source of energy which governs the change of state of water from liquid to gaseous. Also wind speed and direction affects climate of location (Punmia *et.al*, 2009).

Now, major components of hydrological cycle are precipitation, change in terrestrial water storage (ΔTWS) which include both surface and sub-surface water storage, runoff which include infiltration, baseflow and surface runoff, and ET which are helpful for estimating water budget equation for any basin. There are various sources from where these components can be derived or obtained directly. On ground, these can be obtained from gauge stations and various weather stations located at various sites. Since precipitation depends on cloud top temperature, ET on radiation, land cover, vegetation and other parameters, ΔTWS on mass change; these can also be obtained or derived with the help of remote sensing.

1.3 Use of Remote Sensing and GIS in Hydrological Modeling

Hydrological modeling is the mathematical representation of the major components of hydrological cycle in which components are derived with the help of various empirical and physics related formulas. Hydrological models are mainly of two types: Lumped models and Distributed models. In lumped model, spatial heterogeneity is not considered i.e. it considers watershed as single entity with single rainfall input as a whole. It assumes that whole grid is homogenous and physical property such as soil, land cover, climate, etc. are same everywhere. These models do not use physical formulas to derive water balance components. Also variations in meteorological, hydrological and geological parameters are considered as one aggregated value. Whereas in distributed model, grid heterogeneity is considered by dividing whole area into number of homogenous units and all the properties lying in the area are given equal weightage (Krysanova *et al*., 1999) (Singh and Frevert, 2006).

Since remote sensing has a potential to measure spatial as well as temporal variation of climatic parameters which play an important role in hydrology, it is very much helpful in hydrological modeling. Various climatic parameters such as precipitation, snow cover, soil moisture, ET, etc. can be directly or indirectly obtained from remote sensing. Parameters such as runoff cannot be measured from remote sensing but can be generated with the help of hydrological modeling for which inputs are above mentioned climatic variables. Also parameters such as albedo, Leaf Area Index (LAI), flow direction etc., derived from satellite data are used in hydrological modeling.

Also Geographic Information System (GIS) helps in generating various hydrological properties from Digital Elevation Model (DEM) such as drainage network, flow direction map, flow accumulation map, aspect map, stream order, etc. It also helps in satellite data storing, processing, interpreting and analyzing.

Water budget estimation has been done variedly using different types of techniques. Also work has been done in deriving its components separately by either using ground based observation or by using different types of satellite data and different hydrological models.

Main equation of water balance can be written as:

$$P - Q - ET - Baseflow \pm \Delta TWS - (\text{other components}) = 0 \qquad (1.1)$$

Where,

P = Precipitation,

Q = Runoff,

ET = Evapotranspiration,

ΔTWS = Change in Terrestrial Water Storage and, other components include interception, soil moisture, shallow and deep groundwater storage, snow and glaciers, etc.

From this above equation, parameters like precipitation, ET, ΔTWS and other parameters except runoff and baseflow can be directly or indirectly measured with the help of remote sensing whereas parameter like runoff and baseflow can be generated with the help of hydrological modeling or by other technique.

1.4 Surface Energy Balance Method

ET is considered as the most important process which determines the exchange of energy and mass among hydrosphere and biosphere (Pereira, 2004). ET is considered to be a major factor influencing climate change. Remote sensing cannot directly measure ET but it helps to measure evaporative fraction which is the ratio of ET and available energy (Almhab *et al*., 2007). ET includes both evaporation from atmosphere, soil, canopy interception and water bodies, and transpiration from surface of leaves; since these two factors cannot be measured separately. Conventional methods to estimate ET make use of point measurements which are location dependent and hence cannot be used in areas having spatial heterogeneity and also dynamic nature in heat transfer process. And hence remote sensing data can be used to estimate ET which provides high spatial and temporal extent. Surface Energy Balance (SEBS) is an approach to estimate actual ET by using turbulent heat fluxes, for composite terrain at large scale heterogeneous surface on the basis of energy balance at limiting cases (Su, 2002). It uses remote sensing data as an input. SEBS is sensitive to various parameters such as: (1) surface physical parameters like Land Surface Temperature (LST), Albedo, emissivity, fractional vegetation cover, Normalized Difference Vegetation Index (NDVI), LAI and roughness height which is the height of vegetation; (2) meteorological parameters such as air temperature, air pressure, humidity and wind speed measured at reference height; and (3) radiation energy in the form of downward solar radiation and downward longwave radiation. These all parameters can be obtained either from satellite data, meteorological model output or from SEBS model output itself. SEBS tool was introduced in an open source software ILWIS (Integrated Land and Water Information System) by Lichun Wang (Source: International Institute for Aerospace Survey and Earth Science).

1.5 Spatial Rescaling and Downscaling

Rescaling/Downscaling is required to fill the gap between satellite data available at a particular resolution and what is needed for the study. Rescaling changes pixel resolution and contains same value as it was in coarser resolution whereas downscaling changes pixel resolution and value depending on how that parameter is being affected by other dependent parameter, using certain approaches. Thus downscaling technique brings coarser resolution data to finer resolution data. There are mainly two types of downscaling techniques: dynamic and statistical. Dynamic downscaling use global climate models to estimate how they affect local weather whereas statistical downscaling uses equations to derive relationship between global and local scale conditions through statistical regressions. Statistical downscaling has an advantage over dynamic downscaling that it is less computational and also uses a series of equation to derive relation between variations in global and local climate (Spak *et al*., 2007).

1.6 Variable Infiltration Capacity (VIC) Model

Different hydrological models have been used for various studies. Models like TOPMODEL and Systeme Hydrologique Europeen (SHE) are used for hydrological analysis. TOPMODEL has been extended from its previous version by including increased catchment information. SHE has been extended by including sediment transport (Singh and Frevert, 2006). Soil and Water Assessment Tool (SWAT) is a hydrological model developed to study the effect of land management practices in complex watersheds (Source: SWAT model, Wikipedia). However, since water balance has to be closed grid wise and the advantage of considering sub-grid variability in soil moisture, VIC Model has been used. This model is an open source model which is available in two different modes: water balance mode and energy balance mode.

VIC model for 2 soil layers was developed by Liang *et al*.,1996. VIC model is a semi-distributed, macroscale hydrological model which balances both the water and surface energy within a grid cell. Advantages of this model over other hydrological model are: (1) it considers sub-grid variability in land surface vegetation classes and soil moisture storage capacity, (2) assumes non-linear recession of baseflow from lower soil layer, (3) it considers topography which allows orographic precipitation and temperature lapse rate and hence gives more realistic hydrology in mountainous region and also (4) its sub-grid variation are taken statistically. Conceptual VIC diagram explaining its sub-grid variability is as shown in figure 1.2.

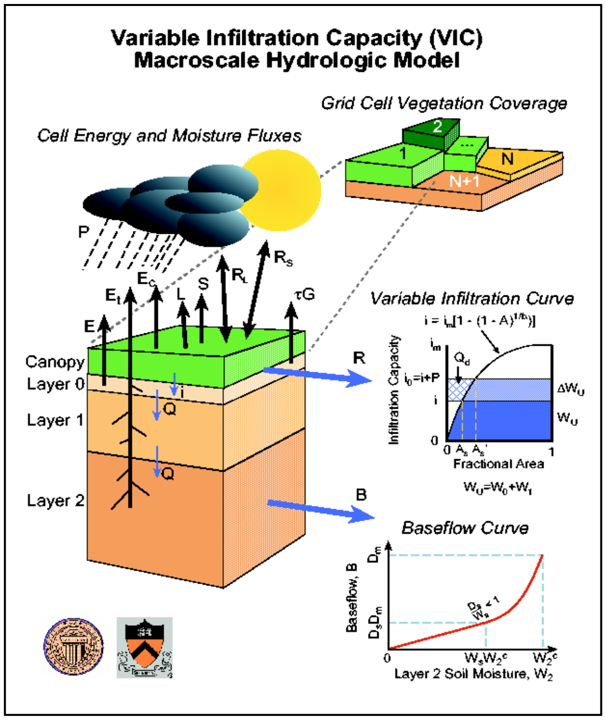


Figure 1.2: Conceptual VIC model diagram

However there are certain limitations of VIC 2L model like (1) it does not allow diffusion of soil moisture between soil layers i.e. it underestimate evaporation by not considering soil moisture movement from lower to upper soil layer, (2) also it does not consider geometry of sub-grid variations and each grid cells are modeled without considering horizontal flow among the cells. To overcome 1st limitation, model was modified by including 3rd thin soil layer to allow diffusion between soil layers; and 2nd limitation was overcome by developing a routing model. In this model, water is not allowed to flow back to the grid cell when once it has reached the channel. Routing model is based on linear transfer function by considering flow direction and Unit Hydrograph for simulating streamflow (Gao *et al.*, 2009).

VIC model simulates the partitioning of incoming energy and moisture as land surface in separate components of water and energy balance. VIC model uses 10 vegetation parameters for simulating ET from bare soil and canopy. Also there are 21 soil parameters out of which 11 are specified for each soil layer and 10 are calibrating parameters controlling the surface and sub-surface flow (explained in section 4.3). Advantage of this model is its sub-grid variability in soil moisture storage capacity, vegetation coverage, precipitation and topography. Also it considers that ET can occur from moisture stored in all the soil layers while baseflow is generated from last soil layer only (Demaria *et al.*, 2007).

1.7 Problem Definition

Many studies have been done recently in which water budget components were derived with the help of various satellite data and their results were combined to close the water budget. However, in these studies, major components such as precipitation, ET and runoff were derived and placed in the equation with these components on one side and it was assumed that the remainder obtained by subtracting these terms is equivalent to error in water balance which include change in water storage, interception, soil moisture, etc., majority being change in water storage (Rodell, 2004).

Water budget estimation has been done previously by using discharge data from in-situ observations. Also, Gravity Recovery And Climate Experiment (GRACE) data was used to obtain ΔTWS. However, this dataset was considered unbiased and used with standard GRACE error value which increased error in water budget closure. Method used was merging satellite datasets with in-situ measurements and then use it in water budget equation (Sahoo *et al*., 2011).

However, in deriving groundwater estimate from GRACE data, main limitation is its minimum area required. GRACE measures even a minute change in centimeters of terrestrial water storage but its grid size is very large (Frappert *et. al*., 2011). And hence downscaling is required to be done to obtain more accurate and spatially distributed groundwater estimate.

MODIS (MODerate resolution Imaging Spectroradiometer) datasets can be used in deriving ET and results obtained can be at finer resolution. But main problem in using MODIS derived ET is that it is not microwave data. And hence there will be cloud cover in monsoon season which will not give proper results for many days.

Precipitation, ET and ΔTWS derived from satellite data has been used in many studies with different study area. However these datasets along with hydrological model outputs has not been used to close the water budget for Indian condition. Work here reflects how water budget components derived from satellite data and from hydrological model can be used to close the water budget for the Ganga basin.

1.8 Research Objectives and Research Questions

Depending on the above mentioned major limitation of previous studies done, it is necessary to derive ΔTWS individually so that error can be reduced in water balance equation and also its closure can be done more accurately. Also, GRACE data used for this purpose should have minimum error so that while using it in water budgeting will further reduce its imbalance. Because of the limitation of coarser resolution, it is necessary to select large area for study.

Taking into account above factor, the Ganga basin having an area of 9,26,080.3734 km^2 represents an ideal place in India for the study which has comparatively depleting and surplus water recharge depending upon season. However while using GRACE dataset in the Ganga basin, areas such as the Himalayas which has complex terrain ranging from low height mountains of the Siwalik range to height mountains in central and northern Himalayas, will give very poor results in such terrain because of its limitation of scale.

Also depending on the satellite data used in water budgeting, errors in balancing may be due to temporal scale variation or spatial scale variation. Hence, proper data is required to be selected to obtain accurate water budgeting after bringing all the datasets in common temporal and spatial resolution

Hydrological models like VIC model or SWAT model can be used for water balancing since these models derive components by considering soil parameters, vegetation parameters, meteorological parameters, Land Use/Land Cover, etc. and hence gives more accurate outputs. However, SWAT model does not consider sub-grid variations and hence considers only one LULC class in one grid. Instead VIC model considers sub-classes lying in same grid and gives more accurate results depending on various soil properties, Albedo, LAI, rooting depth, rooting fraction and meteorological parameters (Lohmann *et al*., 1998a). Also the limitation of using MODIS derived ET can be removed by using ET derived from VIC model during required rain duration.

The aim of present study is to estimate water budget components using different satellite data (MODIS and GRACE) and VIC hydrological model after incorporating scaling issues. Study area selected is the Ganga basin. The outcomes of this study will be more accurate closure of water balance equation by considering all the major components i.e. precipitation, runoff, baseflow, ET and ∆TWS. And hence error in closure will be reduced. Also GRACE which is at present obtained at coarser resolution, will be obtained at comparatively finer resolution which will contribute in further reducing imbalance in water budget.

With these views, major objectives of the present study are:

- To find water balance components from satellite data and VIC model.
- To find water budget components from satellite after incorporating scaling issues.
- To reduce and quantify error in water budget components derived from hydrological model and satellite.

The broad research questions concerned with above research objectives are:

- Which satellite data and models are suitable for estimating water budget components?
- How scaling issues can be addressed for ∆TWS using GRACE data?
- What is the accuracy of water balance components obtained from satellite data and model with respect to actual data and how its error can be reduced?

To answer the above question, the procedure involved is:

- Derive ET from MODIS products like LST, Emissivity, albedo, NDVI and other satellite datasets using Surface Energy Balance approach.
- Downscale ΔTWS obtained from GRACE using proper input dataset.
- Simulation and calibration of Variable Infiltration Capacity model to obtain inputs for water balance equation.
- Reduce the imbalance of equation.

CHAPTER 2

LITERATURE REVIEW

2.1 Precipitation

Precipitation is considered to be the input of water to the earth for water cycle to complete. Precipitation includes water in the form of rainfall, snowfall, hail, drizzle, glaze, sleet, snowflakes, dew, fog, mist, frost, etc. and to measure these, different approaches are used like rain gauges, snow gauges, weather radar, satellite data and many other techniques.

Rain gauges are considered to be the most widely used approach to measure rainfall at a particular point location. Gauges can be manually operated or automatically operated. In case of manually operated or non-recording rain gauges, the rainfall depth is measured by an operator at a fixed time each day, usually at 8:30 am in India. Whereas in automatically operated or recording rain gauges, rainfall depth is measured automatically by making use of different techniques like tipping bucket or weighing type rain gauge and many other techniques. However, this ground observed data may contain error especially at the time of high wind which results in local distortion of wind field around the gauge. However this can be removed by installing reference gauges nearby which are covered by mesh. If these gauges are installed in colder locations, then snow may also block the gauges at the time of snowfall. However there are certain national standard for the installation, operation and assessing the uncertainty in the output. These rain gauges are operated either by river basin management, hydropower, flood warning and/or by other organizations (Subramanya, 1994).

These rain gauges represent the local point observations. However, radar weather stations give higher spatial and temporal resolution. But satellite observations to measure precipitation can be used to fill in radar coverage. This satellite data can be obtained from geostationary, polar or low-orbit satellites which are operated by international, national or private sector organizations (Sene, 2013).

Islam and Uyeda, (2007) used Tropical Rainfall Measuring Mission (TRMM) data to determine the climatic characteristics of rainfall in Bangladesh. Pre-monsoon, monsoon and post-monsoon season has been studied by taking ground based rainfall data as base. TRMM version 4 and 5 3B42 has been used. However, it showed that TRMM is good for long term for studying water resource management but for good for short term events like flood forecasting (Islam and Uyeda, 2007).

TRMM precipitation data has been used by Xiang et al. (2012) for estimating runoff data in Xinjiang catchment, Poyang lake basin by using a distributed hydrological model.

To overcome this, precipitation data derived from National Centre for Atmospheric Research (NCAR) reanalysis products which contains data in the form of bands representing Julian day in a year, has been taken. It gives data in the form of rainfall intensity.

2.2 Evapotranspiration

Simulation of soil water content and actual ET in any catchment depends on accuracy of input data. Since in-situ observations represent only point local observations, remotely sensed data are used to estimate spatial distribution of these. MODIS data has been used for this purpose. Products like LAI, NDVI and surface albedo are considered important inputs for hydrological model (Zhang and Wegehenkel, 2006).

Work has also been done to derive ET from remotely sensed data without site-specific relationships by using Priestley- Taylor equation and Granger's complementary relationship. This relationship incorporates the atmospheric conditions in a relative evaporation coefficient without depending on in-situ conditions. However, this approach does not distinguish between soil and vegetation temperature profile (Venturini *et al*., 2008).

Other method to estimate ET is by using surface temperature-vegetation index (T_s - VI) triangle method. This approach is used to determine quantitatively the dry and wet edges of the triangle space. Dataset used was MODIS. However, determination of these edges involves large degree of uncertainty especially in arid and semi-arid areas. Also in case of cloudy day, it becomes difficult to determine dry and wet pixels and additionally it becomes difficult to determine dry pixels in the short duration after rainfall which will not give minimum ET (Tang *et al.*, 2010).

MODIS global ET is developed by Mu *et al*., 2007. However MODIS global terrestrial ET algorithm was modified in 2011 by simplifying the calculation of vegetation cover fraction, by calculating ET as the sum of day and night time components, by adding soil heat flux calculations, by improving estimates of stomatal conductance, aerodynamic resistance and boundary layer resistance and by separating dry canopy surface from wet and dividing soil surface into saturated wet surface and moist surface. This modification has led to providing even critical information on global terrestrial water and energy cycles and environmental change. However this modification has not been globally validated yet (Mu *et al*., 2011).

Zhang *et al*. (2008) estimated ET by using 3 different models namely Penman- Monteith, Shuttle- Wallace and Clumping model. Shuttleworth-Wallace model assumes that there is blending of heat fluxes from leaves and soil whereas clumping model, by using Shuttleworth-Wallace model, separates soil surface into fractional area inside and outside the influence of canopy. Out of these 3 models, clumping model derived ET was best correlated with the in-situ observation but it over-estimated ET after rainfall duration. However, these results are completely site specific.

Priestley-Taylor equation combined with T_s/NDVI space, MODIS NDVI data and Global Land Data Assimilation System (GLDAS) meteorological data have been used to calculate ET in ungauged basins, making it completely independent of field data. However, in using T_s/NDVI method to estimate ET, limitation is the range of NDVI. Hence this method can be applied only when there is wide range of NDVI so that an expected trapezoid can be generated from T_s/NDVI space; also this method does not consider ET during night time and cloudy daytime (Du and Sun, 2012).

ET derived from Surface Energy Balance Algorithm for Land (SEBAL) provides spatially distributed ET and calculates sensible heat flux by using wind speed from only one weather station (Bastiaanssen et al., 2005). Modification in this traditional SEBAL approach was done by Zhang *et al*. (2011) in which wind speed was interpolated by using inverse distance weightage technique and this interpolated wind speed was used directly to measure friction velocity. Whereas Tasumi method (Tasumi *et al*., 2003) divides whole area into sub-area and then computes soil heat flux individually for each sub-area by selecting coldest ant hottest pixel for each. However, simplified method is validated by Tasumi method only.

MODIS satellite mission also gives ET as a product by using remotely sensed vegetation index and surface temperature in T_s-VI method. By using hourly surface radiation data derived from Geostationary Operational Environmental Satellites (GOES), good correlation is obtained between this remotely sensed ET and that measured by the flux towers in United States. However, this MODIS ET estimation can be applied only to North America because of coverage limitation of GOES data. ET when derived from water balance equation with inputs as precipitation, runoff and ΔTWS obtained from GRACE were applied in Yellow river basin in China, it showed systematic bias in the monthly mean. MODIS ET was higher than water balance ET from May to August and less during September-October and January-February (Tang and Zhang, 2011).

Almhab *et al*. (2007) derived ET with SEBAL method by using satellite data input from Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA-14 satellite and from Landsat Thematic Mapper (TM) in a mountainous terrain of Sana's basin in Yemen. Since mountainous terrain was selected for study area, terrain effect was also considered to estimate net radiation by using DEM information. Results showed that AVHRR derived ET are reasonable however that derived from Landsat showed better results because of its higher spatial resolution.

ET derived from SEBAL method using ASTER, Landsat and MODIS shows that ASTER and Landsat gives better results even at smaller scale however MODIS data can be used for large study area since it is freely downloadable and its processing levels are well standardized, though it is of coarser resolution as compared to other two (Hafeez *et al*., 2002).

SEBS approach has been developed to estimate atmospheric turbulent fluxes and surface evaporative fraction using visible, near infrared and thermal infrared frequency remote sensing data along with meteorological data. This approach does not require any prior knowledge of actual turbulent heat flux. It helps for the determination of roughness length for heat transfer and a new formulation for the determination of evaporative fraction is used on the basis of energy balance at limiting cases (Su, 2002). An application consisting of set of tools for determining surface parameters like albedo, temperature, vegetation coverage, etc. from spectral reflectance and radiance measurements has been introduced in ILWIS software version 3.8.1. Also Penman-Monteith equation is strictly valid only for vegetated canopy.

2.3 Change in Terrestrial Water Storage (GRACE)

Conventional method to derive water storage is a lumped model which includes lengthy and complicated process. Numbers of inputs such as hydro-geological map, LULC, water table depth, soil properties, aquifer properties, etc. are required. Also much work has been done in estimating water budget components using different techniques by estimating precipitation, ET and runoff and considering rest as error which include ΔTWS, snowmelt contribution, change in soil moisture and other parameters. However, this error can be reduced by using ΔTWS measured by GRACE satellite mission developed by National Aeronautics and Space Administration (NASA) and German Aerospace Centre and launched in March, 2002. This satellite mission gives minute change in terrestrial water storage by measuring change in speed and distance between two identical spacecrafts flying at low polar orbit. Several works has been done to determine change in water storage by using GRACE data.

