WATER RESOURCE ASSESSMENT AT A BASIN LEVEL USING WATER BALANCE APPROACH AND REMOTE SENSING INPUTS

Thesis submitted to the Andhra University, Visakhapatnam in partial fulfilment of the requirement for the award of *Master of Technology in Remote Sensing and GIS*

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CERTIFICATE

This is to certify that this thesis work entitled "***WATER RESOURCE ASSESSMENT AT A BASIN LEVEL USING WATER BALANCE APPROACH***" is submitted by Miss Sakshi Shiradhonkar 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 supervision of Dr. Vaibhav Garg, Scientist/Engineer 'SD' and Dr. Bhaskar Nikam, Scientist/Engineer 'SE' at Water Resources Department of Indian Institute of Remote Sensing, ISRO, Dehradun, India.

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ABSTRACT

In this constantly changing environment, the availability and distribution of water will vary in space and time. In order to develop and rationally manage the water resources, an assessment of the quantity and quality of available water is necessary. This study includes the hydrological model selection and its parameterization. VIC model was opted amongst the SWAT, MIKE, HEC-HMS models to be the best suited model for the study. A wind speed variable sensitivity analysis was done on Asan watershed. This showed a remarkable difference in the water budget components. Model was run in two scenarios, including the wind speed parameter and then excluding it. Water resource assessment is the basic theme of this study. A water balance approach is adopted for the assessment studies. Closure of water balance for the year 2005 with maximum possible accuracy needs to be achieved for exact water resource assessment. To close the water budget with minimum error, all the components must be accurately estimated. To achieve this goal, VIC model was run in water balance mode to estimate the water balance components, Runoff, ET, Soil moisture, Baseflow. The model was then run for a period of 30 years (1980-2010) with LULC of 2005 over a 25km x 25km grid size derived from Indian Meteorological Department gridded data and wind speed was also considered in the meteorological forcings. This resulted into better outputs. But for water budget closure groundwater is necessary. A strong correlation was then developed between ∆TWS from GRACE satellite and ∆GWS from CGWB's groundwater level data. Further, ∆TWS was correlated with baseflow from VIC and thus, it was shown that baseflow is the potential recharge of groundwater. This accomplished the groundwater assessment. Runoff estimation is considered as the surface resource assessment. For studying the impact of Land Use change, two LULC scenarios (1985 and 2005) were taken into account. A substantial increase in evaporation (0.56%) component was observed, while the Runoff (42.42%), Baseflow (34.18%), and Discharge (34%) of Narmada basin decreased in 2005 as compared to 1985. It was noticed that the Indira Sagar Dam with a capacity of 12.22 Bm3 was commissioned in 2005. It was the major change in the LULC during the analysis period, which played an important role for the remarkable change in water balance components for the year 2005. The discharge data was validated with in situ (CWC) data. The impact of lake/wetland on basin hydrology is observed. The work also specifies its importance in the accurate water balance and water resource assessment studies.

Keywords: *Water balance, Water resource assessment, VIC model, GRACE, LULC impact.*

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1. INTRODUCTION

1.1 GENERAL

In this constantly changing environment, the availability and distribution of water will vary in space and time. In order to develop and rationally manage the water resources, a quantity and quality assessment of water is necessary. The international Glossary of Hydrology (UNESCO/WMO, 1992) defines water resources assessment (WRA) as the "determination of sources, extent, dependability and quality of water resources for their utilization and control." In reference to evaluate the dynamics of the water resource related to human impacts or demand, WRA can be used as a water resources evaluation tool. Water resources of basin is reckoned by the natural flow in a river basin. "Water resources assessment aims to measure quantity and quality of the water in a system, including data collection, data validation, and water accounting techniques, using both ground and remote sensing", (*www.unesco-ihe.org*). By adding up the observed flow, natural flow at any location on a river can be obtained. "WRA can also be defined as the systematic study of the status of water services and resources, and of trends in accessibility and demand within a specific domain of interest. WRA can be applied to a unit such as a basin, watershed, catchment, sub-catchment or groundwater reservoir." (*www.sswm.info*)

Since WRA deals with measuring, collecting and analyzing parameters on the quantity and quality of water resources for development and a better management of water resources, the required data collection for the study unit becomes a challenging task. Data collection includes:

a) Biophysical data includes the data regarding the topography, soils, geology and vegetation. For setting the environmental constraints and modelling this data is necessary.
b) Hydro-meteorological data: characteristics of climate, surface water and groundwater – required to define the available resource characteristics;
c) Socio-economic data: land use and demography – required for understanding the water needs;
d) Water-use data: required to complete the picture of supply–demand.