GRACE has various applications which include drought assessment. This type of work has been done in Canada by using total water storage anomalies obtained from GRACE. These values were validated by using storage components derived from water balance components precipitation, ET and measured streamflow records; and a strong correlation was obtained between them. However, some discrepancies lie because of uncertainties lying in terrestrial water storage data (Yirdaw *et al*., 2008).

Regional groundwater models play an important role in water resource planning but because of their spatial scale, a detailed characterization is cost prohibitive. Also, these models require field measurements for their calibration. Instead when results of these groundwater models were compared with the values of GRACE, it showed a good correlation, also with GRACE and in-situ ground water levels. However, limitation in using GRACE data is its coarse resolution. Downscaling of GRACE data is needed since most of groundwater models are distributed and modelers rely on models to examine water storage change at areas smaller than its resolution (Sun et al., 2012). This type of work was done by (Lo *et al*., 2010).

Also in un-gauged or poorly gauged water bodies where satellite altimetry plays a powerful role in measuring surface water level change, GRACE satellite gravimetry shows good correlation with geometrical change from altimetry level (Singh *et al*., 2012).

Satellite derived groundwater storage estimates were derived by considering three different methods by Kuss *et al*. (2011). First method include calculating water budget to check GRACE TWS value, second is calculating trend in groundwater anomaly using GRACE TWS value and satellite derived variable and then compare it to hydrological model and third is to directly compare GRACE derived groundwater estimates with in-situ groundwater levels.

Kuss *et al*. (2012) proposed a methodology to downscale GRACE data by using ground water storage derived from hydrological model. Work includes deriving a relationship between GRACE derived change in ground water storage obtained by separating soil moisture, reservoir storage and snow water equivalent from its value and ground water storage derived from hydrological model C2VSIM with in-situ observations which was developed for California region. However to use this method in other region, other input data is required for downscaling GRACE data.

In India especially in Indo-Ganga basin, considerable depletion in static groundwater storage was been seen with a rate of about 4±1 cm per year in Rajasthan, Haryana, Punjab and Delhi. This may be because of unsustainable consumption of groundwater for irrigation and other anthropogenic uses Rodell *et al*. (2009) and Tiwari *et al*. (2009).

GRACE validation has also been done in continental region by using interactions between Soil, Biosphere, and Atmosphere-Total Runoff Integrating Pathways (ISBA-TRIP) where model outputs were compared with in-situ discharge data also. Result show that river storage contribute significantly to GRACE measurements. Model precipitation, ET and runoff were compared with satellite terrestrial water storage change and showed good comparison with some difference throughout which may be because of low resolution and river contamination of GRACE derived ΔTWS (Alkama *et al*., 2010).

Also GRACE data can be validated by deriving water balance components from different satellite datasets such as precipitation from TRMM, ET from MODIS, streamflow from Laser/Radar Altimetry and soil moisture from Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) or Soil Moisture and Ocean Salinity (SMOS). Results obtained by subtracting water balance components: precipitation, ET and runoff give change in ground water storage whereas GRACE gives change in terrestrial water storage. Hence this change in terrestrial water storage was subtracted from soil moisture to obtain change in ground water storage. Results showed considerable match between these two. Also showed that groundwater level rise does not have any link with climate instead it is because of change in cultivation pattern in the study area (Longuevergne *et al*., 2010).

Chen *et al*. (2010) examined El Nino-Southern Oscillation over Amazon basin with the help of GRACE data. Basin average water storage derived from GRACE was highly correlated with Southern Oscillation index. Study done here showed that GRACE provides integrated information of much broader scale than rainfall and in-situ discharge which are at very local response to precipitation forcing. Also ∆TWS quantity can be directly compared to hydrological model outputs.

Also, precipitation minus ET which describes flux of water between atmosphere and earth surface, remains unmeasured because of absence of observations of ET. This P-ET when combined with GRACE ∆TWS and river discharge data showed a good correlation and can be used to validate general circulation models because of its connection to both atmospheric and terrestrial water budgets (Swenson and Wahr, 2009).

2.4 Water Balance and Hydrological Model

In 2008, Montzka *et al.* (2008) modeled water balance of Rur River in Germany and found the impact of remote sensing data on water balance model GROWA. GROWA model gives water balance components such as actual evapotranspiration, surface runoff, total discharge, ground water recharge and interflow. Here, total runoff is the difference between mean annual precipitation and mean annual evapotranspiration. Also, ET derived from this model depends on soil water content, winter and summer precipitation, annual potential ET, slope, and other parameters which depend on land cover type. However, this model is intended for large scale catchments and requires annual meteorological data as input. Hence for deriving ET, average potential crop ET coefficients from monthly data are required to be determined first which reduces accuracy of derived ET and all the results obtained are at annual scale resolution. Also ground water recharge is expressed as constant proportion of total runoff.

Comparison of six daily and sub-daily precipitation datasets was compared and their effect on water balance was determined with the help of MGB IPH model. This model uses topography, soil type and vegetation cover as inputs. However, this model gives soil water balance by considering only one soil type and hence soil moisture content tends to be relatively constant among datasets though varying spatially. Satellite precipitations datasets used in this model showed certain limitations in deriving discharge and rainfall quantity while gauge based precipitation best represented actual precipitation (Getirana *et al*., 2011). However, for large basin and areas having poorly gauged sites, it is not possible to use gauge based data all over.

Macro- PDM model gives water balance components on daily basis with an assumption that soil moisture storage capacity varies statistically across catchment and all other catchment properties and climate inputs are constant across the catchment. This model mainly simulates the effect of climate change over large basins. Model uses Moore's (1985) probability distributed model which is similar to the principles used in developing VIC hydrological model. However performance of this model is poor in arid and semi-arid regions. Also though model simulates at daily time step, finest model output is at monthly resolution. Also this neglects account of sub-grid variability in climate inputs rather it can be used by dividing the area into still finer spatial resolution (Arnell, 1999).

Hydrological model like MIKE System Hydrologique European (SHE) has been used in many studies to solve the water balance. This is a fully distributed physically based hydrological model which considers major hydrological components like precipitation, ET, change in overland storage, change in sub-surface storage, horizontal inflow, horizontal outflow, drain and baseflow. However, many inputs are required for its simulation and it is not an open source model.

Satellite data provides information on one component of water cycle whereas use of hydrological model provides insight in the entire hydrological cycle and also the fluxes between different water balance components. Use of hydrological model like Soil and Water Assessment Tool (SWAT) has been used to estimate water balance components. SWAT model sub-divides the entire basin into sub-basins and further into Hydrological response Units (HRU) which contain soil parameters used for calculation. HRU's are the areas which have same soil type. ET derived from this model has been calibrated by that derived from SEBAL algorithm. However, SWAT does not consider land use connectivity and also expansion of plant parameter database is required (Immerzeel *et al.*, 2008).

Work done by Pan *et al*. (2008) consists of estimating regional water cycle using different satellites and physical based hydrological model. VIC/Land Surface Microwave Emission Model were used to estimate water cycle and there results were updated by assimilating satellite datasets like TRMM and MODIS with the help of statistical tools like particle filter, Ensemble Kalman filter. However it was found that model driven by TRMM rainfall produces reasonable fluxes for water cycle whereas this was not the condition when MODIS derived ET was used to update flux files produced by the model. Components of water cycle included were rainfall, runoff, ET and soil moisture by ignoring change in ground water storage and considering it as an error along with other components.

Water budget was also estimated by using satellite data over ten global river basins (Sahoo *et al.*, 2011). Here water budget components considered were rainfall, ET and change in water storage. Precipitation and ET were derived by merging four precipitations and four ET derived from different models. Change in water storage was obtained from GRACE dataset. Runoff data was taken from in-situ observations. However, all the satellite precipitation products tent to over-estimate summer precipitation. Also precipitation show large discrepancies over complex terrain and during winter season. Here, contribution of change in water storage is comparable to precipitation only. However, the datasets used here are biased with the help of ground based observations and hence more accurate and spatially spread ground observations are required.

Annual water balance of Bornean tropical rainforest in Malaysia was done by Kumagai *et al.* (2005) which is mainly dry with no variability in temperature, precipitation, vapor pressure deficit and radiation. Here, energy balance used to derive ET takes only radiation and air temperature as inputs, neglecting vegetation and LULC classification since it is a forest area. Hence discrepancies between equilibrium and actual evaporation rates were caused due to dry spells which resulted in reduction in transpiration rates.

VIC model as compared to other hydrological models considers sub-grid variability in soil moisture storage capacity and also considers baseflow as non-linear recession. Also it explicitly represents vegetation and closes both surface energy and water balance modes. This model focuses more on horizontal variations in surface property including soil and topography which influence the production of runoff. However, instead of considering where within a grid cell a specific feature of soil property or meteorological property lies, it considers its spatial probality distribution. Also it fails to represent effect of groundwater on land-atmosphere interactions (Lettenmaier, 2001).

Also VIC model simulated runoff values depend on soil thickness, baseflow recession curve and infiltration parameter. However to calibrate this, necessary information about soil thickness or soil moisture content is required (Lohmann et al., 1998b). Distinguishing properties of the model include sub-grid variability in soil moisture storage capacity and vegetation classes, drainage from lower soil moisture zone and effect of topography for orographic precipitation and temperature lapse rate (Gao *et al*., 2009).

VIC model is sensitive to main 6 parameters namely W_s, D_m, D_s, b, d_1 and d_2 (explained in section 4.3.2) which can be calibrated. However in case of gauged catchment, these can be calibrated depending upon various in-situ observations available but in un-gauged catchments, lack of information results in improper calibration. In such case, sensitivity analysis can be done to reduce complex model into more economical form which can be used more efficiently in un-gauged catchments. Objective of sensitivity analysis is to determine the impact of parameters on model response i.e. if the impact of any parameters is small than that parameter can be taken as constant or eliminated. Method like Monte Carlo Analysis Toolbox can be used for this purpose which was designed with an objective to investigate the sensitivity, parameter and output uncertainty of mathematical models by identifying model parameters. However, it lacks in representing surface-groundwater interaction and transmission losses in case of hydrological processes in ephemeral catchments. Also it is necessary to capture the impact of parameter on model while using sensitivity analysis (Demaria *et al*., 2007). Results indicated that 'b' parameter plays key role in separating precipitation into soil moisture and surface runoff especially in dry areas and hence adjust ET demands

Similar work was done by Bao *et al*. (2011) by decreasing 6 calibrated parameters to 3 baseflow parameters (W_s, D_s and D_m) by considering soil and topography properties. Results obtained show less uncertainty in streamflow estimation as compared to results obtained by calibrating all 6 parameters in un-gauged catchment. However, overall results obtained from 6 parameters are better than 3 parameters but difference is not significant. In case of 3 parameters calibration, some original non-sensitive parameters become sensitive and sensitive parameters become more sensitive because of reduction of calibration with decrease of parameter number.

CHAPTER 3

STUDY AREA AND MATERIALS/DATA USED

This chapter presents an overview of the study area including location, extent, climate, land use, soil and other hydrological parameters and data used for the study.

3.1. Study Area

3.1.1 Location

Catchment area of the Ganga basin, with outlet at Farakka barrage in West Bengal state, extends over an area of 9,26,080.3734 km^2 and falls in three countries, namely India, Nepal and Tibet (China); major part of which lies in India. Basin lies between the geographical extent of north 22.625° to 31.375° latitude and east 73.375° to 88.875° longitude.

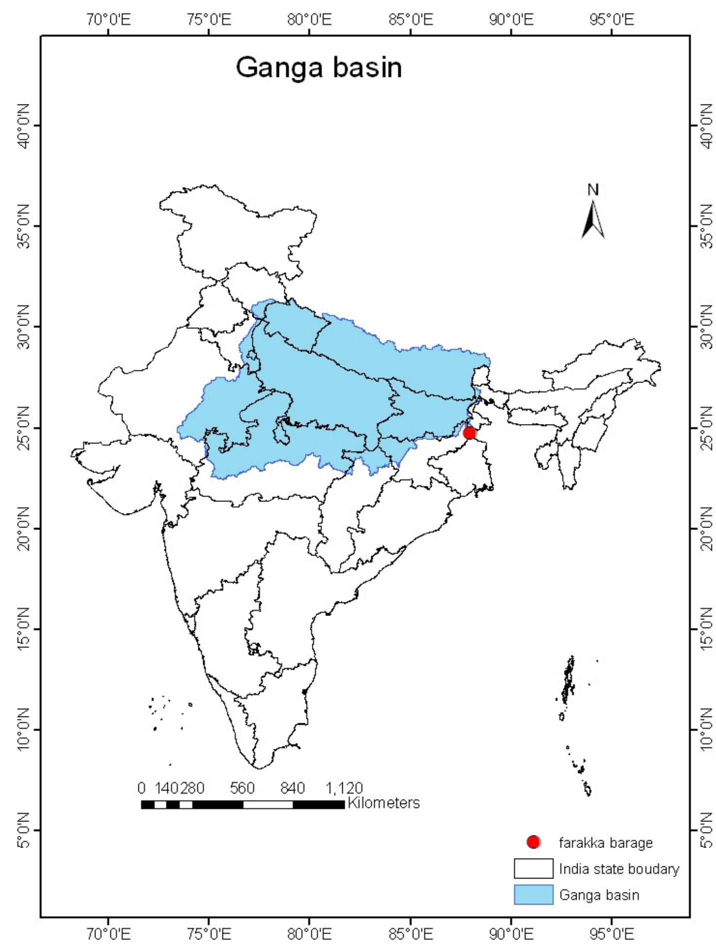


Figure 3.1: Study area

The Ganga basin is bounded by the Himalayas on the North; Aravali ranges along with the ridge separating the Ganga basin and the Indus basin on the West, Vindhyas and Chhotanagpur plateaus on the South and Brahmaputra ridge on East. In India, the basin lies in the states namely Uttarakhand, Himachal Pradesh, Uttar Pradesh, Union Territory of Delhi, Haryana, Madhya Pradesh, Rajasthan, Bihar and West Bengal. The Ganga River enters into the plains near Haridwar in Uttrakhand from where it flows in south/south-east direction. It meets tributary Yamuna River at the right bank of Allahabad in Uttar Pradesh from where the Ganga flows in east direction (Jain *et al.*, 2007).

3.1.2 Drainage

The Ganga River is traditionally considered to be originated from the Gangotri glacier near Gomukh at an elevation of 7010m above sea level in the state of Uttrakhand from where the Bhagirathi River rises. Other main stream is the River Alaknanda which originates from the Satopanth glacier at an elevation of 7000m in the same state. These two rivers while flowing downhill are joined by a number of streams and finally meet at a place named Devprayag from where the combined flow is known by the name Ganga. Major tributaries joining the Ganga river through its 2525 km course are Tons, Yamuna, Ramganga, Ghaghara, Gandak, Kosi, Mahananda, Punpun, Kiul, Burhi Gandak and Sone. Among these, tributaries like Kosi (which is a Perennial River), Ghaghara and Gandak originate from Nepal amounting drainage area of 190,000 km^2. Catchment area of Kosi River also includes the world's highest glaciers Mt. Everest and Kanchanjunga (Jain *et al*., 2007).

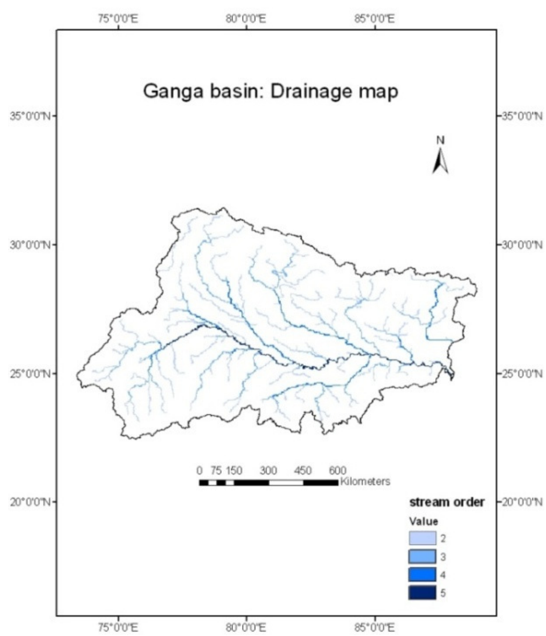


Figure 3.2: Drainage map

The whole Ganga basin can be divided in four main sub-basins namely: Upper Ganga, Yamuna, Chambal and Lower Ganga sub-basin.

3.1.3 Climate

Climate of the Ganga basin is generally temperate with great variation in terms of temperature, rainfall. Northern region of the basin is mainly influenced by the Himalayas where winters are very cold and summers are moderate. Whole basin receives 80% of the rainfall because of south-west monsoon. Average rainfall over the catchment varies from 40cm to 150cm. In region like Nepal and north-east part of Uttrakhand state of India, temperature goes negative during winters because of glaciers. Whereas as in other part of the basin, temperature varies from 3-4° C in winters and goes above 40° C in summers (Jain *et al*., 2007).

3.1.4 Soil

According to National Bureau of Soil Survey and Land Use Planning (NBSSLUP) for India and Food and Agriculture Organization (FAO) for Nepal, dominant soil types in the basin are sandy, clayey, loamy, and their combination such as sandy loam, clayey loam, and other types such as loamy skeletal, clayey skeletal, glacier, rock outcrop, glacier and rock outcrop.

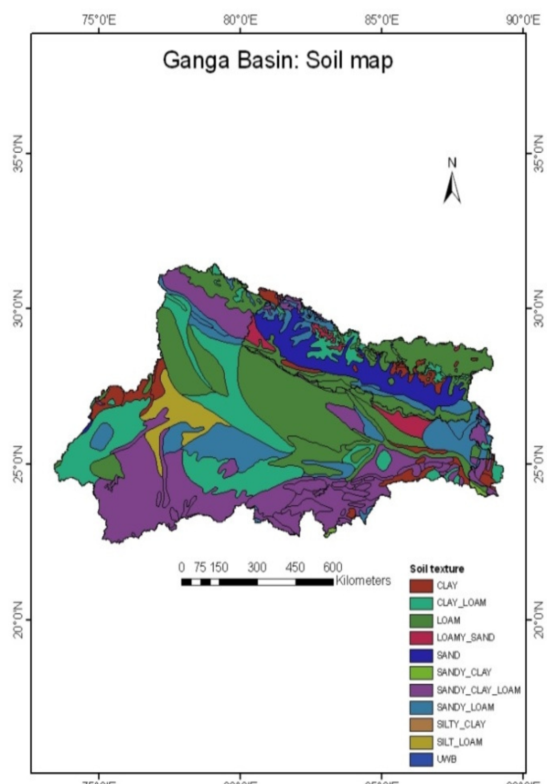


Figure 3.3: Soil map

(Source for FAO: www.fao.org/geonetwork/srv/en/main.home and source for NBSSLUP: bhuvan3.nrsc.gov.in/bhuvan/bhuvan/bhuvan2d.php#)

Spatial resolution of NBSSLUP soil map, revised by NRSC is 1:2,50,000 and that of FAO soil map is 1:50,00,000.

3.2. Materials/Data Used

For the study, various datasets and software resources have been used which are described below.

3.2.1 Remote Sensing Data

- MODIS products:
  - MOD11A2 Terra Land Surface Temperature/ Emissivity level 3 data at 1km spatial and 8 day temporal resolution
    (Source: http://glovis.usgs.gov/)
  - MOD13A2 Terra Normalizes Difference Vegetation Index level 3 data at 1km spatial and 16 day temporal resolution
    (Source: http://glovis.usgs.gov/)
  - MOD43B3 Terra-Aqua combined Albedo level 3 data at 1km spatial and 16 day temporal resolution
    (Source: http://glovis.usgs.gov/)
  - MOD16A2 Terra Evapotranspiration level 3 data at 1 km spatial and 8 day temporal resolution
    (Source: http://www.ntsg.umt.edu/project/et#data-product)
- GTOPO arc 30 Digital Elevation Model at 30 arc seconds~ 1km spatial resolution (Source: https://lta.cr.usgs.gov/GTOPO30)
- Gravity Recovery And Climate Experiment (GRACE) version 5 data at 1° spatial resolution and 1 month temporal resolution
  (Source:http://gracetellus.jpl.nasa.gov/data/gracemonthlymassgridsland/)
- Other satellite data products:
  - Downward longwave and shortwave radiation at 1° spatial and daily temporal resolution (Source: http://rda.ucar.edu/datasets/ds314.0/)
  - Advanced Very High Resolution Radiometer (AHVRR) imagery derived Land Use/ Land Cover at 1km spatial resolution with 14 classes
    (Source: http://glcf.umd.edu/data/landcover/)
  - Système Pour l'Observation de la Terre(SPOT) imagery derived Land Use/ Land Cover at 1km spatial resolution with 36 classes lying in study area(Source: bioval.jrc.ec.europa.eu/products/glc2000/products.php)

- LULC prepared for ISRO Geosphere Biosphere Program under project entitled "Landuse/ Landcover Dynamics and Impact of Human Dimension in Indian River Basins" at a resolution of 1:2,50,000.
- Minimum and maximum temperature, precipitation data from Indian Meteorological Department (IMD) for year 2004 and 2005 at 0.5° spatial and daily temporal resolution (Source: www.imd.gov.in)
- Minimum and maximum temperature, precipitation data from National Centre for Atmospheric Research (NCAR) for year 2004 to 2008 at 1° spatial and daily temporal resolution (Source: http://rda.ucar.edu/datasets/ds314.0/)

3.2.2 Ancillary Data

- Ground water level data for year 2007, 2008 and 2009 from Central Ground Water Board (CGWB) at various point locations
- Soil data for India from NBSSLUP
- Soil data for Nepal and Tibet from FAO

3.2.3 Software and Programming Language Used

- ERDAS Imagine 9.1
- ArcGIS 9.1, 10
- Quantum GIS
- ENVI 4.3
- ILWIS 3.3, 3.7, 3.8
- Geomatica version 9.1
- VIC model code setup
- Python version 2.5, 2.6 and 2.7
- IDL version 6.3

CHAPTER 4

METHODOLOGY

This chapter overview the methodology adopted in the study. For the ease of understanding, methodology can be divided in following five parts:

- Preparation and collection of material for the study.
- Preparing inputs for SEBS method for deriving ET.
- Preparing water level data in the GRACE data format, for downscaling.
- Preparing the inputs required for VIC model and simulate it.
- Analysis of these inputs and closure of water balance.

The methodology used in the study can be understood by the following flow chart:

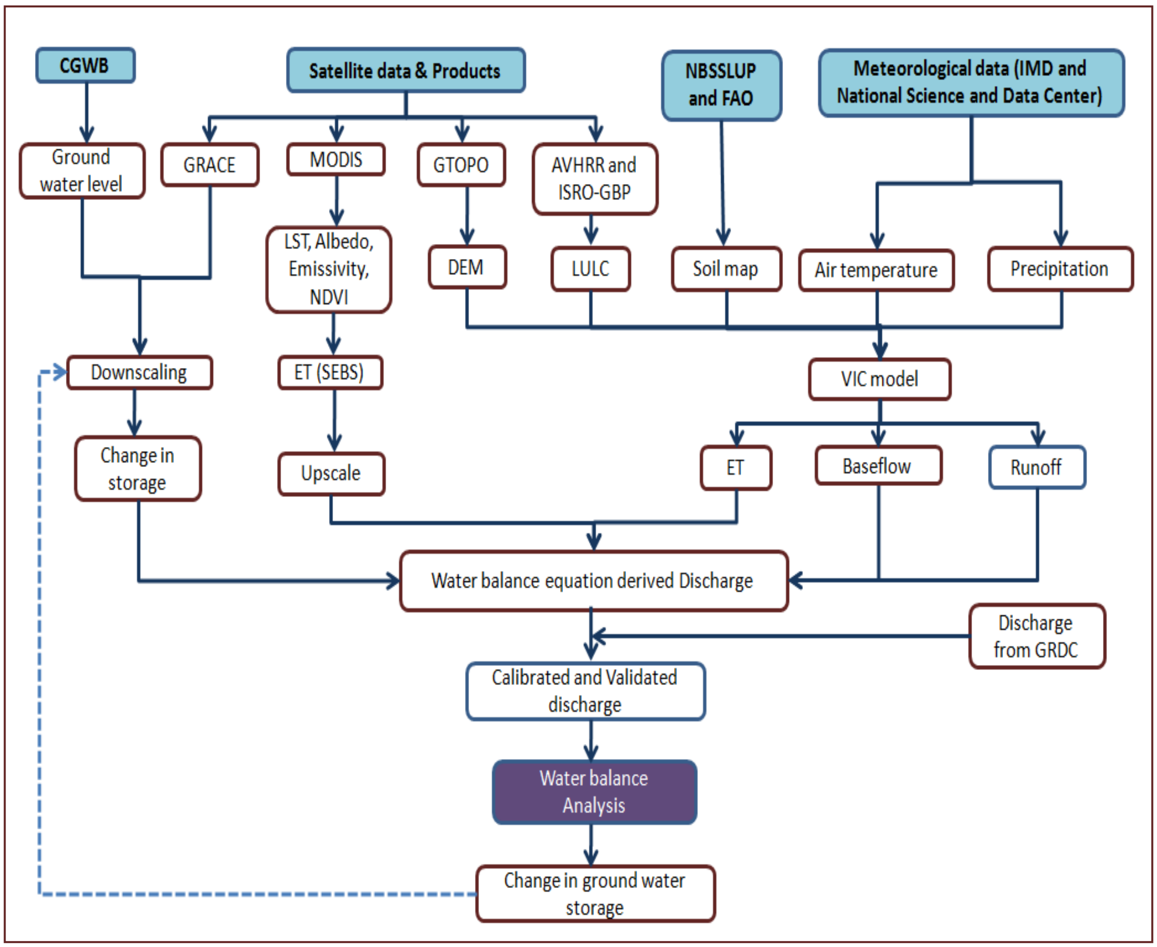


Figure 4.1: Methodology

By taking precipitation data as satellite derived, other water budget components were derived by using following techniques.

4.1 Preparation of inputs for SEBS Approach

For deriving ET from SEBS, satellite data products like LST, albedo, emissivity, NDVI were obtained from MODIS sensor. MODIS contains 36 bands ranging in wavelength from 0.4µm to 14.4µm. MODIS Terra sensor uses bands 20, 22, 23 and 29 to derive LST by making use of geolocation, cloud masking, land use, atmospheric temperature, water vapor and snow. Emissivity product makes use of bands 31 and 32 from both Terra and Aqua sensor. NDVI 16 day product represents maximum NDVI which was there within those 16 days. It is prepared by making use of surface reflectance data. Albedo is a combined product of terra and aqua sensor which uses multi-date surface reflectance and Bidirectional Reflectance Distribution Function (BRDF) in its derivation. Thus by making use of these satellite products, preparation of inputs of SEBS involves:

- Downloading data: For this, MODIS land data was downloaded for year 2004, 2005 and 2008. Tiles falling under study area were h24v04, h24v05, h24v06, h25v05 and h25v06. Data downloaded include LST, albedo, emissivity and NDVI. Also data such as Digital Elevation Model, Land Use/Land Cover, radiation data and meteorological data such as air temperature, wind velocity were downloaded from sources mentioned in section 3.2.1.
- Processing: Processing of MODIS datasets in terms of projection and scale factor involves following steps:
  - Data available were in the form of tiles and hence these tiles were mosaic to obtain a spatial image,
  - Now these mosaic images are available in sinusoidal projection and hence these all datasets were first converted in Geographic Coordinated System WGS1984 geo lat/long,
  - Projected datasets were then masked from the Shapefile which contains boundary of study area,
  - Now MOD11A2 product contains LST as well as emissivity both. Out of 13 layer of this product, 1st layer refers to LST and 11th layer refers to emissivity. These layers were separated by using spectral subset for each image. Also MOD13A2 contains 11 layers out of which 1st layer represents NDVI and for this also spectral sub-setting was done.
  - Now these products are raw products and needs a factor to be multiplied to remove error. LST product was multiplied with a scale factor of 0.02 which will give data in degree Kelvin. Emissivity was multiplied with 0.002 and an offset of 0.49 was added. Albedo was multiplied with 0.001 and NDVI with 0.0001.
- To derive ET from Surface Energy Balance approach, SEBS tool in ILWIS 3.8 version was used. This tool takes following inputs: (1) surface physical parameters like LST, Albedo, emissivity, fractional vegetation cover, NDVI, LAI and roughness height which is the height

of vegetation; (2) meteorological parameters such as air temperature, air pressure, humidity and wind speed measured at reference height; and (3) radiation energy in the form of downward solar radiation and downward longwave radiation. However this model has a limitation in using these products as all these datasets should have same georefernce and coordinate system. Hence these all datasets were georeferenced by using NDVI day 1 data by first upscaling it to 0.25° spatial resolution and then was used as reference and were all converted into ILWIS raster format which is accepted by the tool.

- Canopy height map, displacement height map and surface roughness map were prepared from LULC classes by using following formula:
  $Z_{0m} = 0.07h_c$, and
  $d = \frac{2h_c}{3}$
  Where, Z_{0m} = surface roughness height,
  d = displacement height, and
  h_c = canopy height which is obtained from reference values given for LULC classes in SEBS help

After placing all these inputs, SEBS follows following equations to derive ET (Su, 2002):

- Main energy balance equation is represented as:

$$R = G_0 + H + \lambda E \quad (4.1.1)$$

Where,
R = Net radiation in W/m^2,
G_0= Soil heat flux in W/m^2,
H = Turbulent sensible heat flux in W/m^2, and
λE= Turbulent latent heat flux where λ is latent heat of vaporization and E is actual evapotranspiration.

- Net radiation is derived by the formula:

$$R_n = (1 - \alpha) \cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4 \quad (4.1.2)$$

Where,
R_n = Net radiation in W/m^2,
α= Albedo which is unitless,
R_{swd} = Downward solar radiation in W/m^2
ε = Emissivity which is unitless,
R_{lwd} = Downward longwave radiation in W/m^2
σ = Stefan-Boltzmann constant
T_0 = Land surface temperature in Kelvin

- Soil heat flux is obtained by the formula:

$$G_0 = R_n \cdot [\Gamma_c + (1 - f_c) \cdot (\Gamma_s - \Gamma_c) \quad (4.1.3)$$

Where,

G_0 = Soil heat flux,
R_n = Net radiation,
Γ_c = Ratio of soil heat flux to net radiation
= 0.05 for full vegetation (Liakatas *et al.*, 1986)
Γ_s = 0.3115 for bare soil (Kustas and Daughtry, 1989)
f_c = Fractional canopy coverage derived from LULC

- To formulate evaporative fraction, following derivation and formula's takes place in SEBS tool:
  - To estimate evaporative fraction, energy balance conditions at limiting dry and wet conditions is considered. For dry limit, latent heat is zero since soil moisture is almost zero and sensible heat flux is maximum. Hence for dry limit, equation becomes:

$$\lambda E_{dry} = R_n - G_0 - H_{dry} = 0, \text{ or}$$
$$H_{dry} = R_n - G_0 \quad (4.1.4)$$

For wet limit, sensible heat flux becomes minimum and equation becomes:

$$\lambda E_{wet} = R_n - G_0 - H_{wet}, \text{ or}$$
$$H_{wet} = R_n - G_0 - \lambda E_{wet} \quad (4.1.5)$$

  - Now relative evaporation is given by the formula:

$$\Lambda_r = \frac{\lambda E}{\lambda E_{wet}} = 1 - \frac{\lambda E_{wet} - \lambda E}{\lambda E_{wet}} \quad (4.1.6)$$

Placing equations (4.1.1) and (4.1.5) in above equation,

$$\Lambda_r = 1 - \frac{R_n - G_0 - H_{wet} - R_n + G_0 + H}{R_n - G_0 - H_{wet}}$$

$$= 1 - \frac{H - H_{wet}}{H_{dry} - H_{wet}} \quad (4.1.7)$$

Where,

$H_{dry} = R_n - G_0$, and

$$H_{wet} = \left\{ \frac{(Rn - G0) - \left(\frac{\rho C_p}{r_{ew}} \cdot \frac{e_s - e}{\gamma}\right)}{1 + \frac{\Delta}{\gamma}} \right\}$$

Above equation is derived by using equation (4.1.5) and Penman-Monteith equation where 'ρ' is density of air, 'e_s' is saturated vapor pressure and 'e' is actual vapor pressure, 'C_p' is specific heat of moist air, 'Δ' is rate of change of saturation vapor pressure with temperature, 'γ' is psychrometric constant and 'r_{ew}' is aerodynamic resistance which is given by:

$$r_{ew} = \frac{1}{ku_*}\left\{ ln\left(\frac{z - d_0}{z_{0h}}\right) - \Psi_h\left(\frac{z - d_0}{L_w}\right) + \Psi_h\left(\frac{z_{0h}}{L_w}\right)\right\}$$

$$L_w = -\frac{\rho u_*^3}{kg \cdot 0.61 \cdot (R_n - G_0)/\lambda}$$

Where,

$u_* = (\tau_0/\rho)^{1/2}$ is the friction velocity with τ_0 is the surfaceshear stress

k = 0.4 which is von Karman's constant,

z_0 = Scalar roughness height for heat transfer,

z = Height above surface

d_0 = Zero plane displacement,

Ψ_h = Stability correction functions for sensible heat transfer,

L_w = Obukhov length

γ = Psychrometric constant

$= \frac{C_p \cdot P}{m_w \cdot \lambda} \times 10^3$, where P is atmospheric pressure, m_w is ratio of molecular weight of water vapor to dry air which is equal to 0.622, λ is latent heat of vaporization MJ/kg

- The evaporative fraction is given as:

$$\Lambda = \frac{\lambda E}{R_n - G} = \frac{\Lambda_r \cdot \lambda E_{wet}}{R_n - G} \quad (4.1.8)$$

From this, sensible heat flux and latent het flux are given as:

$$\lambda E = \Lambda \cdot (R_n - G), \text{ and} \quad (4.1.9)$$

$$H = (1 - \Lambda) \cdot (R_n - G) \quad (4.1.10)$$

4.2 Preparing Water Level Data in the GRACE format for Downscaling

GRACE satellite data uses microwave K-band to measure minute change in terrestrial water storage. Data obtained is in the form of anomaly. Also, GRACE image contains certain error which is removed by multiplying each image with a scale factor image. Now to downscale this data from 1° to 0.25° spatial resolution, two methods has been applied to GRACE data by deriving statistical relationship between GRACE ΔTWS image and (1) CGWB ground water level data, and (2) hydrological model outputs since change in ground water storage obtained from hydrological model outputs is directly related to ΔTWS (Kuss *et al*., 2011).

4.2.1 Downscaling GRACE ΔTWS using CGWB's ground water level data (Method 1)

Input data used for this purpose was ground water level data available online from Central Ground Water Board's website. Steps involved were:

1. Data available on the site consists of water level for a particular state under which data is available at different point location lying within a particular district. Within Ganga basin, around 130 district's data is available. Hence these datasets were exported in excel sheets for year 2007, 2008 and 2009.
2. After exporting it, since required downscale resolution is 0.25°; point locations lying within the district were averaged for four months viz. January, May, August and November which are represented as winter/cold season month, pre-monsoon/summer/hot season month, south-west monsoon/summer monsoon month and post-monsoon/north-east monsoon/retreating south-west monsoon month respectively, by Central Ground Water Board.
3. All these values were brought to one common worksheet from which seasonal difference was calculated at all the location. Data available is in centimeter units.
4. After calculating the seasonal difference, anomalies were generated from those as value minus average till last month.
5. Now this data is ready to use as an input for downscaling GRACE data.

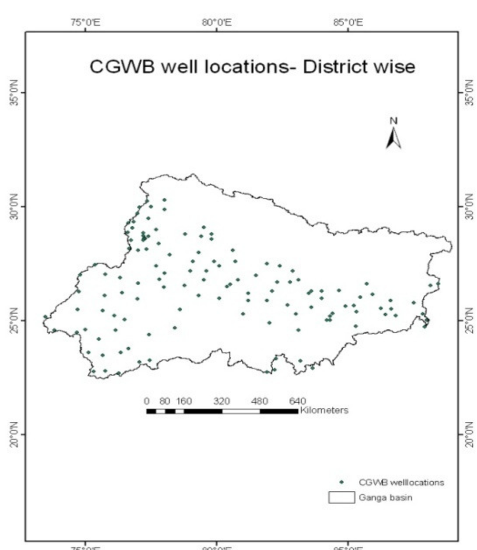


Figure 4.2: Central Ground Water Board's groundwater level measuring stations (district wise)

(Source: http://gis2.nic.in/cgwb/Gemsdata.aspx)

The technique used for downscaling involves deriving statistical relationship between interpolated images of GRACE and CGWB's water level data. For this, point data of water level anomaly were interpolated using point based interpolation technique with the help of Geomatica image processing software at 0.25° spatial resolution using 12 neighboring points. Same procedure was followed in case of GRACE imagery. GRACE raster image for months January, May, August and November were first converted into point data and then was interpolated using same point based interpolation technique with cell size of 0.25° spatial resolution and 12 surrounding points. After this, both GRACE and CGWB's water level data were exported to excel with the help of programming. Corresponding months of these two were brought in same worksheet.

GRACE and CGWB's pixel values were then compared for January month and a linear equation with 'x' equal to CGWB's interpolated values and 'y' equal to GRACE interpolated values, was developed with the help of scatter plot deriving the relationship between these two corresponding pixels columns. Similarly, equations were derived for May, August and November. Now with the help of programming, an empty image was created in which all the pixels contain zero value. In this image, equations derived earlier were applied with the help of codes developed in Python which will assign these pixels, certain value to obtain downscaled image of GRACE. In this linear equation, 'x' term was taken as CGWB ground water level interpolated image.

4.2.2 Downscaling GRACE ΔTWS using hydrological model derived change in ground water storage data (Method 2)

For this purpose, input data used has been taken from modified water balance derived change in ground water storage as explained in section 5.3. Here, 'x' term in linear statistical equation has been taken as hydrological model derived annual change in ground water storage and 'y' as annual GRACE ΔTWS for that particular year and obtained equation has been applied to GRACE ΔTWS image by taking hydrological model derived change in ground water storage as 'y' term.

4.3 Preparation of inputs for VIC Model setup and Simulation

VIC model uses a variety of spatial or attribute inputs which take part during simulation and calibration of results. These inputs are summarized below depending on various raster/vector or attribute inputs.

4.3.1 Grid preparation over basin extent

Grid/Fishnet was generated lying over the area with the geographical extent of basin corresponding to the central latitude and longitude of each grid with spatial resolution of 25×25 km in ArcGIS. Grid can also be generated in Quantum GIS software which is open source software. Grid prepared, contains 42 rows and 62 columns, starting from the upper left corner and going right-downward direction and numbering for each grid cell was accordingly. Total numbers of grids formed were 2729 out of which run grids were 1387. Shapefile of grid map contain following attributes which are required to run VIC model:

Table 4.1: Grid file description

Attribute name	Description
Latitude	Contains central latitude in degrees of each grid cell
Longitude	Contains central longitude in degrees of each grid cell
Grid number	Contains grid number starting from top left corner and going in right-downward direction further
Run grid	Either equal to 1 or 0, if the grid lies inside or 40% within the basin boundary then value is 1 otherwise 0
Soil_1	Soil index code of 1st soil depth layer
Soil_2	Soil index code of 2nd soil depth layer
Slope	Mean slope gradient in m/m
Elevation	Mean elevation of each grid in meter
rain	Mean annual rainfall of each grid in millimeters

To prepare these grid attributes, following data was used:

4.3.1.a. Digital Elevation Model

The most common method of acquiring elevation data is to digitize contour maps from scanned topological sheets and then create raster using interpolation technique. But occurrence of hard and soft-break lines limits this approach. Hence, by using remote sensing technique, digital elevation model can be generated. For this study, filled GTOPO arc 30 DEM was used which is at 1km resolution. From this raster map, elevation and slope gradient in m/m was used in the grid attribute.

4.3.1.b. Soil

For basin area lying in India, soil layer prepared by NBSSLUP was used and for area lying in Nepal, soil map prepared by FAO was used. Recoding was required to be done for soil codes followed by NBSSLUP and FAO. Each grid cell was assigned with the soil texture ID.

4.3.1.c. Rainfall

For the year 2004 and 2005, mean annual rainfall map was generated by using data from Indian Meteorological Department's gridded rainfall data and its values were assorted to each grid. For year 2008, precipitation data has been used which is a product of NCEP/NCAR reanalysis, disaggregated in space to 1.0 degree by statistical downscaling using relationships developed with the Global Precipitation Climatology Project (GPCP) daily product.

4.3.2. Soil database

A significant amount of precipitation reaching the ground surface is usually absorbed by the surface layers of the soil which demands appropriate description of soil water holding capacity and transmission characteristics of the soil profile (Saxton et al. 2006). VIC model is sensitive to soil property and main 6 parameters which can be calibrated are:

- W_s = Fraction of maximum soil moisture of the third layer where non-linear baseflow occurs
  = (subgrid field capacity)/ (subgrid saturated soil moisture)
- D_m = Maximum baseflow that occur from the third soil layer
  = K_{sat} × slope of grid cell
- D_s = Fraction of Dm where non-linear baseflow occurs
- b = Defines shape of the variable soil moisture capacity curve (depends on soil depth)
- d_1 = Soil depth of 1st layer
- d_2 = Soil depth of 2nd layer

Soil parameter file describes the characteristics of each soil layer for each grid cell which also include grid cell information. The soil parameter file contains following grid information.