The data is essential and requires high accuracy for systematic WRA of a basin. But practically, it is not possible to obtain the ground data as required for the assessment. In such scenarios, remote sensing and GIS technique plays a vital role for accurate and correctly formatted data collection. Advantage in satellite derived data is the consistency in terms of temporal and spatial extent. Another advantage of the data obtained from remote sensing is that it can be easily incorporated into the hydrological models. This helps in achieving more accurate estimates of the Water budget cycle. For a proper WRA, one should understand the hydrological cycle and its components thoroughly.

1.2 PROBLEM STATEMENT AND MOTIVATION

The dynamic water resource assessment at the basin/region/country level is the need of hour. Knowledge of available water in the basin will create an awareness of utilizing the water efficiently and to improve the sustainability of the ecosystem. Not all hydrological components of Water Balance equation can easily be estimated using available hydrological models. However, remote sensing can give better assessment/quantification of such parameters. It is essential to use both the approach in conjunction to the assessment water resources at basin level.

The Central Water and Power Commission (CW and PC) worked out the surface water resources of different basins during the period from 1952 to 1966. This study was mostly based on statistical analysis of the flow data wherever available and rainfall-runoff relationships wherever data were meagre. When Central Water Commission was compiling material for the chapter on water resources potential during 1987-88 for their publication on "Water Resources of India", they realized that the assessment studies made on the basis of observed river flows needed some correction since over the years ground water extraction had increased to a significant extent and the observed river flows were corrected for the additional evapotranspiration that was occurring due to the use of ground water. Estimates based on Khosla's formula, however, do not need any correction since by Khosla's formula, runoff is estimated from the observed rainfall and temperature and no observed river flows are used as such in the estimation. For making corrections on the average annual flows worked out on the basis of observed river flows, Central Water Commission (CWC) in the above report made use of the district- wise estimates of ground water drafts made by Central Ground Water Board for the year 1983-84. The total ground water draft for the country as a whole for that year was about 100 km^3.

No further overall assessment studies were carried out subsequent to the above. However, some studies were done from time to time in respect of a few basins for specific purposes. For instance, in the case of Godavari basin, Krishna-Godavari Commission estimated in 1962 the average annual runoff in Godavari. Cauvery Fact Finding Committee estimated the runoff in Cauvery in 1972. Similarly an estimate of Krishna flows were made in 1973 for Krishna Water Disputes Tribunal and of Narmada flows in 1979 for the Narmada Water Disputes Tribunal. Central Water Commission made fresh studies in respect of a few river basins such as Ganga, Mahanadi, Subernarekha, Sabarmati and Tapi.

Over these many years, the Land Use Land Cover (LULC) and the climate has changed to a remarkable extent. WRA which was done statistically earlier, can now be done using hydrological model. The world of hydrological modelling has boomed up such that models like VIC considers the sub-grid variability to calculate the water balance grid wise. Remote sensing data can easily be incorporated into the model to get more precise results. This methodology of using remote sensing data and hydrological modelling will definitely help in accomplishing more accurate water resource assessment. Here we are using a water balance approach to assess the water resource.

The Water Budget equation can be written as:

$$P = Q + Baseflow + ET + SM \pm \triangle TWS + (other\ components) \quad (1.1)$$

Where,

P = Precipitation,

Q = Runoff,

ET = Evapotranspiration,

SM = Soil moisture,

$\triangle$TWS = Change in Terrestrial Water Storage and other components include interception, shallow and deep groundwater storage, snow and glaciers, etc.

From the above equation, parameters like precipitation, ET, $\triangle$TWS and other parameters can be measured with the help of remote sensing. Whereas parameter like runoff and baseflow can be generated with the help of a hydrologic model (VIC). The model outputs are mandatory to be validated with the ground truth. On ground, precipitation can be obtained from rain gauge stations and various weather stations located at different sites. Since precipitation depends on cloud top temperature, ET on radiation, land cover, vegetation and other parameters, ΔTWS on mass change; these can be obtained or derived with the help of remote sensing.

Studies have been done recently to close the water budget by combining the results of water budget components derived with the help of various satellite data. However, in these studies, major water budget variables such as ET, precipitation and runoff were derived. Then subtracting each component from precipitation was assumed to be the error in water balance which include ΔWS, interception and ΔSM, etc., majority being Δwater storage (M. 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 △TWS. 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 'cm' of terrestrial water storage but its grid size is very large (Frappert et. al., 2011). And hence downscaling is required to obtain more accurate and spatially distributed groundwater estimate.