Table 4.2: Soil parameter file description

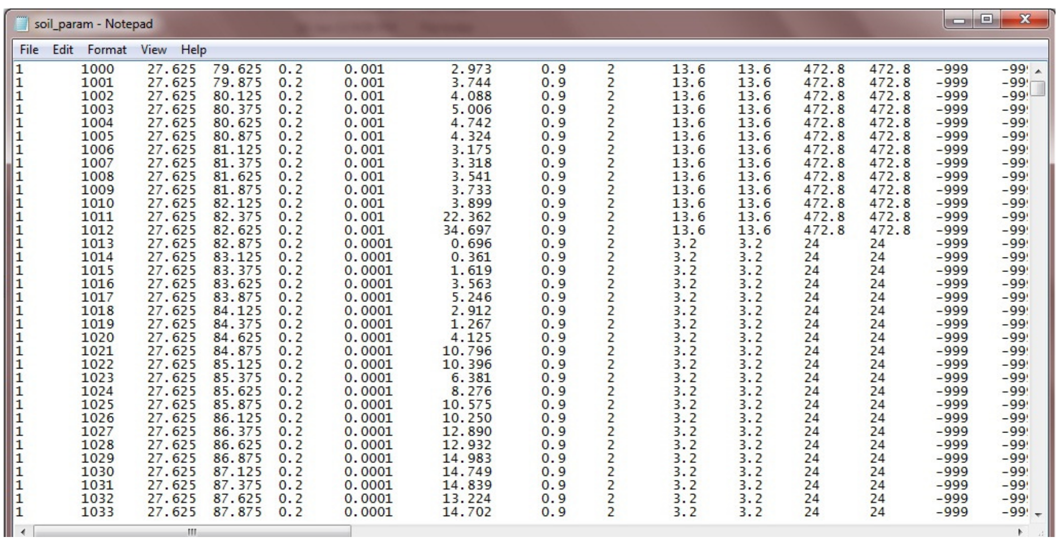
Sr. no.	Parameter name	unit	Description	Calibrated
1	RUN	n/a	Equal to 1 for run grid and equal to 0 for non-run grid	n/a
2	Grid_num	n/a	Grid cell number	n/a
3	latitude	degree	Grid centre latitude	n/a
4	longitude	degree	Grid center longitude	n/a
5	b_{infilt}	n/a	Variable Infiltration curve parameter.	Ranges from 10^{-5} to 0.4, more the value more will be runoff and lesser infiltration
6	D_s	fraction	Fraction of D_{smax} where non-linear baseflow occurs	Ranges from 0.001 to 1 but kept less than 1. Higher the value, higher the baseflow at lower water content in the lowest soil layer.
7	D_{smax}	mm/day	Maximum velocity of baseflow	Calculated = K_{sat} × slope of grid cell

8	W_s	fraction	Fraction of maximum soil moisture where non-linear baseflow occurs	Ranges from 0 to 1 but usually kept initial value as 0.9. Higher the value, higher will be the water content required for rapidly increasing, no-linear baseflow which will tend to delay runoff peak.
9	c	n/a	Exponent used in baseflow curve	Usually set to 2
10	expt	n/a	Parameter describing the variation of K_{sat} with soil moisture	Calculated and its value should be greater than 3. = 3 + 2b
11	K_{sat}	mm/day	Saturated hydraulic conductivity	n/a
12	Phi_s	mm	Initial layer moisture content	Currently this parameter is not implemented and its value is set to -999
13	Initial-moisture	mm	Initial soil moisture of layer	Calculated = 0.7 × field capacity × depth in mm
14	elevation	m	Average elevation of grid cell	n/a
15	depth	m	Thickness of each soil moisture layer	Assumed. n/a
16	Bulk density	kg/m^3	Bulk density of soil layer	n/a
17	Soil density	kg/m^3	Soil particle density	Normally 2685 kg/m^3
18	Off_gmt	hour	Time zone offset from GMT	n/a
19	W_{cr}_frac	fraction	Fractional soil moisture content at critical point (~70% of field capacity)	Calculated =(0.7× field capacity× depth in m)/(porosity × depth in m)
20	W_{pwp}_frac	fraction	Fractional soil moisture at wilting point	Calculated = (wilting point × depth in m)/(porosity × depth in m)
21	rough	m	Surface roughness of bare soil	Initial value kept as 0.001

22	Annual_prec	mm	Average annual precipitation of each grid cell	n/a
23	Resid_moist	fraction	Soil moisture layer moisture	Calculated. When it is 0 mm/mm then soil hydraulic conductivity relationship collapses to Campbell (1974) otherwise it follows Brooks and Corey (1964) equation
24	Fs_active	n/a	Defines frozen soil algorithm activated or not	Equal to 1 for activated and 0 for dis-activated

(Source: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/SoilParam.shtml) And Gao *et al*., 2009

Soil parameter file prepared is as below:



soil_param - Notepad

File Edit Format View Help

1	1000	27.625	79.625	0.2	0.001	2.973	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1001	27.625	79.875	0.2	0.001	3.744	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1002	27.625	80.125	0.2	0.001	4.088	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1003	27.625	80.375	0.2	0.001	5.006	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1004	27.625	80.625	0.2	0.001	4.742	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1005	27.625	80.875	0.2	0.001	4.324	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1006	27.625	81.125	0.2	0.001	3.175	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1007	27.625	81.375	0.2	0.001	3.318	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1008	27.625	81.625	0.2	0.001	3.541	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1009	27.625	81.875	0.2	0.001	3.733	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1010	27.625	82.125	0.2	0.001	3.899	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1011	27.625	82.375	0.2	0.001	22.362	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1012	27.625	82.625	0.2	0.001	34.697	0.9	2	13.6	13.6	472.8	472.8	-999	-99
1	1013	27.625	82.875	0.2	0.0001	0.696	0.9	2	3.2	3.2	24	24	-999	-99
1	1014	27.625	83.125	0.2	0.0001	0.361	0.9	2	3.2	3.2	24	24	-999	-99
1	1015	27.625	83.375	0.2	0.0001	1.619	0.9	2	3.2	3.2	24	24	-999	-99
1	1016	27.625	83.625	0.2	0.0001	3.563	0.9	2	3.2	3.2	24	24	-999	-99
1	1017	27.625	83.875	0.2	0.0001	5.246	0.9	2	3.2	3.2	24	24	-999	-99
1	1018	27.625	84.125	0.2	0.0001	2.912	0.9	2	3.2	3.2	24	24	-999	-99
1	1019	27.625	84.375	0.2	0.0001	1.267	0.9	2	3.2	3.2	24	24	-999	-99
1	1020	27.625	84.625	0.2	0.0001	4.125	0.9	2	3.2	3.2	24	24	-999	-99
1	1021	27.625	84.875	0.2	0.0001	10.796	0.9	2	3.2	3.2	24	24	-999	-99
1	1022	27.625	85.125	0.2	0.0001	10.396	0.9	2	3.2	3.2	24	24	-999	-99
1	1023	27.625	85.375	0.2	0.0001	6.381	0.9	2	3.2	3.2	24	24	-999	-99
1	1024	27.625	85.625	0.2	0.0001	8.276	0.9	2	3.2	3.2	24	24	-999	-99
1	1025	27.625	85.875	0.2	0.0001	10.575	0.9	2	3.2	3.2	24	24	-999	-99
1	1026	27.625	86.125	0.2	0.0001	10.250	0.9	2	3.2	3.2	24	24	-999	-99
1	1027	27.625	86.375	0.2	0.0001	12.890	0.9	2	3.2	3.2	24	24	-999	-99
1	1028	27.625	86.625	0.2	0.0001	12.932	0.9	2	3.2	3.2	24	24	-999	-99
1	1029	27.625	86.875	0.2	0.0001	14.983	0.9	2	3.2	3.2	24	24	-999	-99
1	1030	27.625	87.125	0.2	0.0001	14.749	0.9	2	3.2	3.2	24	24	-999	-99
1	1031	27.625	87.375	0.2	0.0001	14.839	0.9	2	3.2	3.2	24	24	-999	-99
1	1032	27.625	87.625	0.2	0.0001	13.224	0.9	2	3.2	3.2	24	24	-999	-99
1	1033	27.625	87.875	0.2	0.0001	14.702	0.9	2	3.2	3.2	24	24	-999	-99

Figure 4.3: Soil parameter file

4.3.3 Vegetation parameter file database

Vegetation parameter file mainly depends on Land Use/Land Cover. Land use describes the way and purpose for which human beings employ the land and its resources, while land cover describes the physical state of the land surface. The amount of precipitation actually reaching the ground surface is largely dependent upon the nature and density of the vegetation cover and land use/land cover practices. Hydrologic fluxes mainly depend on LAI property of LULC. However, VIC model assumes that LAI value do not change from year to year and is same for particular class type throughout and hence inter-annual variations of vegetation characteristics are ignored. Other parameters include roughness length, rooting depth, displacement height, architectural resistance and minimum stomatal resistance.

For basin region in India, LULC map used was prepared by ISRO-GBP under project entitled "Landuse/ Landcover Dynamics and Impact of Human Dimension in Indian River Basins" and for region in Nepal, LULC was taken from University of Maryland prepared by using AVHRR imagery which contains 14 classes of water, bare ground, closed shrubland, cropland, deciduous broadleaf forest, deciduous needleleaf, evergreen broadleaf forest, evergreen needleleaf forest, grassland, mixed forest, open shrubland, urban and built-up, wooded grassland and woodleaf. However, since vegetation library file, taken from GLDAS, was prepared using AVHRR LULC, ISRO-GBP LULC was recoded according to it. Vegetation library file contains following land cover property on monthly average basis.

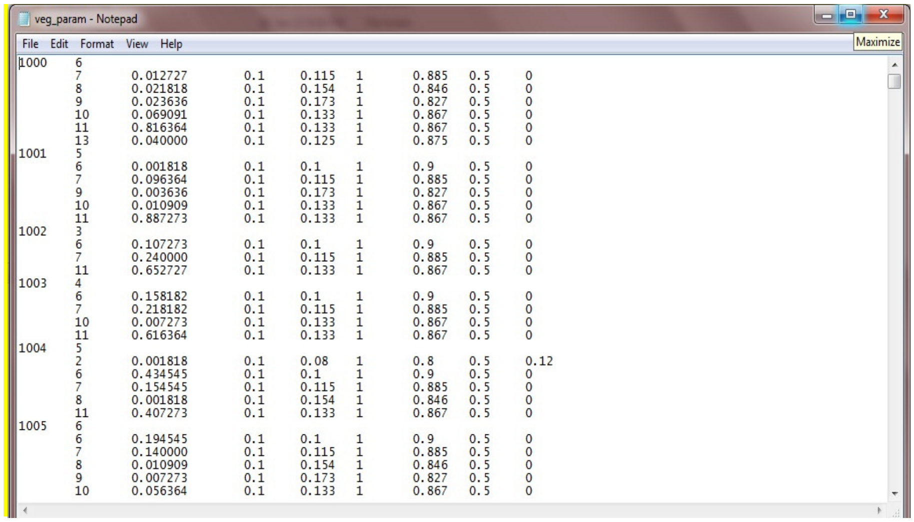
Table 4.3: Vegetation library file description

Variable Name	**Units**	**Description**
veg_class	n/a	Vegetation class value number
overstory	n/a	It value is 1 for overstory present [*e.g.* trees], 0 for overstory not present [*e.g.* grass]).
rarc	s/m	Architectural resistance of vegetation type (~2 s/m)
r_{min}	s/m	Minimum stomatal resistance of vegetation type (~100 s/m)
LAI		Leaf-area index of vegetation type. It has different value for each month.
albedo	fraction	Shortwave albedo for vegetation type. It has different value for each month.
rough	m	Vegetation roughness length (typically 0.123 * vegetation height) for each month
displacement	m	Vegetation displacement height (typically 0.67 * vegetation height) for each month
wind_h	m	Height at which wind speed is measured.

Variable Name	Units	Description
RGL	W/m^2	Minimum incoming shortwave radiation at which there will be transpiration. For trees this is about 30 W/m^2, for crops about 100 W/m^2
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. The default value has been 0.5.
trunk_ratio	fract	Ratio of total tree height that is trunk (no branches). The default value has been 0.2.
comment	N/A	Here, LULC class names are commented

(Source: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/VegParam.shtml)

LAI vegetation parameter was prepared by GLDAS by using UMD vegetation classification scheme and other classification including IGBP, NCAR, etc. These mapped parameters are averaged to form a generic parameter value. (Source of LAI: http://ldas.gsfc.nasa.gov/nldas/NLDASmapveg.php)
Also to prepare vegetation parameter file, vegetation database file which include rooting depth and rooting fraction of each LULC class type is required. Using this file, vegetation library, LULC of same class with same value number and grid Shapefile, vegetation parameter file is prepared which contains run grid number, class value falling in that grid, fraction of grid cell covered by each class in that grid, rooting depth (root zone thickness) and rooting fraction (fraction of root in the current root zone).




```
1000	6
	7	0.012727	0.1	0.115	1	0.885	0.5	0
	8	0.021818	0.1	0.154	1	0.846	0.5	0
	9	0.023636	0.1	0.173	1	0.827	0.5	0
	10	0.069091	0.1	0.133	1	0.867	0.5	0
	11	0.816364	0.1	0.133	1	0.867	0.5	0
	13	0.040000	0.1	0.125	1	0.875	0.5	0
1001	5
	6	0.001818	0.1	0.1	1	0.9	0.5	0
	7	0.096364	0.1	0.115	1	0.885	0.5	0
	9	0.003636	0.1	0.173	1	0.827	0.5	0
	10	0.010909	0.1	0.133	1	0.867	0.5	0
	11	0.887273	0.1	0.133	1	0.867	0.5	0
1002	3
	6	0.107273	0.1	0.1	1	0.9	0.5	0
	7	0.240000	0.1	0.115	1	0.885	0.5	0
	11	0.652727	0.1	0.133	1	0.867	0.5	0
1003	4
	6	0.158182	0.1	0.1	1	0.9	0.5	0
	7	0.218182	0.1	0.115	1	0.885	0.5	0
	10	0.007273	0.1	0.133	1	0.867	0.5	0
	11	0.616364	0.1	0.133	1	0.867	0.5	0
1004	5
	2	0.001818	0.1	0.08	1	0.8	0.5	0.12
	6	0.434545	0.1	0.1	1	0.9	0.5	0
	7	0.154545	0.1	0.115	1	0.885	0.5	0
	8	0.001818	0.1	0.154	1	0.846	0.5	0
	11	0.407273	0.1	0.133	1	0.867	0.5	0
1005	6
	6	0.194545	0.1	0.1	1	0.9	0.5	0
	7	0.140000	0.1	0.115	1	0.885	0.5	0
	8	0.010909	0.1	0.154	1	0.846	0.5	0
	9	0.007273	0.1	0.173	1	0.827	0.5	0
	10	0.056364	0.1	0.133	1	0.867	0.5	0
```

Figure 4.4: Vegetation parameter file

4.3.4 Meteorological forcing file

Meteorological data plays important role in model to produce all the outputs in both water balance and full energy balance mode. High accuracy forcing data is required as it is the variable which affects runoff and deriving hydrological cycle. Precipitation plays an important role as it is the main input of water to earth. Satellite data gives more accurate results with more spatial coverage in case of sparsely located weather stations and hilly terrain where rainfall depends on orography. Many meteorological parameters are required to simulate VIC model like maximum temperature, minimum temperature, precipitation, wind speed, atmospheric pressure and humidity, relative humidity, incoming shortwave and longwave radiation. However, many of these variables are derived by model itself depending on other parameters. So essential parameters required are maximum and minimum air temperature in °C and precipitation in mm either on daily or sub-daily basis.

For year 2004 and 2005, meteorological forcing was prepared by using IMD’s gridded precipitation data available at 0.5° spatial resolution and temperature data at 1° spatial resolution for basin area lying in India. For region lying in Nepal, forcing data was taken from National Climate data center which is available at 1° spatial resolution. These forcing files were prepared by taking z-profile of tmax, tmin and precipitation for each pixel and placing those values in American Standard Code for Information Interchange (ASCII) file with name “data_y_x” where y is the latitude and x is the longitude of that pixel location.

For year 2008, input data for preparing forcing file was taken from National Climate data center where data contained 366 bands, each band representing a day in Julian calendar. Here, files where prepared with the help of programming codes developed in Python. Different codes were developed for each step of generating forcing file. Steps involved are:

1. Extracting basin area from daily global raster map of tmax, tmin and precipitation,
2. Extracting all the bands of each image into separate raster map,
3. Snapping all these images according to the grid Shapefile,
4. Rescaling the outputs of above step to 0.25° spatial resolution
5. Extracting tmax, tmin and precipitation values of defined latitude and longitude by following a loop and placing those values in excel sheets giving name to those sheets as per required by the model,
6. Converting these sheets in the ASCII format which is accepted by the model.

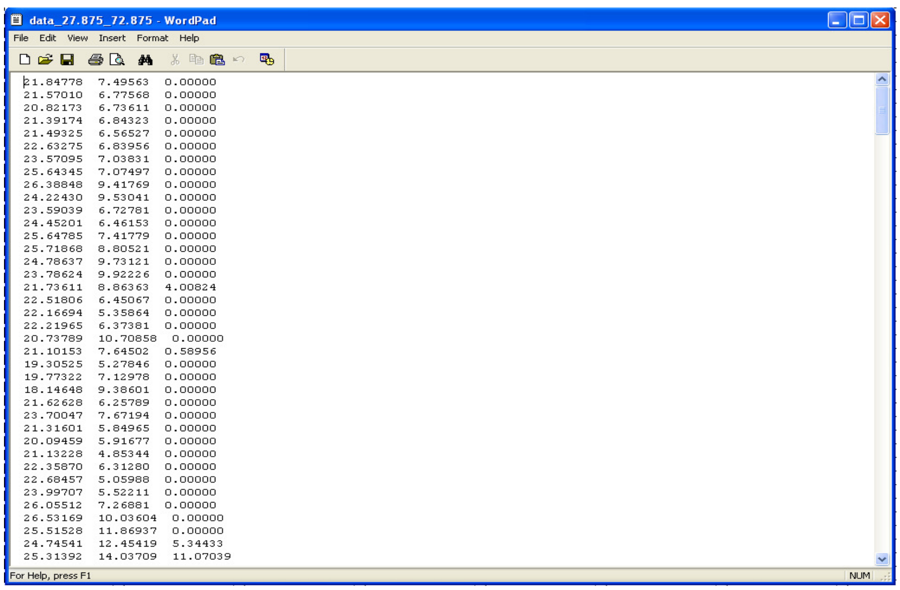


Figure 4.5: Meteorological forcing file

4.3.5 VIC model simulation and equations used to derive model outputs:

After the preparation of these inputs for simulation, model code setup was installed from VIC website. In CYGWIN, using MAKE command, model is installed. After installation, following steps are followed to run the model: (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/SourceCode/Download.shtml).

1. *cd (path where VIC source file is prepared)*

   This will take you to the workspace where model is installed and contains all the files required to obtain required outputs.
2. *./vicNL –g (path where global parameter file is saved)*

Global parameter file contains path of all the above obtained parameter files viz. soil parameter file, vegetation parameter file, vegetation library, forcing file and also the path where output will be stored.

3. Pressing *enter* will run the model. While it's run, it may give stop where soil property is not given properly. In that case, that soil parameter needs some correction.

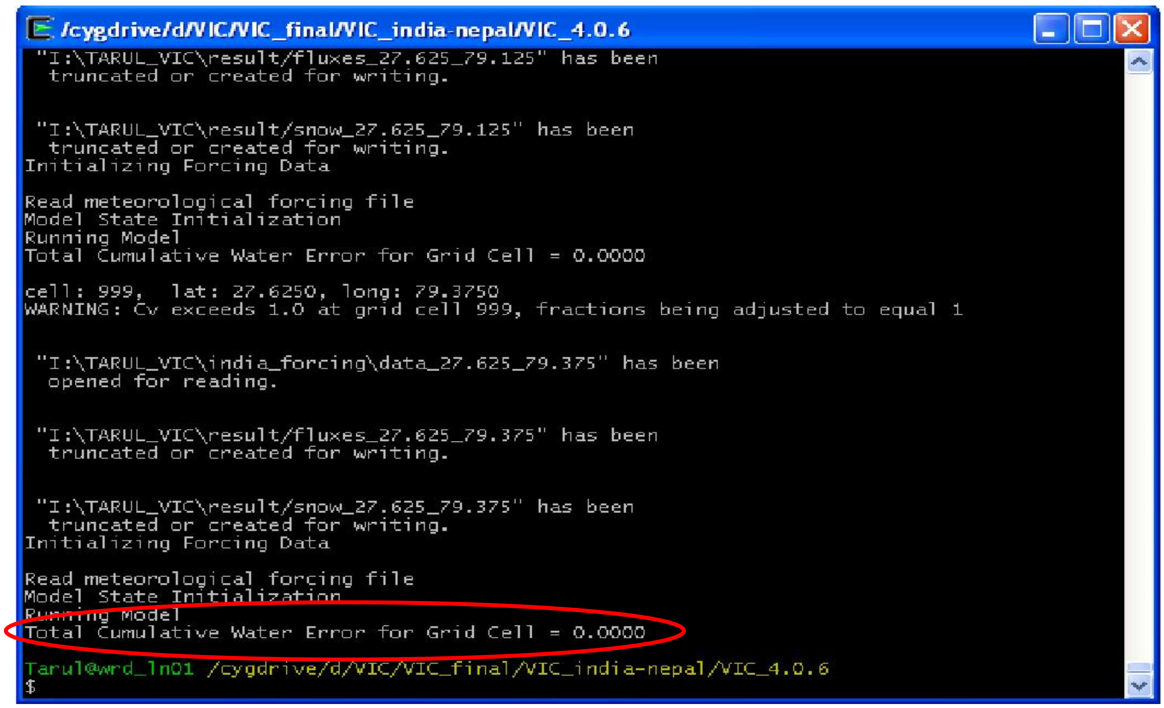


Figure 4.6: VIC run (screenshot)

The above figure shows that the entire components derived using model is successfully closing the water balance with zero error for each grid cell.

During run of model, following equations are followed:
(Source: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Overview/ModelOverview.shtml)

- Water balance derived from the model uses following equation (Gao et al., 2009):

$$\frac{\partial S}{\partial t} = P - E - R \qquad (4.3.1)$$

Where,

dS/dt = Change in water storage in mm,

P = Precipitation in mm,

E = Evapotranspiration in mm and
R = Runoff in mm

Over canopy interception, VIC model follows different equation which states that:

$$\frac{\partial W_i}{\partial t} = P - E_c - P_t \tag{4.3.2}$$

Where,

W_i = Canopy intercepted water in mm,
P = Precipitation in mm,
E_c = Evaporation from canopy in mm and
P_t = Throughfall in mm

- VIC model considers three types of evaporation: evaporation from bare soil, evaporation from canopy cover and evaporation through transpiration (Liang *et al*., 1996). Total evaporation over a grid cell is computed as the sum of these components, weighted by the respective surface cover area fractions. The formulation of the total evapotranspiration is (Gao *et al*., 2009):

$$E = \sum_{n=1}^{N} C_n \cdot (E_{c,n} + E_{t,n}) + C_{N+1} \cdot E_1 \tag{4.3.3}$$

Where,

C_n = Vegetation fractional coverage for the n^{th} vegetation tile,
C_{N+1}=Bare soil fraction, and $\sum_{n=1}^{N+1} C_n = 1$,
E_c = Evaporation through canopy in mm,
E_1 = Evaporation from bare soil,
E_t = Evaporation through transpiration in mm

1. When continuous rainfall rate is higher than canopy evaporation, evaporation from canopy depends on maximum amount of water intercepted by canopy in mm, Leaf Area Index, architectural resistance which depends on humidity gradient between canopy and overlying air, aerodynamic resistance which depends on wind speed at defined height and water transfer coefficient, potential evapotranspiration (mm) derived from Penman-Monteith equation. However, when rainfall is lower than canopy evaporation then the intercepted water is not sufficient for meeting the atmospheric demand within one time step. In this case, canopy evaporation calculation value derived from above equation is

multiplied with a term which is fraction of time step for canopy evaporation to exhaust the intercepted water. When continuous rainfall rate is higher than canopy evaporation, Evaporation from canopy is given by the formula:

$$E_c^* = (\frac{W_i}{W_{im}})^{2/3} E_p \frac{r_w}{r_w + r_o} \tag{4.3.4}$$

Where,

W_i = Canopy intercepted water in mm,

W_{im} = Maximum amount of water intercepted by canopy in mm, equal to 0.2 times LAI (Dickinson, 1984),

r_0 = Architectural resistance,

r_w = Aerodynamic resistance, and

E_p = Potential evapotranspiration measured with the help of Penman-Monteith equation (FAO, 1998).

2. Evaporation from bare soil occurs only on the top thin soil layer. When the top soil layer is not saturated, evaporation rate from bare soil (E_1) is calculated using the Arno formulation. ET in this case depends on point infiltration capacity derived from model using (Ren-Jun, 1992), potential evapotranspiration and fraction of bare soil that is saturated. It is given by:

$$E_1 = E_p \left(\int_0^{A_S} dA + \int_{A_S}^{1} \frac{i_0}{i_m (1-(1-A)^{1/b_i})} dA \right) \tag{4.3.5}$$

Where,

E_p = Potential evapotranspiration,

A = Fraction of area for which the infiltration capacity is less than infiltration capacity (i),

i_0 = Corresponding point infiltration capacity,

i_m = Maximum infiltration capacity in mm,

b_i = Infiltration shape parameter.

3. Evaporation through transpiration depends on canopy resistance, temperature, vapor pressure deficit, soil moisture, Photosynthetically Active Radiation flux (PAR) factor (Blondin, 1991; Ducoudre*et al*.,1993; Wigmosta*et al*.,1994).

$$E_t = (1-(\frac{W_i}{W_{im}})^{2/3}) E_p \frac{r_w}{r_w + r_o + r_c} \tag{4.3.6}$$

Where,

r_c = Canopy resistance.

- For runoff and soil moisture, VIC model uses variable infiltration curve to account for spatial heterogeneity. It assumes that runoff from upper two soil layers occurs when precipitation exceeds storage capacity of soil (Gao *et al*., 2009).

1. Total runoff obtained is the sum of direct runoff and baseflow.

$$Q = \sum_{n=1}^{N+1} C_n \cdot (Q_{d,n} + Q_{b,n}) \tag{4.3.7}$$

Where,

$Q_{d,n}$= Direct runoff for n^{th} land cover type which depends on precipitation, infiltration capacity, soil porosity(θ_s), and

$Q_{b,n}$ = Baseflow for n^{th} land cover type, derived using Arno's equation(Bao et al., 2011).

➢ Direct runoff being obtained by the formula:

$$Q_d = \begin{cases} P - z_2 \cdot (\theta_S - \theta_2) + z_2 \cdot \theta_S \cdot (1 - \frac{i_0 + P}{i_m})^{1+b_i}, & P + i_0 \le i_m \\ P - z_2 \cdot (\theta_S - \theta_2), & P + i_0 \ge i_m \end{cases} \tag{4.3.8}$$

Where,

P = Precipitation,

i_0, i_m, θ_s and b_i = Infiltration capacity associated terms used in deriving infiltration capacity

➢ Arno's equation used to derive baseflow is given by:

$$Q_b = \begin{cases} \frac{D_S D_m}{W_S \theta_S} \cdot \theta_3, & 0 \le \theta_3 \le W_S \theta_S \\ \frac{D_S D_m}{W_S \theta_S} \cdot \theta_3 + (D_m - \frac{D_S D_m}{W_S})(\frac{\theta_3 - W_S \theta_S}{\theta_S - W_S \theta_S})^2, & \theta_3 \ge W_S \theta_S \end{cases} \tag{4.3.9}$$

Where,

D_m = Maximum subsurface flow,

D_{smax} = Fraction of D_m,

W_s= Fraction of soil moisture

2. VIC model follows one-dimensional Richard's equation(Walker *et al*., 2001) since it assumes that there is no lateral flow in top soil layer. Equation is given by:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(D(\theta)\frac{\partial\theta}{\partial z}) + \frac{\partial K(\theta)}{\partial z} \qquad (4.3.10)$$

Where,

θ = Volumetric soil moisture content,

D(θ) = Soil water diffusivity in mm^2/day,

K(θ) = Hydraulic conductivity in mm/day,

z = Soil depth in m

4.3.6 Preparation of input files for routing:

(Source:www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/Routing/Routing Input.shtml)

After the simulation of VIC model in water balance mode, results obtained are in the form of daily basis contained in flux files for each central latitude-longitude of the grid. This daily output contains runoff and baseflow along with other outputs, produced for each grid cell. Routing model first transports this runoff and baseflow to the grid outlet and then to the river network. Also it assumes that flow can exit grid cell in eight possible directions i.e. north, north east, east, south east, south, south west, west and North West; and also this flow must exit in same direction. This flow is weighted according to the fraction of grid cell lying within the boundary. Hence, to run routing model, these flux files are required as inputs along with fraction file, unit hydrograph, flow direction file and station location file as necessary inputs.

- For preparation of fraction files, following steps were followed:
  1. Both basin boundary and grid Shapefile were converted into feature class,
  2. Selecting only run grids, grid Shapefile was exported to new feature class,
  3. Basin boundary and this new feature class were then intersected which will give area of each grid cell, then
  4. Dividing this area field with 0.0625 (area of square grid of 0.25º), will give fraction of cell lying within the basin boundary.

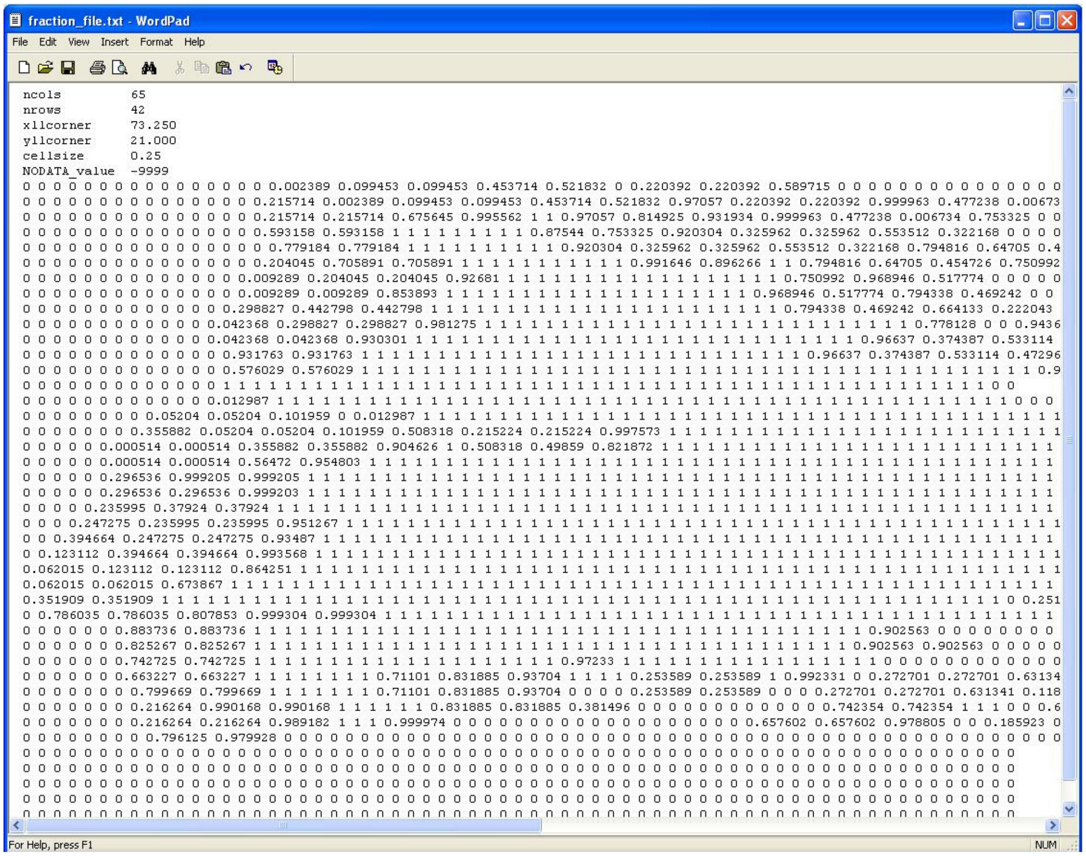


Figure 4.7: Fraction file

- For preparing unit hydrograph file, out of unit one, fraction of single values were given to each month depending on rainfall occurring during those months. This file represents the grid cell impulse response function whose sum over all the months will be equal to 1 (Source: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/Routing/UH.shtml).

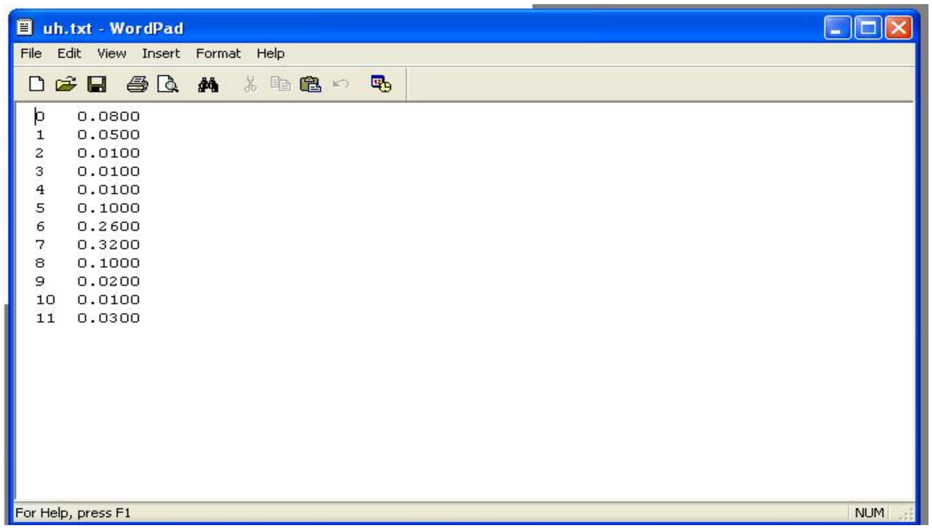


Figure 4.8: Unit Hydrograph file

- Preparing flow direction file requires DEM. Steps involved are:
  1. Correct DEM by using FILL operation in ArcHydro tool,
  2. Use FLOW DIRECTION operation in the same tool,
  3. This tool uses following number code of representing direction:
     1→ East
     2→ South-East
     4→ South
     8→ South-West
     16→ West
     32→ North-West
     64→ North
     128→ North-East

  However, VIC route source code requires numbering in following pattern:
     1→ North
     2→ North-East
     3→ East
     4→ South-East
     5→ South
     6→ South-West
     7→ West
     8→ North-West

  Hence, flow direction file was modified according to the above coding.

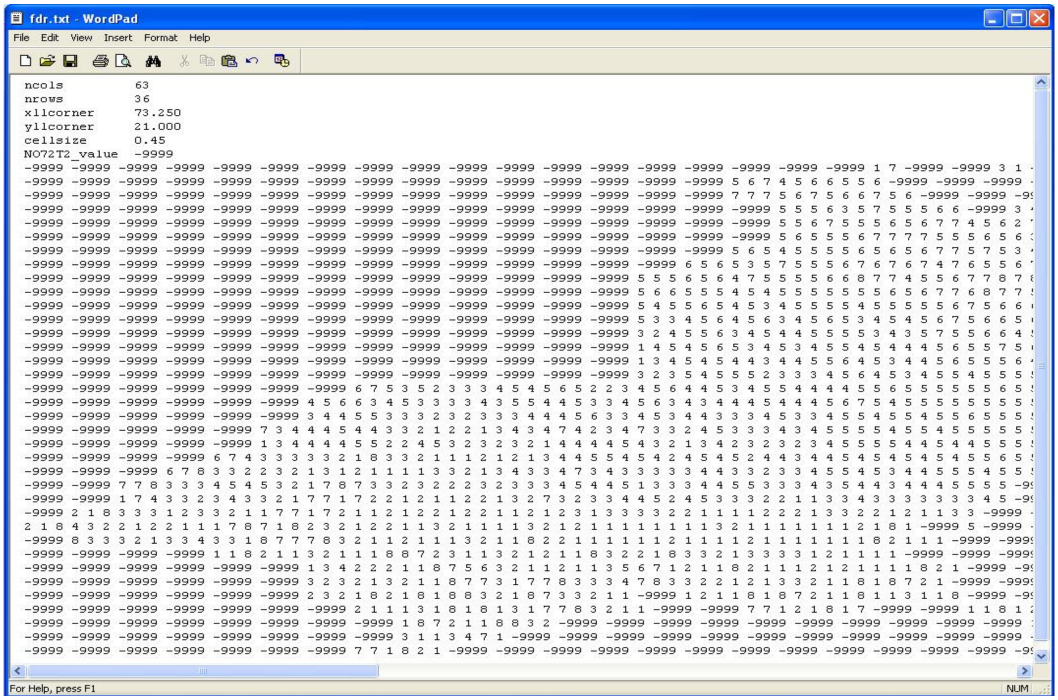


Figure 4.9: Flow direction file

- Routing model input also requires station location where it will produce output flow data. This file contains: (1) 1 for active and 0 for non-active station, (2) station name, (3) column number of location from left, (4) row number of the location from bottom, (5) basin area which has not been used at present, and (6) whether routing model should generate a new uh_s file in current directory (set to NONE) or read the defined uh_s file.

4.3.7 VIC Routing model simulation and equations used to derive model outputs:

After the preparation of these inputs for simulation, routing model code setup is installed from VIC website. VIC routing model requires LINUX for its simulation. In LINUX command window, using MAKE command, model is installed. After installation, following steps are followed to run the routing: (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/SourceCode/Download.shtml).

1. *./rout (path where input file is saved)*

   Input file contains path of all the above obtained files viz. fraction file, Unit Hydrograph file, station location file, flow direction file and output location where output runoff and discharge values in daily, monthly and yearly time step will be obtained in separate files.

2. Pressing *enter* will run the routing model. While its run, it may stop if there is any 'nan' value or if header from the flux files is not removed. So, before using flux files as input in routing, header is required to be removed and also there should not b any '*nan*' value.

During run of routing model, following equations are followed:

Routing model runs in two modes: first it considers that flow exits each grid and then the flow from each grid outlet meets the channel flow. Hence routing formulation is divided in two parts: (1) routing within grid cell and (2) river channel routing. Following equations are involved in these (Gao *et al*., 2009).

(1) Routing within grid cell:

Within grid cell, discharge is divided into two components: slow component and fast component. Hence to obtain them separately, first they are separated by using following equation:

$$\frac{dQ^S(t)}{dt} = -k \cdot Q^S(t) + b \cdot Q^F(t) \qquad (4.3.11)$$

Where,

$Q^S(t)$ = Slow flow,

$Q^F(t)$ = Fast flow, and

$Q(t)$ = Total flow

$= Q^S(t) + Q^F(t)$

In this equation, ratio of 'b' and 'k' is considered to be the ratio of water in slow flow and fast flow. These terms are assumed to be constant over the period of calculation. Hence, slow and fast components over a time step of Δt, are connected as:

$$Q^S(t) = \frac{\exp(-k \cdot \Delta t)}{1 + b \cdot \Delta t} Q^S(t - t) - \frac{b \cdot \Delta t}{1 + b \cdot \Delta t} Q(t) \qquad (4.3.12)$$

Fast component and effective precipitation (P^{eff}) are connected by considering an assumption that there exists a linear relationship between these two components. With the help of this assumption, unit hydrograph and P^{eff} can be calculated by using following equation iteratively:

$$Q^F(t) = \int_0^{t_{max}} UH^F(\tau) P^{eff}(t - \tau) d\tau \qquad (4.3.13)$$

Where,

$UH^F(\tau)$ = Unit hydrograph for fast flow component, and

t_{max} = Time taken for all fast processes to decay.

This equation is solved iteratively for *n* data points at time step of Δt and t_{max} as (m -1) ·Δt, starting with the measured precipitation. After each iterations, following constraint is applied by considering fixed fraction of water in fast and slow flow component:

$$\sum_{i=0}^{m-1} UH_i^F = \frac{1}{1+\frac{b}{k}} \text{ with } UH_i^F \geq 0 \; \forall i \tag{4.3.14}$$

This calculated UH^F is put in the above discrete function to solve P^{eff}. After each iteration, constraint ($0 \leq P_i^{eff} \leq$ Precipitation, ∀i) is applied and then P^{eff} calculated in each iteration is put back into discrete equation and deconvolutions are repeated every time till it reaches the convergence.

(2) River channel routing:

This routing follows linearized Saint-Venant equation which assumes that water can exit the grid only in the form of river flow. It is given by:

$$\frac{\partial Q}{\partial t} = D\frac{\partial^2 Q}{\partial x^2} - C\frac{\partial Q}{\partial x} \tag{4.3.15}$$

C and D are considered to be effective parameters taken from either measurement or from geographical data which govern the fact that there may be condition when there is more than one stream within the same grid cell. With this equation, each grid cell ends up with one C and one D value which characterize water transported within the grid cell.

The above Saint-Venant equation is solved with convolution integrals as:

$$Q(x,t) = \int_0^t U(t-s)h(x,s)ds \tag{4.3.16}$$

Where,

$$h(x,t) = \frac{x}{2t\sqrt{\pi t D}}\exp\left(-\frac{(Ct-x)^2}{4Dt}\right)$$

Which is the unit hydrograph function of Saint-Venant equation with h(x,0) = 0 for x>0 and h(0,t) = δ(t) for t ≥ 0.

CHAPTER 5

RESULTS AND DISCUSSIONS

Water balance has been first closed by using satellite data. Precipitation, ET and ΔTWS were taken annually which were either satellite or derived product. For this, precipitation data has been used which is a product of NCEP/NCAR reanalysis, disaggregated in space to 1.0 degree by statistical downscaling using relationships developed with the Global Precipitation Climatology Project (GPCP) daily product. ET has been calculated using MODIS datasets along with other satellite datasets. ΔTWS has been taken from GRACE satellite. Since GRACE satellite gives equivalent water thickness at 1° spatial resolution, it has been first downscaled to 0.25° spatial resolution by using statistical downscaling technique using CGWB's groundwater level difference as input. Downscaling ΔTWS has also been done by using water balance derived change in ground water storage obtained by incorporating the water balance error in ET. of Results of satellite derived ET for year 2004 and 2008, downscaled ΔTWS for year 2008 and VIC model outputs for year 2004, 2005, 2006, 2007 and 2008 are given below.

5.1 Satellite derived ET

ET has been derived using SEBS tool in ILWIS for the year 2004 and 2008. Final output obtained was at 1 Km spatial resolution and 8 day temporal resolution. But since water balance has to be closed here by using spatial resolution of 0.25° with annual temporal resolution, 1km map was first upscaled using simple averaging technique (Ershadi *et al.*, 2013) and then were added to prepare monthly ET maps for year 2004 and 2008.

This ET when compared to MODIS 16A2 ET monthly product gave very good correlation (Figure 5.1). However because of certain un-realistic value of Emissivity and Albedo at certain locations, ET obtained at those places was not acceptable. And hence, ET in those areas was spatially replaced by that of MODIS ET product and for other regions ET was kept as calculated.

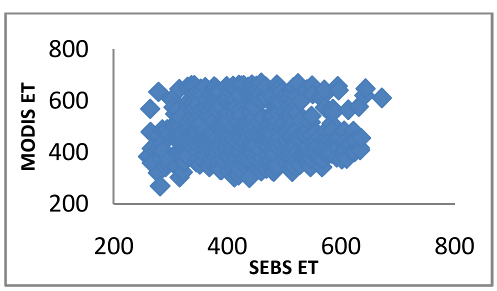


Figure 5.1: Correlation plot between MODIS and SEBS ET at 25Km resolution

Monthly ET maps for year 2004 and 2008 show that ET increased in May as compared to January because of high temperature in summer season. However, in August, high ET has been seen because of North-West monsoon rainfall over a large spatial extent. In November, ET reduces overall as compared to previous months.

Results show that average ET over whole basin was found to be 430.342 mm for year 2004 and 501.586 mm for year 2008.

Following images show upscaled ET for year 2004.