For different study areas, satellite derived precipitation, ET and ΔTWS has been used in many studies. However, very few studies show that to close the water budget, these datasets along with hydrological model outputs has been used for India. Work here reflects closure of water balance with maximum possible accuracy for the Narmada basin using satellite data and hydrological model.

Depending on the above mentioned constraints of studies done previously, in order to reduce the error in water budget and its accurate closure it is necessary to derive ΔTWS individually. 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 the above factor, the Narmada basin having an area of 340496 km^2 is selected. Depending upon season, India possesses an ideal place with comparatively diminishing and excess water recharge.

Errors in balancing may be due to temporal scale variation or spatial scale variation apart from depending on the satellite data used in water budgeting. Hence, proper data is required to be selected to obtain accurate water budgeting after bringing all the datasets in common temporal and spatial resolution. For precise water budget, hydrological models like VIC model or SWAT model which derives component by considering soil parameters, vegetation parameters, meteorological parameters, Land Use/Land Cover, etc. Instead of sub-grid variations only one LULC class in one grid is considered by SWAT model. While, VIC model considers sub-grid LULC and soil moisture variations in same grid and gives more accurate output along with albedo, LAI, rooting depth, rooting fraction and meteorological forcings (Lohmann et al., 1998a).

WRA enables us to study the impact of LULC changes on the availability of the water resources. Change in LULC quantitatively affects the Runoff, ET and Groundwater (Water Balance components) of the WRA unit. Hence, study of the effect of LULC changes on hydrology of the unit is important. The influence of LULCC can be determined by comparing the outputs obtained from hydrological model or the satellite data and observed ground data (Eg. Discharge at an outlet of the basin, Groundwater level fluctuations, etc.).

1.3 VARIABLE INFILTRATION CAPACITY MODEL (VIC)

For water resources management, land-atmosphere interactions and climate change the widely used hydrological model is variable infiltration capacity (VIC) model (Liang et al., 1994, 1996b). VIC has vital roles, when combined to GCM, of both a hydrologic model and land surface scheme. Within a grid cell, both the water and surface energy budgets are balanced by this semi-distributed macroscale hydrological model (VIC). Variations in the sub-grid are statistically captured by the VIC model.

VIC model has some distinguished characteristics namely, LULC subgrid variability and soil moisture retaining capacity, nonlinear base flow, includes orographic precipitation and temperature lapse rates in mountainous regions. This gives a more realistic hydrology. (Water Budget Record from Variable Infiltration Capacity (VIC) Model Algorithm Theoretical Basis Document) by (Gao et al., 2007). Post processing of the VIC outputs with linear based transfer function independent routing model (Lohmann, et al., 1996; 1998a; b) is necessary in order to stimulate the stream flow. Representation of water management effects which has reservoir operation, irrigation diversions and return flows are allowed to be adapted by VIC model (Haddeland et al., 2006a; b; 2007).

1.4 IMPORTANCE OF REMOTE SENSING AND GIS IN HYDROLOGICAL MODELLING

Hydrological modeling is the mathematical representation of the major components of Water cycle. In the 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). At a basin scale, the distributed hydrological model gives more accurate estimate of Water budget components. Assimilation of accurate data in the hydrologic model helps to produce better results. Remote sensing has potentials to measure spatial as well as temporal variation of climatic parameters and variables. These parameters play a vital role in hydrology. Hence integrating remote sensing data into hydrologic model will help generating valid outputs. Parameters such as precipitation, snow cover, ET, soil moisture, etc. can be obtained from remote sensing. Runoff cannot be measured from remote sensing directly but can be generated with the help of hydrological modeling. Also parameters such as albedo, Leaf Area Index (LAI), flow direction etc., derived from satellite data are used in hydrological modeling. Using Digital Elevation Model (DEM), GIS generates various hydrological properties such as drainage network, flow direction, aspect, height, etc. It also helps in storing, processing, interpreting and analyzing the satellite data.

1.5 RESEARCH OBJECTIVES AND RESEARCH QUESTIONS

The aim of present study is to assess the water resources in the basin in terms of surface water and groundwater by using water balance approach. The water budget components are estimated using satellite data and VIC hydrological model after incorporating scaling issues. Study area selected is the Narmada basin.

1.5.1 Research Objectives

- To set up hydrological model and its parameterisation at basin level.
- To study water balance of the basin through surface water and ground water resources assessment using hydrological model and remote sensing inputs in the basin.
- To study of the impact of LULC change on water resource in the basin.