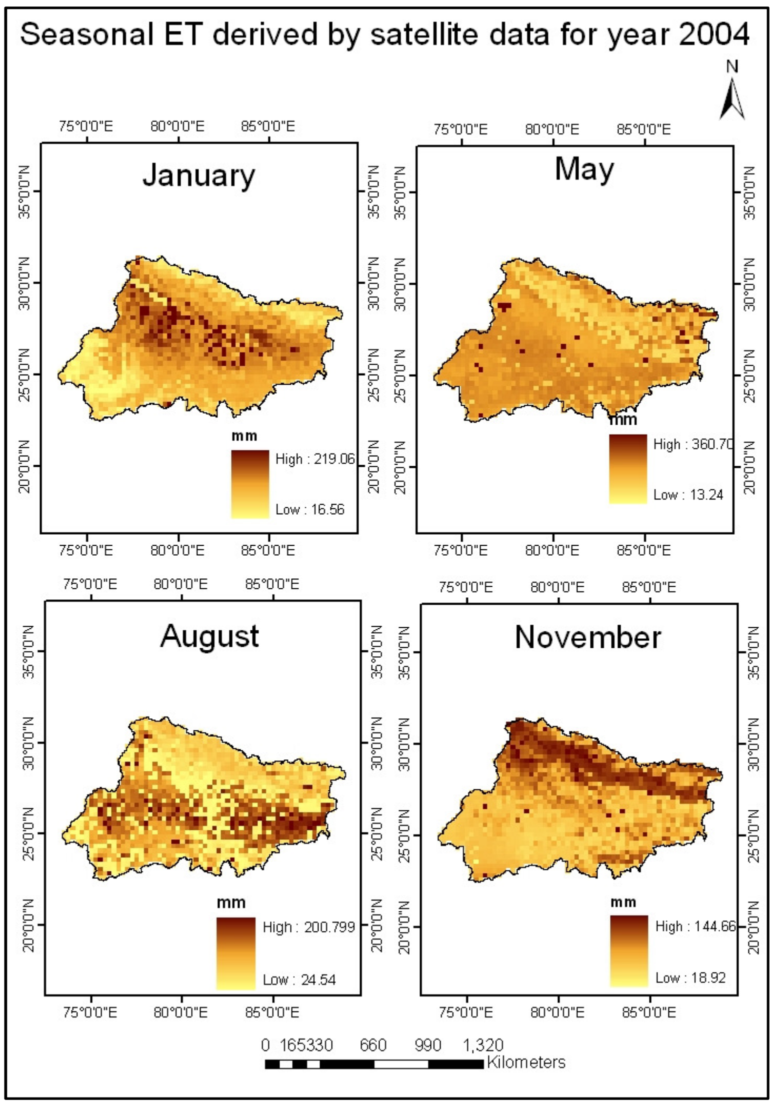


Figure 5.2: Seasonal satellite derived ET for year 2004

Following images show upscaled ET for year 2008.

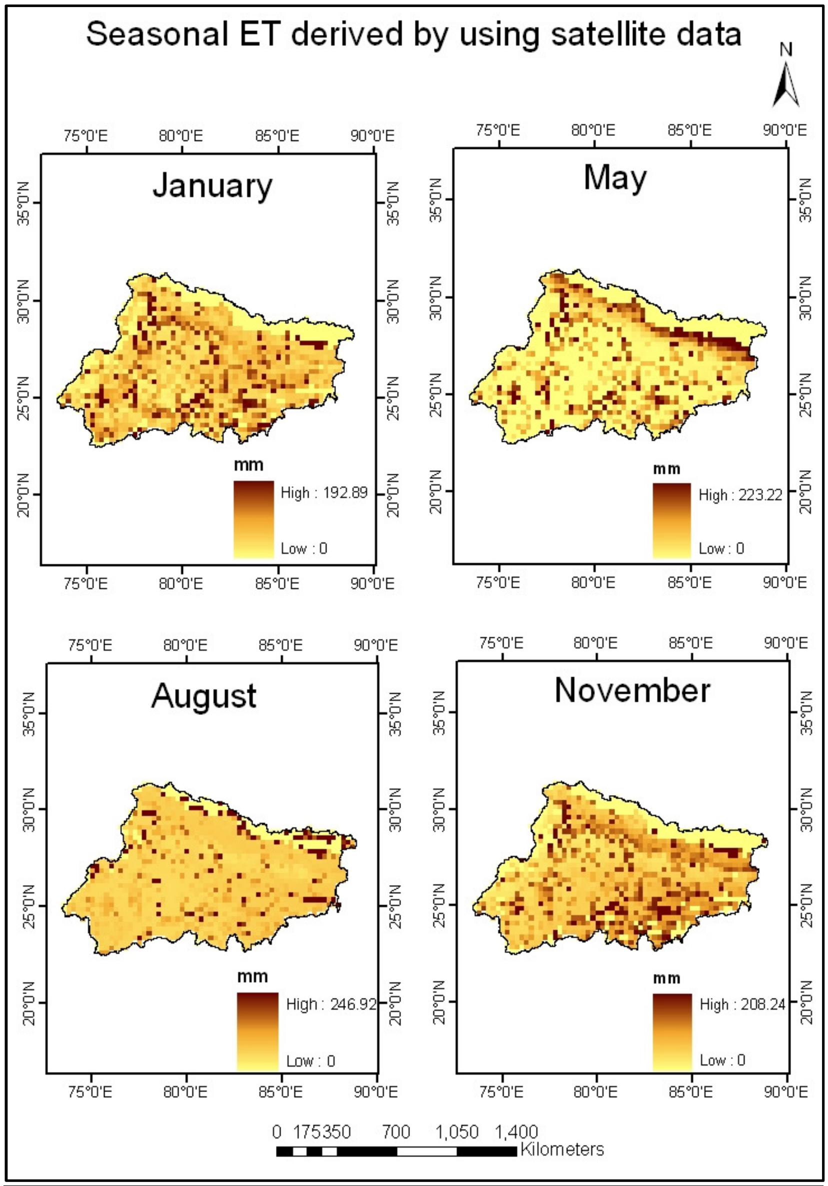


Figure 5.3: Seasonal satellite derived ET for year 2008

Following images show total ET in year 2004 and 2008 respectively.

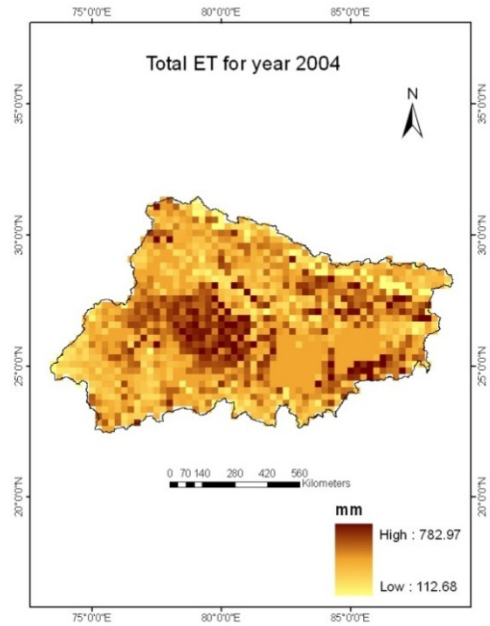


Figure 5.4: Total ET in 2004

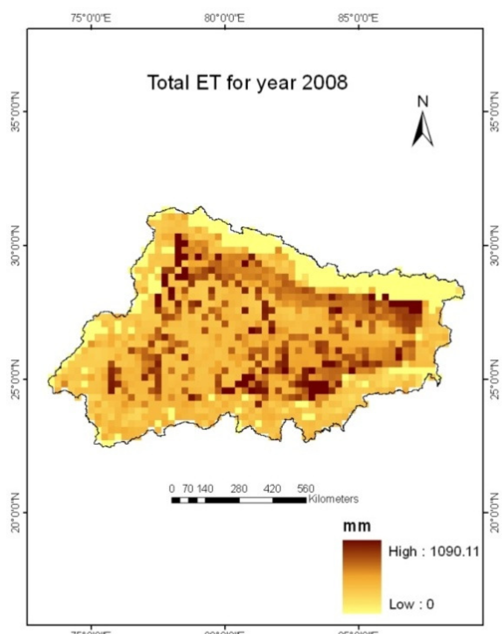


Figure 5.5: Total ET in 2008

5.2 Downscaling of Satellite derived ΔTWS

For downscaling GRACE ΔTWS, as referred by Kuss *et al*., 2011, groundwater level difference was taken as input. However, to prepare difference in water level, atleast two years data is required of which difference can be calculated. Since CGWB groundwater level data is available from 2007, downscaling technique was applied to year 2008 for seasonal months. Data available was in the form of seasonal water level below ground surface. This was processed to get data in the form of difference at every location w.r.t. previous seasonal month. This difference in cm was used as input. By following statistical downscaling technique explained in section 4.2.1 (method 1), following linear statistical relationship between CGWB's ground water level difference data and GRACE ΔTWS was developed for 4 different seasonal months.

For January, y = -0.003x – 3.315

For May, y = -0.006x – 15.87

For August, y = 0.017x + 14.43

For November, y = -0.010x + 2.96

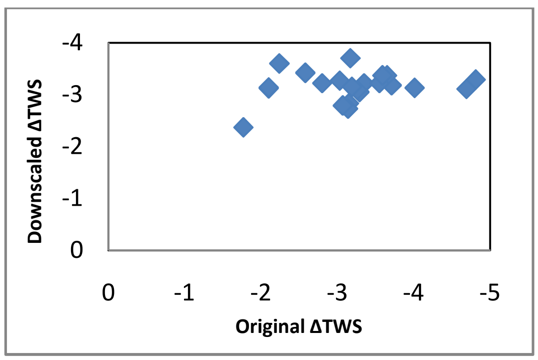


Figure 5.6: Correlation plot at different places, between original and downscaled ΔTWS (Method 2)

By applying these equations to interpolated CGWB interpolated images, it was found that good correlation exists in areas where water level point locations were densely located. Because of absence of sufficient number of water level point locations in hilly terrain, correlation in those areas was not as good. Following table compares original and downscaled ΔTWS values at certain locations for the month of January, 2008.

Table 5.1: Comparison of original and downscaled ΔTWS

Location	Original GRACE ΔTWS (cm)	Downscaled ΔTWS (cm)
Allahabad	-2.10	-3.12
Bahraich	-3.71	-3.18
Barabanki	-2.10	-3.14
Bareilly	-2.80	-3.22
Basti	-4.01	-3.13
Bilaspur	-3.15	-2.83
Delhi	-1.77	-2.37
Faizabad	-3.14	-2.73
Gaya	-4.81	-3.29
Ghaziabad	-2.58	-3.42
Ghazipur	-4.69	-3.11
Jaunpur	-3.29	-3.05
Meerut	-3.65	-3.37
Mirzapur	-3.07	-2.79
Moradabad	-3.17	-3.70
Muzaffarnagar	-3.35	-3.22
Nainital	-3.55	-3.22
North Delhi	-2.24	-3.60
Pilibhit	-3.03	-3.27
Rampur	-3.59	-3.37
Varanasi	-3.26	-3.09
Mean	-3.19	-3.15

Downscaled ΔTWS values for months January, May, August and November showing seasonal variations are shown in figure 5.8. GRACE data is originally at low spatial resolution available globally and hence boundary condition has to be neglected after downscaling at basin level. Seasonal values show that in January, water storage increased in central and western part of basin with decrease in eastern part. In summer month, water storage is declined in almost all parts of the basin. Monsoon month resulted in recharge of water table especially in eastern part which include Bihar and Eastern U.P. which received heavy rainfall in year 2008 (Source: Indian Meteorological Department). Same was the pattern in November with comparatively less storage. Figure 5.7 shows interpolated GRACE seasonal image (without downscaling).

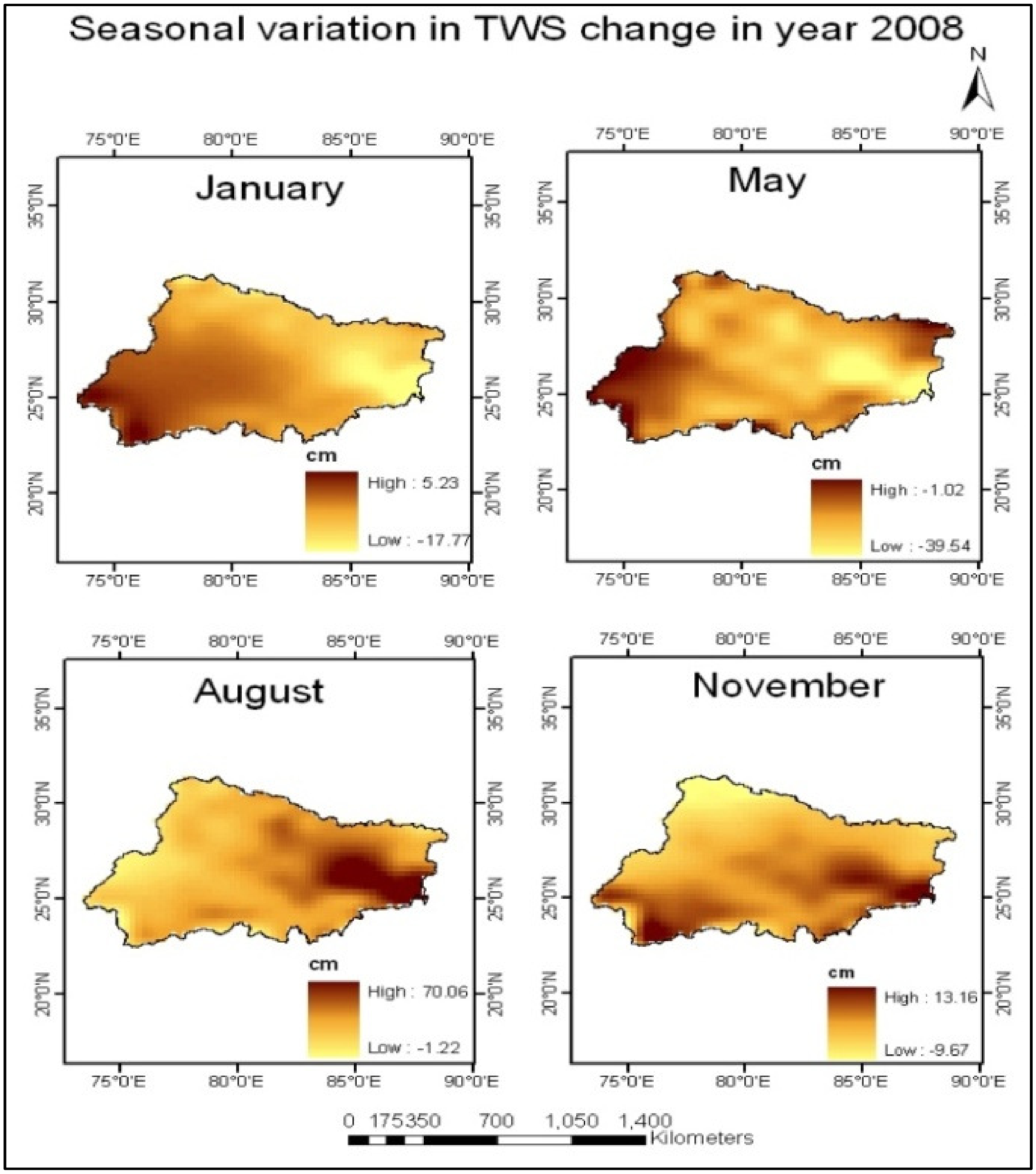


Figure 5.7: ΔTWS (original) seasonal variation in year 2008

Figure below shows downscaled GRACE seasonal image:

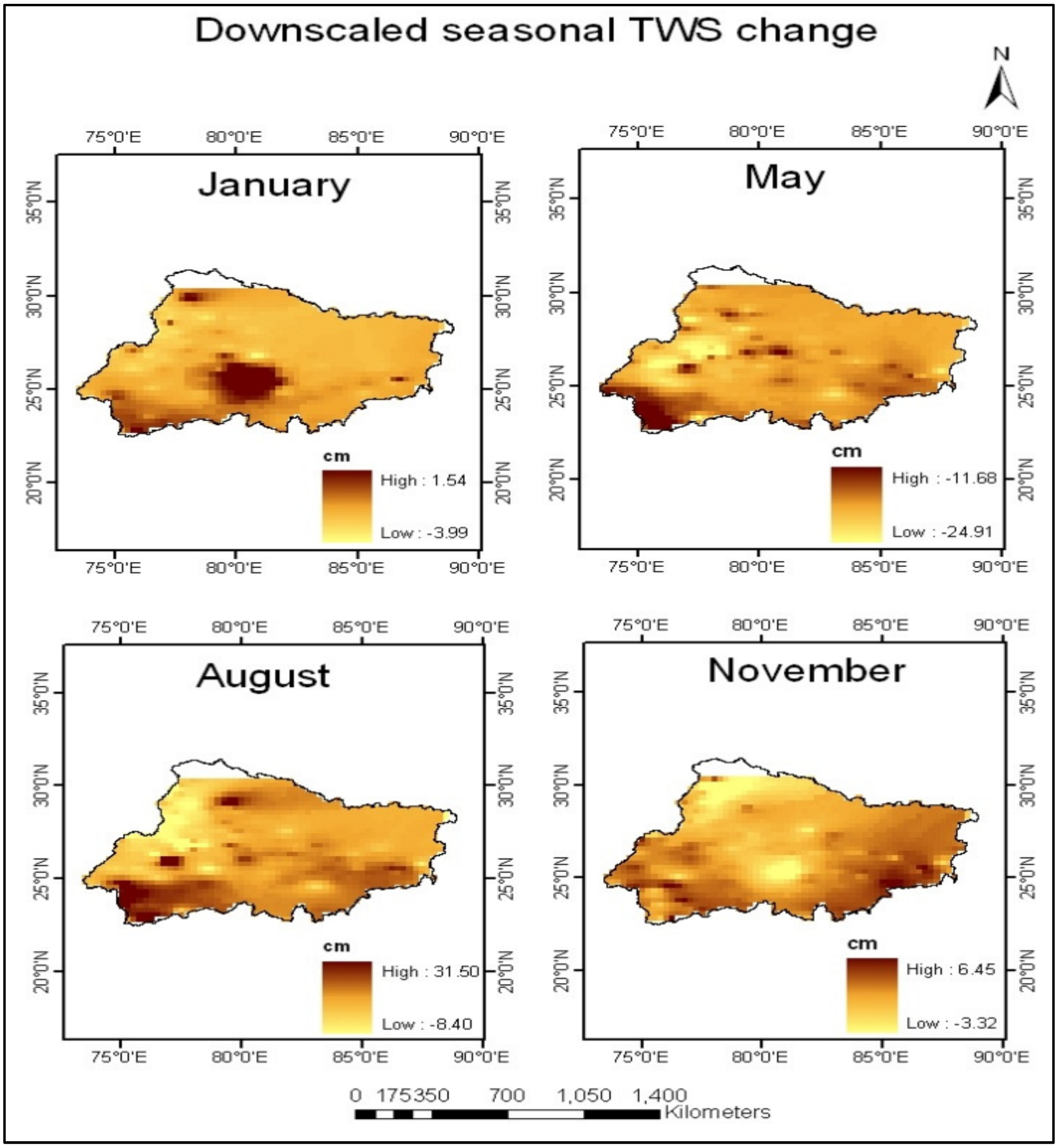


Figure 5.8: ΔTWS (downscaled) seasonal variation in year 2008

In the above figure, in the northern and eastern part of the basin, there is no data because of the extent of CGWB's point locations.

Now water balance equation was applied to satellite derived Precipitation, ET and ΔTWS. This result was compared with observed runoff value. Since ΔTWS was downscaled only for year 2008, equation was applied to year 2008. Results of average values of water budget components over whole basin are as shown below:

Table 5.2: Water budget using satellite data for year 2008

Water budget components	**Value in mm**
Precipitation	1099.301
ET	501.586
ΔTWS	-25.443
Runoff Calculated (VIC) and Observed	546.86 and 403
Water balance error (VIC and observed)	72. 13 and 220.158

Imbalance of 220.158mm was observed when satellite derived data has been used to close the water balance. Also, average ET in 2008 over whole basin was found to be 501.586 which is only about 45.62% of precipitation in that year.

5.3 VIC Model calibration and method development

VIC model helps in studying complex terrain and soil properties and their effect on runoff, ET and other water cycle components. However, every model depends on its assumption and inputs given. VIC model considers 10 calibrating parameters out of which 6 parameters are considered main which will affect the results considerably. They are: W_s, D_m, D_s, b, d_1 and d_2 (discussed in section 4.3). Among these, considering depth of soil layers as un-altered, other parameters are calibrated. Model input parameters give only physical properties of the basin and may contain certain uncertainties at grid or catchment scale and hence, calibration is required. Calibration method can be of two types: Parameter specification in which calibration of initial values is done by using previous knowledge and behavior of basin properties and Parameter estimation in which calibration is done depending on field observations. Calibration can be done depending upon the reference availability, by adjusting parameters till the performance of the model closely matches the observed behavior of the basin.

Here, parameter estimation method of calibration is used to minimize the difference between model output and observed data which is runoff/discharge on annual basis. First of all, to start with, model was simulated by considering initial values of calibrating parameters. Keeping the results obtained from these initial values as reference for increase/decrease required in calibrating parameters, calibration was done accordingly. Now keeping W_s parameter as unchanged, other parameters viz. b and D_s were adjusted until the average runoff over the basin matched closely with the observed value (Ganga Basin, S.K. Jain). Percentage error of runoff value was determined during every simulation with respect to observed value. However, model efficiency varies from year to year. Following table shows effect of calibrating values on the results for year 2008:

Table 5.3: Calibrating parameters effect on runoff for year 2008

A	B	Soil type									C	D
		1	2	3	12	24	100	102	103	104		
1	b_{infilt}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	4.457	2.89
	D_s	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001		
2	b_{infilt}	0.4	0.3	0.3	0.3	0.4	0.2	0.2	0.2	0.2	4.454	2.96
	D_s	0.008	0.005	0.003	0.001	0.001	0.001	0.001	0.001	0.001		
3	b_{infilt}	0.4	0.3	0.25	0.25	0.4	0.2	0.2	0.2	0.2	4.479	2.41
	D_s	0.008	0.005	0.003	0.001	0.001	0.001	0.001	0.001	0.001		
4	b_{infilt}	0.3	0.25	0.25	0.25	0.3	0.2	0.2	0.2	0.2	4.670	1.74
	D_s	0.006	0.004	0.0025	0.001	0.001	0.001	0.001	0.001	0.001		

In the above table, ‘A’ represents VIC runs number, ‘B’ represents soil parameter’s which are calibrated, ‘C’ represents Average runoff derived from VIC in $10^{11}m^3$ and ‘D’ represents percentage error in derived runoff w.r.t. to observed.
In the above table, soil type classification is as follow: 1 (sandy), 2 (loamy), 3(clayey), 12 (clay skeletal), 24 (loamy skeletal), 100 (rock outcrop), 102 (water body), 103 (glacier) and 104 (glacier and rock outcrop).

Also, values of {(Precipitation)-(ET)-(Runoff)-(Baseflow)} were compared for all the runs with GRACE ΔTWS yearly change. Since VIC water balance mode has been run for annual basis, concern is for annual change in that particular year. And hence, scale factor multiplied values for January, 2009 and January, 2008 were subtracted which will give actual change in water storage in year 2008. However, downscaled GRACE values were not taken since this method is spatial location dependent. This downscaling technique will give more accurate results where ground water level point locations are densely located and also since CGWB data is available at monthly scale, downscaling has also been done at seasonal scale. But to close water balance over whole basin, it may result in imbalance. Instead, GRACE January 2008 and January 2009 difference map was interpolated with the help of grid point interpolation at 0.25° spatial resolution. Also, ET when compared to that derived by using MODIS datasets using SEBS tool and also from MOD16A2 ET product, was found acceptable. Hence, to close water budget, ET values were taken by that derived from VIC model.

Following table shows results of water budget for all 4 runs. It can be seen that decrease in b_{infilt} and D_s in VIC run 4 results in decrease of runoff and baseflow with increase in infiltration. This infiltration gets stored in soil as it is contributing less to the baseflow and will get evaporated, which results in soil water deficit and increase in ET. And hence, change in water storage for VIC run 4 is more as compared to other runs.

Table 5.4: Water budget for different VIC simulations for year 2008

VIC runs	P-ET-Q-baseflow (in mm)	ΔTWS (in mm)	Imbalance (in mm)
1	-4.176	-25.443	21.267
2	-2.805		22.638
3	-4.640		19.197
4	-38.013		-17.725

Combining the results of both above tables and water balance closed by using satellite data, it was found that results of VIC run 4, are most acceptable and contain minimum error. And hence, results obtained from this run were used for water budget closure. Also the imbalance remaining in the water budget was further reduced by assuming that among all the major water budget components, satellite derived precipitation and ΔTWS does not contain any error. Also, since runoff was used for validation, it cannot be altered. Hence, error was incorporated in ET.
Routing model when simulated using calibrated soil parameters file, shows following results at different station locations:

Table 5.5: Routing model results at different station locations for year 2008

Station location	Runoff value in mm/year	GRDC observed value in mm/year
Benighat	830.632	800
Chisapani	746.926	930
Chambal	289.882	-
Devghat	1169.1	1513
Farakka	546.855	403
Ghaghara	566.706	-
Gomti	639.663	-
Ramganga	320.797	-
Sone	258.720	-
Tajewala	462.656	-
Tons	511.586	-

Results were compared at station locations: Benighat, Chisapani, Devghat and Farakka with the observed value as per Global Runoff Data Centre (GRDC) which showed acceptable values since GRDC data is long term average from 1949 to 1973and that obtained in 2008 is with increase of 143.855mm/year in 2008 as compared to long term average till 1973.
Following are the results obtained after model calibration for year 2008. Figures show that there is a high annual precipitation eastern part of U.P. and Bihar and correspondingly there is high runoff and ET in those areas. Annual ET is high in almost whole basin with comparatively

lesser values in extreme mountainous terrain of Himalayas and also in Chambal sub-basin. Annual ΔTWS shows that there is declination in the ground water storage in whole basin except in parts of Bihar. Also, runoff value in the upper Himalayan region calculated by VIC model does not consider snow-melt runoff. By simulating total energy balance mode of VIC model, more accurate results can be obtained for such snow cover areas.

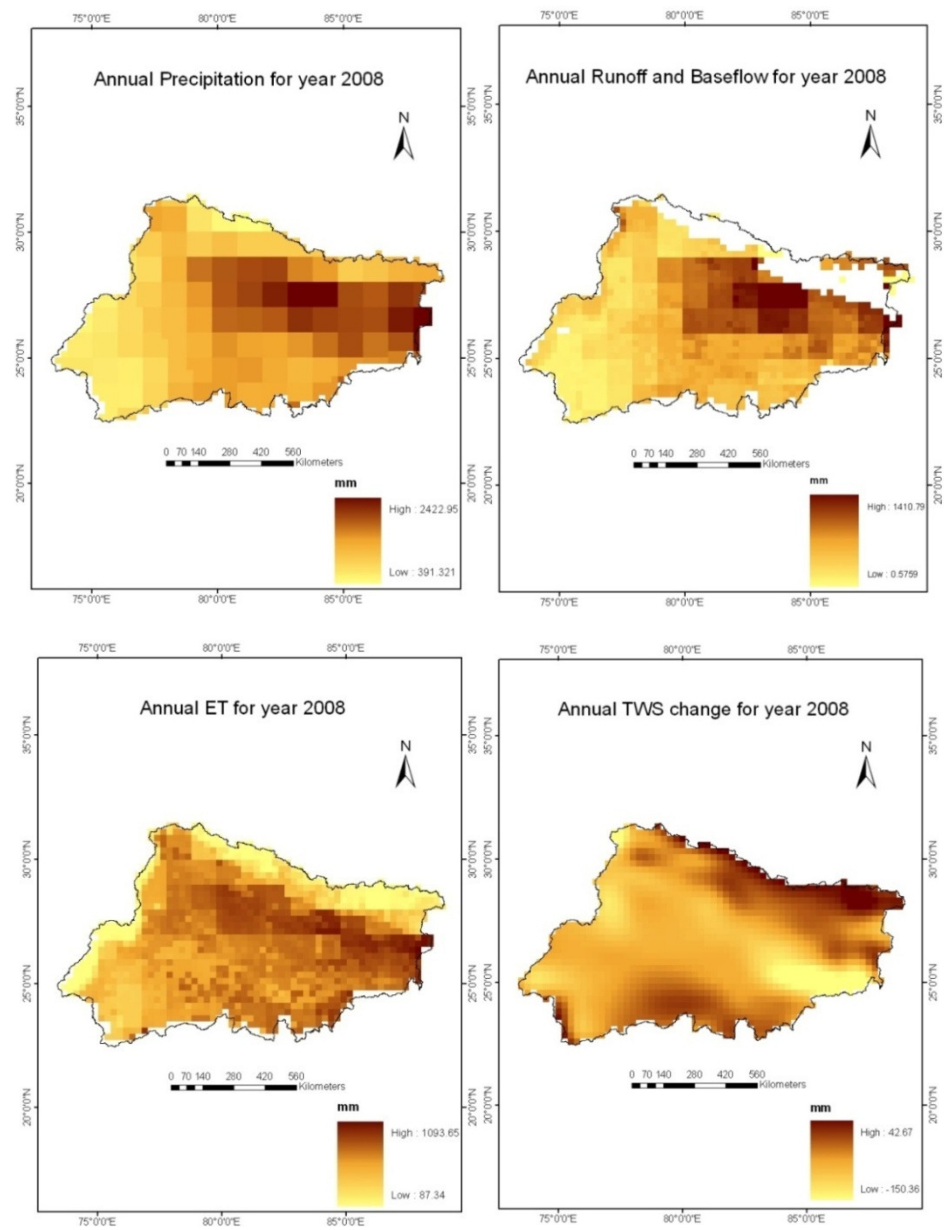


Figure 5.9: Water budget components for year 2008

VIC model results obtained for year 2008 are shown in graphical format as below:

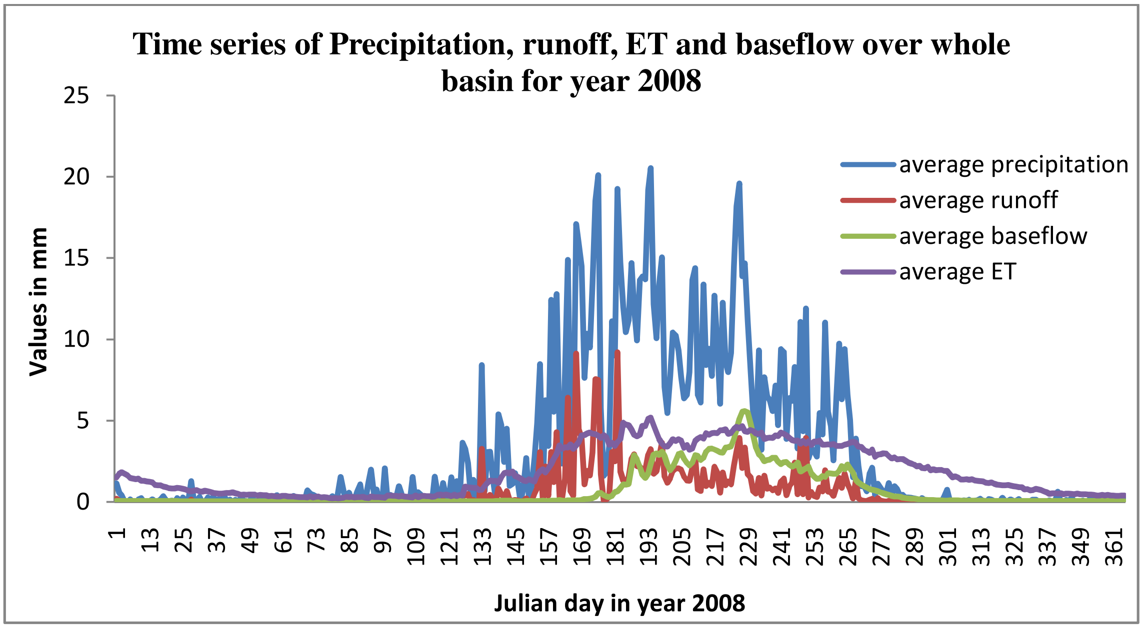


Figure 5.10: VIC model output for year 2008

Average value of water balance components over whole basin for year 2008 is given below:

Table 5.6: Water budget for year 2008

Water budget components	**Values in mm (percentage of precipitation)**	**Values in mm (with modified ET)**
Precipitation	1099.301	1099.301
Runoff	210.140 (19.11%)	210.140 (19.11)
Baseflow	246.455 (22.41%)	246.455(22.41)
ET	680.719 (62%)	690.554 (62.81)
ΔTWS	-25.443 (-2.31%)	-19.49 (-1.77)
Error	-17.725	0.0

By using this soil parameter file, VIC model was validated for the year 2004, 2005, 2006 and 2007.

For year 2004, similar procedure was followed by using calibrated soil parameter file. Since precipitation amount is not same every year, the error in water balance closure was considered to be because of ET since precipitation and ΔTWS values were measured with the help of remote sensing and were assumed to be correct. And hence ET was modified by the error and then was finally used for water budget closure. VIC model results obtained for year 2004 are shown in graphical format as below:

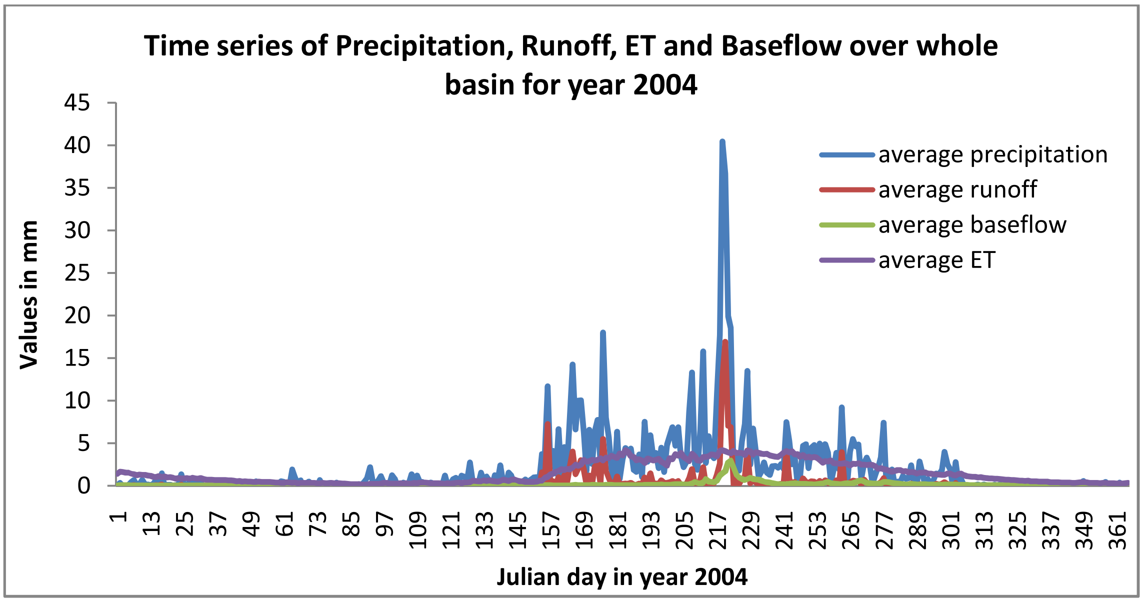


Figure 5.11: VIC model output for year 2004

After incorporating imbalance in ET, modified ET map is as below:

Basin average values of water budget components for year 2004 are as below:

Table 5.7: Water budget for year 2004

Water budget components	**Values in mm (percentage of precipitation)**	**Values in mm (with modified ET)**
Precipitation	686.134	686.134
Runoff	123.256 (17.96%)	123.256 (17.96%)
Baseflow	42.219 (6.204%)	42.219 (6.20%)
ET	496.568 (72.308%)	584.766 (85.22%)
ΔTWS	-64.099 (-9.34%)	-64.512 (-9.40%)
Error	88.19	0.0

Similar procedure was followed for year 2005, 2006 and 2007.

VIC model results obtained for year 2005 by using calibrated soil parameter file are shown in graphical format as below:

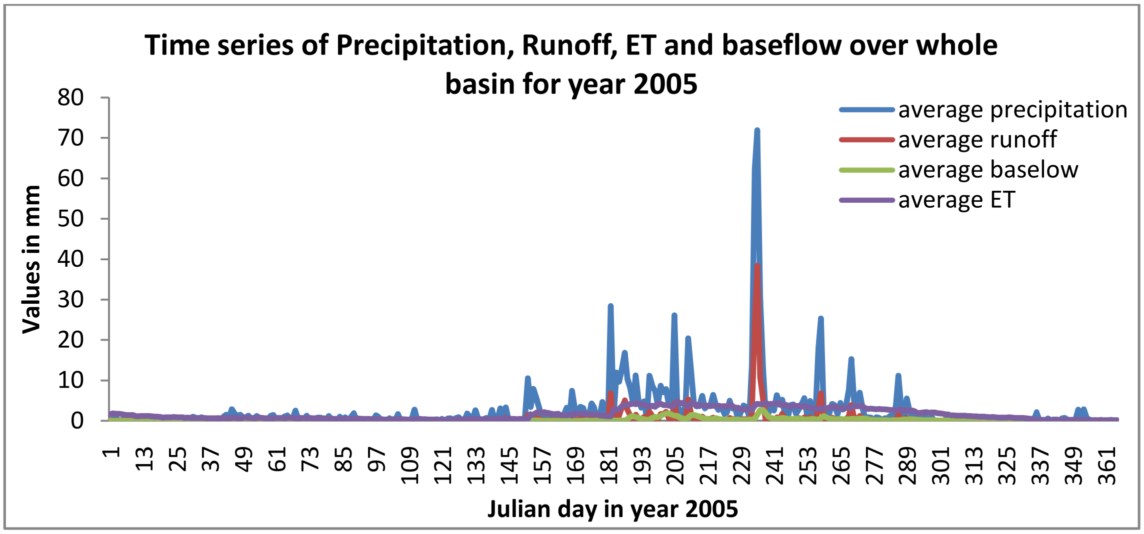


Figure 5.12: VIC model output for year 2005

Following table shows average values of water budget components with original ET and ET after incorporating imbalance.

Table 5.8: Water budget for year 2005

Water budget components	**Values in mm (percentage of precipitation)**	**Values in mm (with modified ET)**
Precipitation	838.478	838.478
Runoff	147.678 (17.61%)	147.678 (17.61%)
Baseflow	61.325 (7.31%)	61.325 (7.31%)
ET	544.093 (64.89%)	595.40 (71.00%)
ΔTWS	34.19 (4.07%)	34.19 (4.07%)
Error	83.6	0.0

Year 2005 was a wet year for western and south western states with more than 20% of normal yearly rainfall. However, for states lying in Ganga basin, all the states except Bihar and Jharkhand received normal rainfall with -19 to +19% variation w.r.t. normal rainfall. Basin received as high as 71.95mm average rainfall for 236th Julian day (Source: http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm)

For year 2006, VIC model results in graphical representation is as below.

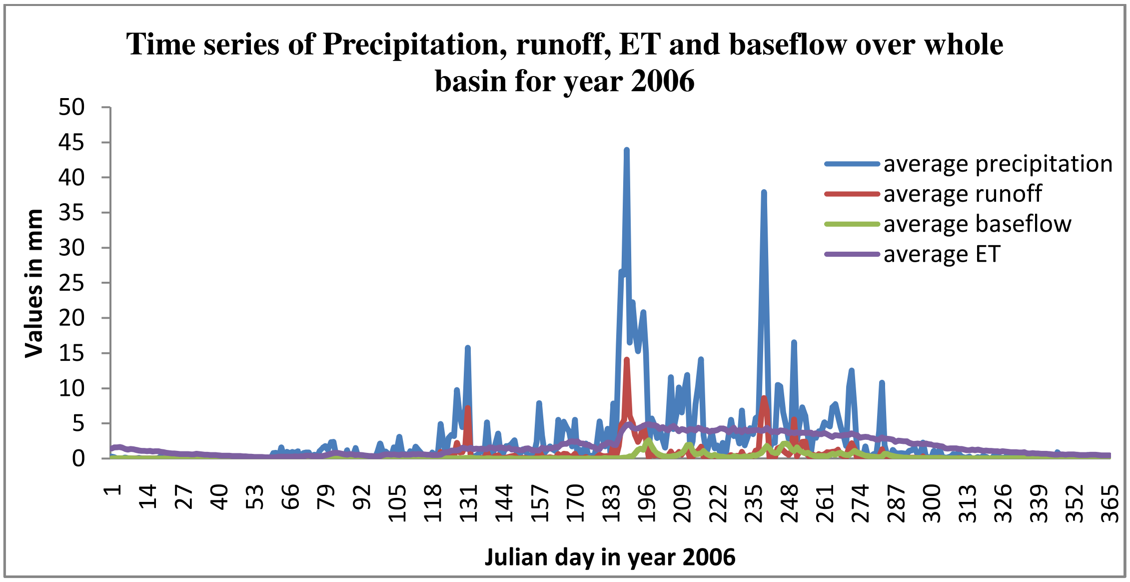


Figure 5.13: VIC model output for year 2006

Following table shows average values of water budget components over whole basin with original ET and ET after incorporating imbalance.

Table 5.9: VIC model output for year 2006

Water budget components	Values in mm (percentage of precipitation)	Values in mm (with modified ET)
Precipitation	876.433	876.433
Runoff	141.825 (16.18%)	141.825 (16.81%)
Baseflow	69.102 (7.88%)	69.102 (7.88%)
ET	605.690 (69.10%)	696.166 (79.43%)
ΔTWS	-30.978 (-3.53%)	-30.978 (-3.53%)
Error	28.838	0.0

In year 2006, deficit affected states were more as compared to year 2005. Uttrakhand, U.P and Delhi received as much as 43% less than normal rainfall in western U.P. Maximum average daily rainfall received in the basin was 43.9765mm in 190th Julian day. (Source: http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm)

For year 2007, VIC model results in graphical representation is as below.