1.5.2 Research Questions

- Which hydrological model is suitable for basin level water balance studies and which parameters are sensitive to the model outputs?
- How to solve water balance of a basin by assessing surface water and ground water resources using hydrological model and remote sensing inputs?
- What is the impact of LULC change on the hydrology of the basin?

2. LITERATURE REVIEW

2.1 WATER RESOURCE ASSESSMENT

The study from (García et al., 2008) describes a work designed to estimate surface water resources in twelve basins in north Spain simply by numerical tools. Basins are generally characterized by their small surface area, short length, steep slope, in addition to scarce hydrological gauging. The viewable facts possesses conditioned use of any lumped continuous simulation hydrological model. HEC-HMS program throughout continuous soil moisture accounting (SMA) model were chosen. The model application form permitted assessment of the daily flow sequence on different main stream locations in the course of the continuous date period up in order to thirty-three water years. These kinds of series has become consumed. In the same way, input facts with regard to instream flows reports right after guidelines of a European Water Framework Directive. The processing associated with results helped pertaining to analysis of any hydrological behavior of a harvested basins focusing in low water periods.

During the situation of stressed surface water and deteriorating groundwater supplies, it becomes necessary to make decisions in the water resources in order to have consistent water stores of sufficient quantity and quality. This condition is true especially for the semi-arid regions. The emerging reliable sources of information for hydrological components are the remote sensing datasets. (A. AghaKouchak, 2013) highlights the applications of satellite derived data for drought monitoring, precipitation, flood forecasting and management of available water resources.

The paper transacts the methodology used intended for conducting a water resource assessment as core components of water resources. This is the quantitative and also qualitative water resource balance (WRB) as well as a great essential element of a soon or maybe long-term planning regarding sustainable in addition to environmentally sound river basin development along with management. He stated that employed the water resource management balance instead of any water resource balance (water budget), the idea includes the water withdrawals and discharges on the balance equation must possibly to be favored in water resource assessment. By having a water resource management balance, multiple use of a granted volume associated with water will be accounted pertaining to making it possible to be able to satisfy larger water prerequisites in comparison with through the natural water budget approach, concludes (R.M. Miloradov et al., 1995).

The study by (Sharma et al., 2015) focuses at suggesting short term corrective ways regarding improving water supply to be able to Shimla city, Himachal Pradesh. The location is actually getting water be taken via seven located inside three watersheds. 37% of any produce water require associated with water can be being drawn from Giri River. Resource assessment inside Giri watershed performed utilizing Remote Sensing procedures and also GIS based Arc-SWAT Hydrological Model. Study derived water budget components were the percentage with respect to average annual precipitation. He considered Water Balance equation as the criteria for validation because ungauged watershed do not have statistical information for authentication. Coefficient regarding correlation 'R' between observed Rainfalls along with simulated Runoff was 0.94 thus enough to verify the result. He also revealed that the surplus inflow works extremely well to be able to fulfill extra water demand of the Shimla city by creating room for water storage.

(M.Rodell, 2013) states that "force of Earth's gravity field varies in proportion to the amount of mass near the surface." The Gravity Recovery and Climate Experiment (GRACE), the first satellite mission dedicated for monitoring temporal variations with the gravity field. Current monthly gravity anomaly maps shipped from GRACE because 2002 usually are meant to infer changes with terrestrial water storage (the amount connected with groundwater, soil moisture, surface waters, in addition to snow along with ice. Additional remote sensing strategies are unable to detect water below the primary few centimeters of your land surface. Conventional ground-based approaches can be employed to monitor terrestrial water storage, but groundwater, soil moisture, and also snow observation networks usually are sparse with almost all parts of a world and the nations. Thus, GRACE is usually unique in its ability to give the global information in variations on the availability associated with freshwater, that'll be both important to life on land along with vulnerable to climate variability and also mismanagement.

A water resource vulnerability (WRV) assessment is actually clicks to maintain water resource security throughout a basin. An index system, including four subsystems the hydrological subsystem, socioeconomic subsystem, eco-environment subsystem plus the hydraulic engineering subsystem, can be made with regard to the integrated WRV assessment connected with Guanting Reservoir Basin, North China. The parametric technique (PS) program. In accordance with background signal can be obtained because of its quantitative WRV assessment involving each subsystem and also of the integrated water resource system. Once assessment technique as well as results, plus the attributes of any process used, continues to be compared throughout anybody of any fuzzy optimization (FO) technique and also the grey relational analysis (GRA) method, explains (Wang et al., 2012).