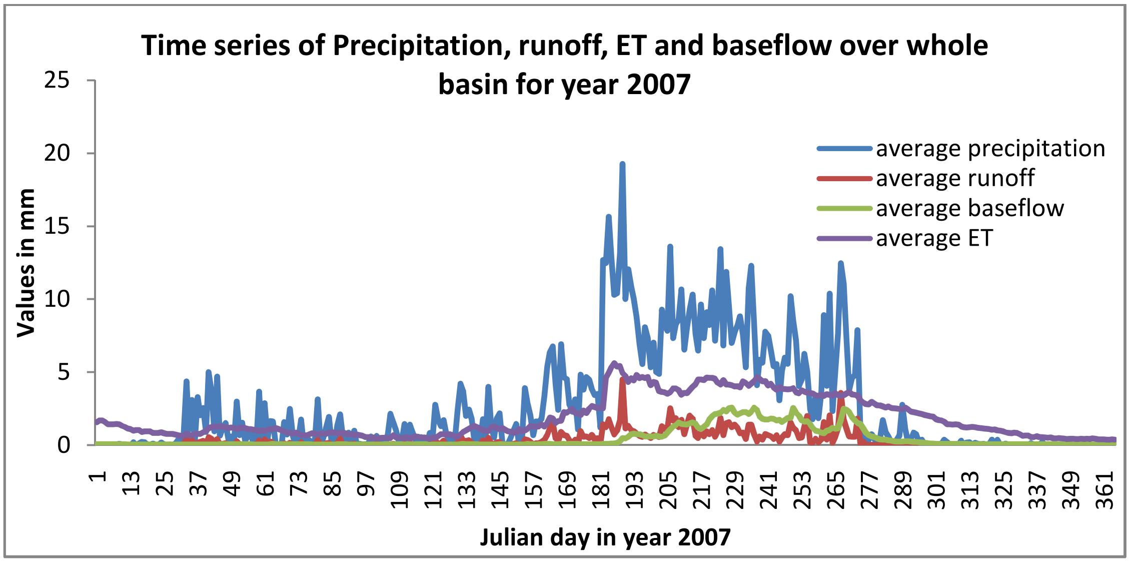


Figure 5.14: VIC model output for year 2007

Following table shows average values of water budget components over whole basin with original ET and ET after incorporating imbalance.

Table 5.10: VIC model output for year 2007

Water budget components	**Values in mm (percentage of precipitation)**	**Values in mm (with modified ET)**
Precipitation	900.087	900.087
Runoff	105.530 (11.72%)	105.530 (11.72%)
Baseflow	116.024 (12.89%)	116.024 (12.89%)
ET	638.549(70.94%)	716.323 (79.58%)
ΔTWS	-14.008 (-1.55%)	-14.008 (-1.55%)
Error	53.992	0.0

In year 2007, Uttrakhand and Bihar received excess rainfall with about 28% more than normal. But states like Delhi, East M.P., and Western U.P. were water deficit with as low as 39% less than normal rainfall in Western U.P. basin received maximum daily average rainfall of about 19.2538mm in 190the Julian day. However, numbers of rain event were more as compared to previous year. (Source: http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm)

Hence, by using soil parameter file obtained after calibrating for year 2008, table below shows error in water budget for year 2004, 2005, 2006 and 2007.

Table 5.11: Water budget results for year 2008 to 2004

Year	**Original ET (mm)**	**Modified ET (mm)**	**Water budget imbalance in mm (average over whole basin) original**	**Water budget imbalance in mm (average over whole basin) after modification**
2008	680.719	690.554	-17.725	0.0
2007	638.549	716.323	53.992	0.0
2006	605.690	696.166	28.838	0.0
2005	544.093	595.40	83.6	0.0
2004	496.568	584.766	88.19	0.0
Mean	593.123	656.641	47.379	0.0

Table above shows that by assuming satellite derived water budget components as accurate and incorporating the imbalance in ET, average error over whole basin was found to be closed. And hence a balance in water balance was created over whole basin.

Table 5.12: Annual water budget components for years 2004 to 2008 (without modification)

Year	**Precipitation(mm)**	**ET (mm)**	**Runoff (mm)**	**Baseflow (mm)**	**ΔTWS (mm)**
2008	1099.301	680.719	210.140	246.455	-25.443
2007	900.087	638.549	105.530	116.024	-14.008
2006	876.433	605.690	141.825	69.102	-30.978
2005	838.478	544.093	147.678	61.325	34.17
2004	686.134	496.568	123.256	42.219	-64.099
Mean	880.087	593.124	145.686	107.025	-20.072

Table above shows that for year 2005, GRACE ΔTWS was increased as compared to other years which may be due to heavy rainfall received by Bihar and Jharkhand. This resulted in excess ground water storage in the soil and hence increase in average ΔTWS over whole basin.

- ***Downscaling GRACE ΔTWS using modified Water Balance derived change in ground water storage (Method 2):***

  Using above obtained precipitation, runoff, baseflow and modified ET; change in ground water storage has been derived on annual basis for year 2004 to 2008, by using following water balance equation as explained in section 4.2.2 (method 2):

  P – (Modified ET) – runoff – baseflow = change in water storage

  This change in ground water storage has been used to downscale annual change in GRACE ΔTWS by deriving statistical linear relationship between these two by taking 'x' as water balance derived ground water storage change and 'y' as satellite derived ΔTWS and applying equations to water balance derived product. Figure 5.14 shows correlation between modified water balance derived change in ground water storage and GRACE ΔTWS for year 2008.

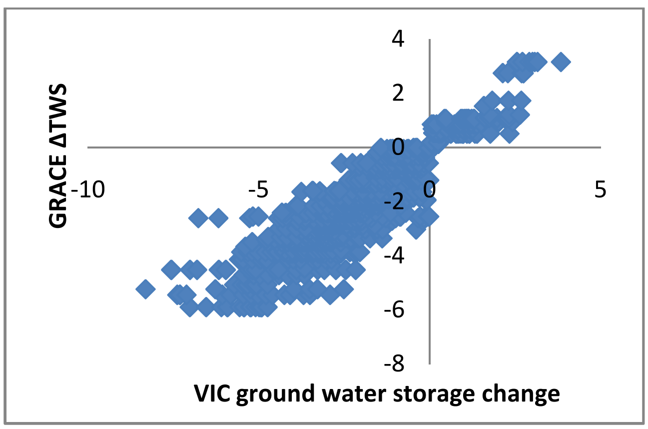


Figure 5.15: Correlation plot between Water Balance derived and GRACE derived ΔTWS

Downscaled results obtained for year 2004, 2005, 2006, 2007 and 2008 by using this input are as shown in figures 5.16, 5.17 and 5.18.

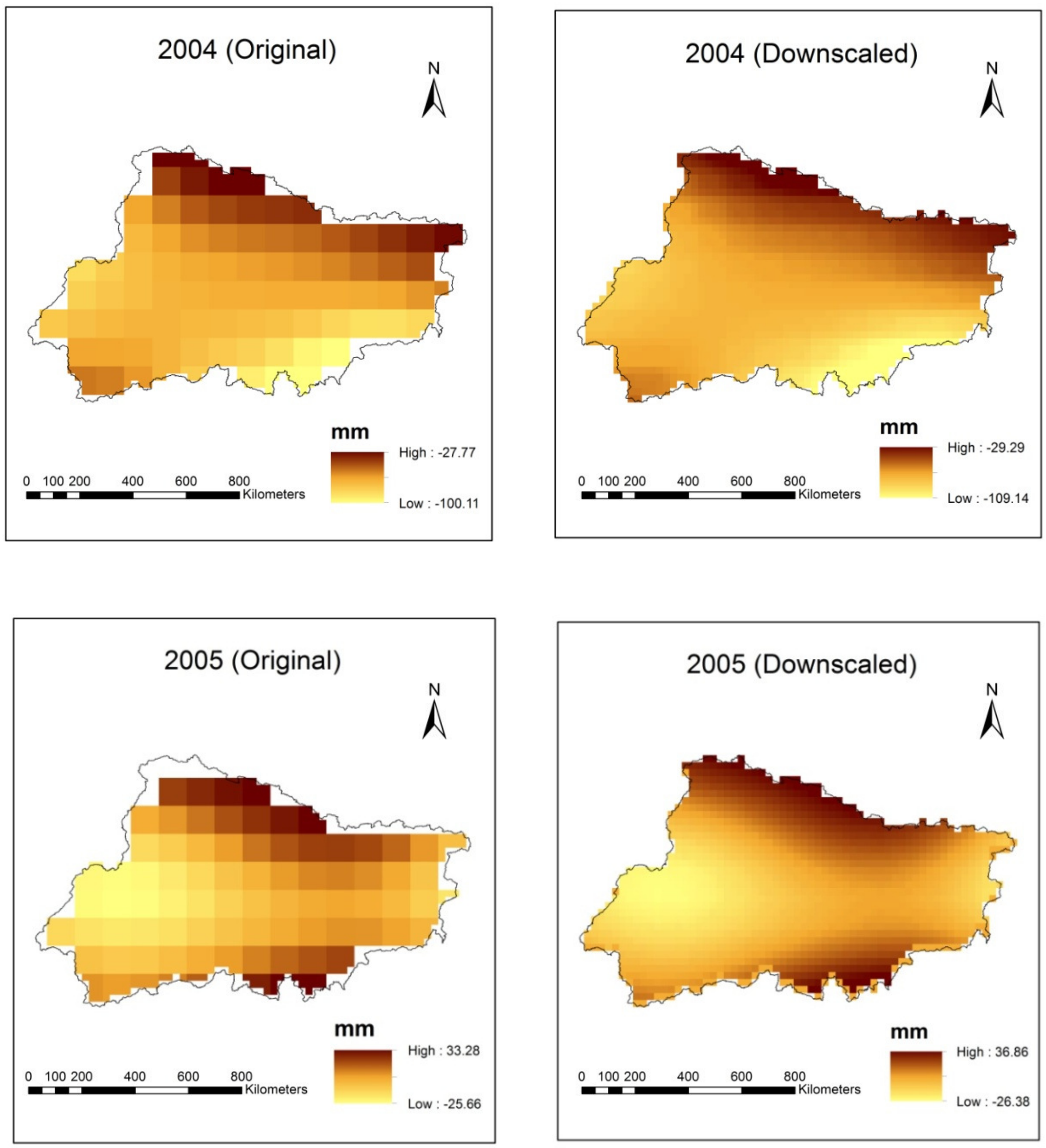


Figure 5.16: Original and downscaled ΔTWS for year 2004 and 2005

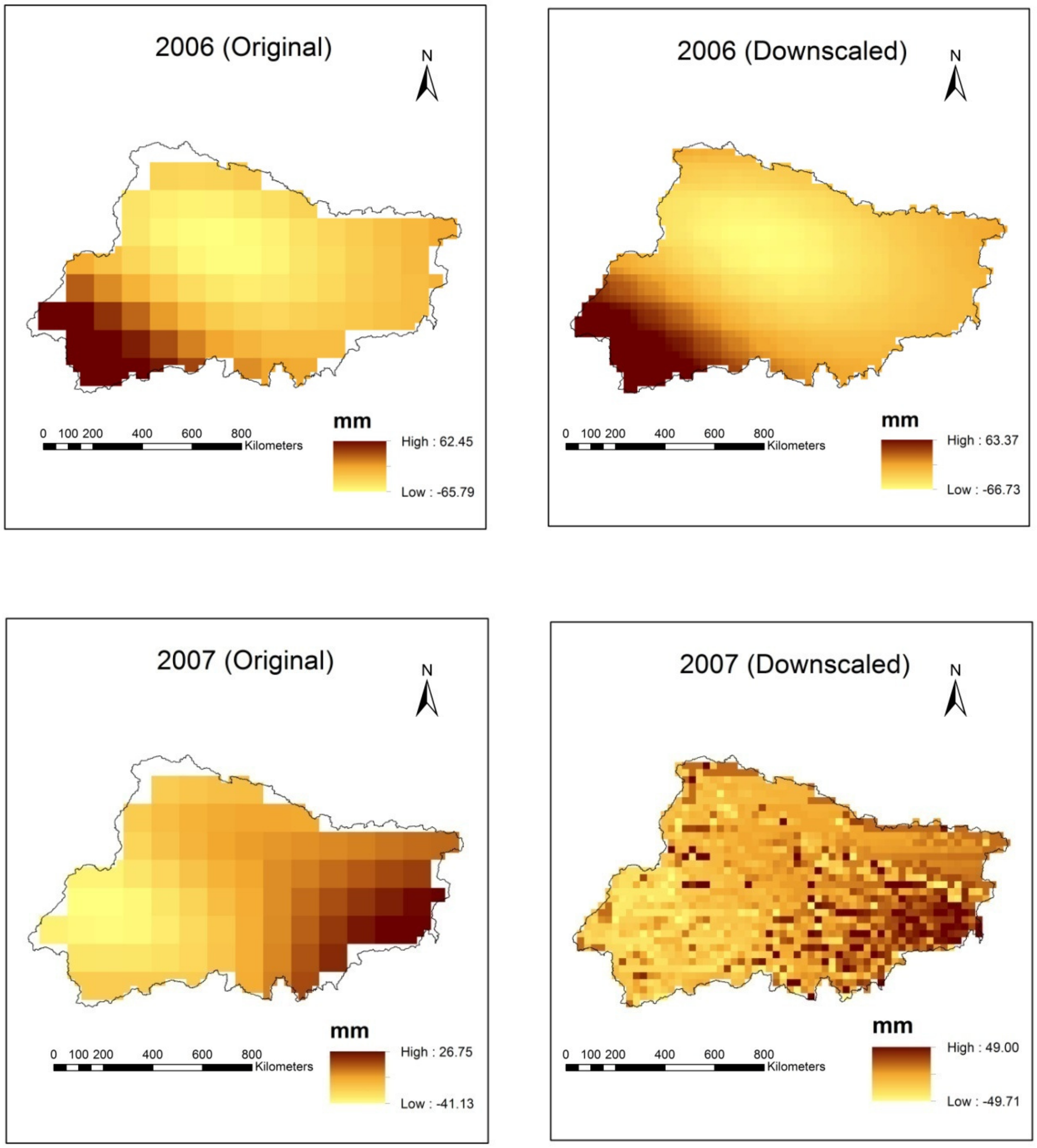


Figure 5.17: Original and downscaled ΔTWS for year 2006 and 2007

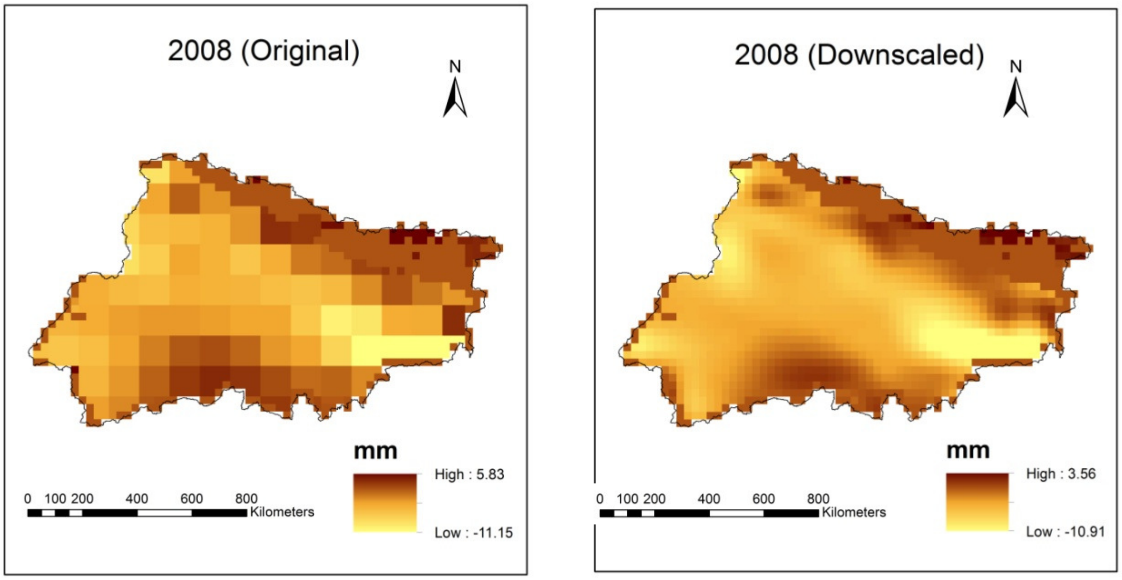


Figure 5.18: Original and downscaled ΔTWS for year 2008

Table below shows average values of original and downscaled ΔTWS over whole Ganga basin for all 5 years.

Table 5.13: Difference between original and downscaled ΔTWS (in mm)

Year	**Original**	**Downscaled**	**Difference**
2004	-64.157	-63.873	-0.284
2005	0.115	0.983	-0.868
2006	-31.799	-31.108	-0.691
2007	-14.536	-13.172	-1.364
2008	-2.309	-1.909	-0.4
Mean	-22.537	-21.815	-0.721

However, this study is based on hypothetical assumption that satellite derived precipitation and ΔTWS does not contain any error and the imbalance created in water budget is because of only left parameter which is ET since (runoff + baseflow) has been used for calibration as the observed data available combines both runoff and baseflow. But satellite derived products also contain error. GRACE derived ΔTWS has an accuracy upto 1cm which vary according to location. Precipitation derived from NCEP/NCAR reanalysis is available in the form of rainfall intensity. Since the percentage of distribution of each water budget components in the water cycle is not known and also it varies from location, it is not possible to divide this imbalance accordingly among all the components.

Because of the above reason, imbalance occurred in water budget has been completely incorporated in ET calculation. This resulted in about 85% ET of precipitation for year 2004 which was a dry year for majority of Ganga basin.

CHAPTER 6

Conclusions and Recommendation

6.1 Conclusions

From the results obtained with necessary assumptions, depending on the research questions associated with this study, flowing conclusions have been made.

- Which satellite data and models are suitable for estimating water budget components?

  Precipitation, ET and ΔTWS data can be taken from ground based observations. But since this data represents only local conditions, satellite derived data has been used. Precipitation data has been taken from NCAR/NCEP reanalysis product. ET can be derived using different satellite imagery like Landsat, MODIS, etc. MODIS dataset has been used here to derive ET by using LST, Emissivity, albedo and NDVI since all these parameters affect the evapotranspiration process. Surface energy Balance approach has been used to derive ET which takes into account incoming and outgoing solar energy in the form of radiation. For this, ILWIS SEBS tool has been used which showed acceptable results when compared to MODIS 16A2 ET product. Results show that average ET over whole basin was found to be 430.342mm for year 2004 and 501.586mm for year 2008. Also ET has been derived from Variable Infiltration Capacity (VIC) model, after incorporating various parameters affecting the hydrological process. VIC model has an advantage of taking into account sub-grid soil moisture variability and also considers the LULC classes sub-grid wise along with the benefit of being an open source model. Because of this reason, VIC model has been used for this study. Instead of considering change in terrestrial water storage in imbalance, this value has been separately considered by taking it from GRACE satellite dataset.

- How scaling issues can be addressed for change in terrestrial water storage using GRACE data?

  GRACE ΔTWS is available at 1° spatial resolution with global coverage. However, to use this data at finer scale, it is necessary to downscale. For downscaling, statistical approach has been used. Mathematical relationship has been developed between GRACE ΔTWS seasonal change and corresponding seasonal difference in water level derived by using Central Ground Water Board's ground water level data. Results show mean error of 0.04cm between original and downscaled ΔTWS for selected locations. However, to get accurate results of spatial downscaling over whole Ganga basin, modified water balance derived change in ground water storage has also been used as input for statistical downscaling. This showed a mean error of 0.721 mm average over whole basin.

- What is the accuracy of water balance components obtained from satellite data and hydrological model derived with respect to actual data and how its error can be reduced in closing the water balance?

  Water balance, when closed by using satellite derived Precipitation, ET and ΔTWS, gives an imbalance of 220.158 mm when runoff has been taken from GRDC and an error of 72.13 mm when hydrological model derived runoff has been used in the equation. Water balance has also been closed by using satellite derived precipitation and ΔTWS; and model derived other water balance components viz. ET, runoff and baseflow. After calibration of combined runoff and baseflow parameter according to observed value, imbalance of 17.725 mm has been found in closing water balance since satellite derived precipitation and ET consists of different algorithm and hence there is no direct correlation between them while using for water balance; however, in hydrological model, parameters are retrieved by considering whole cycle and processes. But, since the exact contribution of these components in the hydrological cycle is not known, it is assumed that imbalance has been created due to ET, as precipitation and ΔTWS used are satellite derived and their accuracy varies with location. With this assumption, water balance has been obtained for year 2004 to 2008 by increasing ET ranging from 0.81% in year 2008 upto 13% in year 2004.

6.2 Recommendations

Above results and their conclusion recommends that:

- Precipitation used, is at 1° spatial resolution which is a product derived from NCEP/NCAR reanalysis. However, instead of coarser resolution, finer resolution satellite derived precipitation data such as TRMM can be used for more accurate closure of water balance. Also, ET can be derived from other techniques which will further increase the accuracy of water balance.
- GRACE downscaling can be done by using other spatially spread dependent variable, which affects ΔTWS to get accurate results and can be further be used for water balancing.
- In this study, it is assumed that the imbalance created in water balance is because of ET since contribution of components in water cycle is not known. If this contribution can be identified, imbalance can be divided accordingly instead incorporating it completely in ET.
- Also, ΔTWS values have been affected by the snowmelt as terrestrial water storage includes snowmelt. Since about 10-20% of Ganga basin is covered with snow during winter, GRACE data should be studied separately for snow covered areas. For such areas, VIC snowmelt runoff model should be simulated.

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APPENDIX

FIELD PHOTOS OF TEHRI DAM

Tehri dam has been constructed at the confluence of the Bhagirathi River and its tributary Bhilangana River in Tehri, Uttrakhand. It is an earthfill embankment dam used for multiple purposes which includes irrigation, municipal water supply and generation of hydroelectricity. It is the highest dam of the country. This dam is however located in the Central Himalayan Seismic zone which is a geological fault zone. Below are field photographs of Tehri dam and its surrounding.

Slide gates of main dam structure

Toe erosion and Landslide along the vicinity of the dam

Submerged Tehri town and toe erosion along the reservoir

Morning Glory

Spill-way and downstream side of dam

Tehri Reservoir as viewed from New Tehri town