2.2 WATER BUDGET COMPONENTS

2.2.1 Precipitation

Precipitation is considered to be the input of water on the earth for water cycle to complete. Precipitation includes water in the forms 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 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. This error 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, explains (Subramanya, 1994).

The 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. The satellite data can be obtained from geostationary, polar or low-orbit satellites which are operated by international, national or private sector organizations, concludes (Sene, 2013).

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.

2.2.2 Evapotranspiration

The web page http://geochange.er.usgs.gov/sw/changes/natural/et/ says, evapotranspiration varies regionally in addition to seasonally, in the course of a drought this varies. According to weather, considering that related to most of these variabilities, water managers who are usually responsible for planning and adjudicating the distribution in connection with water resource need for getting the comprehensive understanding of a evapotranspiration method in addition to knowledge. About the spatial in addition to temporal rates in connection with evapotranspiration.

While in drought, the significance involving evapotranspiration is magnified, because the evapotranspiration maintains to be able to deplete limited remaining water inside lakes along with streams plus the soil. The more important points include net solar radiation, lakes, wind speed, density in addition to type involving vegetative cover, availability connected with soil moisture, root depth, reflective land-surface characteristics, along with season of year.

(Almhab et al. 2007) derived ET with SEBAL method by using satellite data input from Advanced Very High Resolution Radiometer (AVHRR) on board 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.

(Swenson and Wahr, 2006) says, observations involving important components of any earth's large-scale water as well as energy budgets tend to be sparse or even nonexistent. Important component, precipitation minus evapotranspiration (P - ET), persists largely unmeasured to its absence connected with observations associated with ET. Precipitation minus evapotranspiration describes flux of water between atmosphere and also the earth's surface, as well as so offers key facts in regards to the interaction of the atmosphere from the land surface. Large-scale changes throughout continental water storage derived from satellite gravity facts by the Gravity Recovery and Climate Experiment (GRACE) project tend to be combined within river discharge details to have estimates associated with tend to be ally averaged P-ET. Immediately after constructing a good equation describing large-scale terrestrial water balance reflecting temporal sampling connected with GRACE water storage estimates, GRACE-derived P-ET estimates are in comparison with those consumed through a good reanalysis dataset in addition to land surface model drive within observation-based forcing [Global Land facts Assimilation technique (GLDAS)/Noah] regarding a couple of large U.S river basins. Showing how GRACE P-ET estimates can be utilized to validate model output, the accuracy of GRACE estimates involving both seasonal cycle as well as the monthly averaged rate of P-ET will be examined. Finally, potential with regard to estimating seasonal evapotranspiration is demonstrated via combining GRACE seasonal P-ET estimates inside independent estimates of seasonal cycle regarding precipitation.

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).

2.2.3 Groundwater

(Döll et al., 2012) states that humans have strongly impacted your current global water cycle, not single water flows but in addition water storage. It's done at an initial global-scale analysis of an impact associated with water withdrawals with water storage variations, while using the global water as well as utilize involving model WaterGAP. This necessary estimation connected with fractions of whole water withdrawals by groundwater, considering all 5 water use sectors. As outlined by the assessment, the source associated with 35% of water withdrawn world-wide (4300 km3/year in the course of 1998–2002) is actually groundwater. Computed net abstractions indicate, to its very first time in the global scale, by which and as soon as human water withdrawals straight down or increase groundwater or perhaps surface water storage. In regions inside extensive surface water irrigation, similar to Southern China, net abstractions via groundwater usually are negative, i.e. groundwater is usually recharged via irrigation. Opposite can be genuine intended for areas dominated by groundwater irrigation, such as at the High Plains aquifer of central USA, where net abstraction involving surface water is usually negative since return flow connected with withdrawn groundwater recharges surface water compartments.

In this actual study by (Swenson et al., 2008), they estimated a time frame sequence associated with regional groundwater anomalies coming from combining terrestrial water storage estimates via GRACE satellite mission within in situ soil moisture observations of the Oklahoma Mesonet. Making use of supplementary information by the division connected with Energy’s Atmospheric Radiation Measurement (DOE ARM) network, they develop an empirical scaling factor with that in order to associate soil moisture variability on the top 75 cm sampled through the Mesonet sites for overall variability for the upper 4 m of an unsaturated zone. From subtracting this estimate of an full unsaturated zone soil moisture anomalies, they arrived in time series connected with groundwater anomalies, spatially averaged a lot more than a great region of approximately 280,000 km^2 inside area. Results tend to be than observed correctly level particulars from a larger surrounding region, in addition to show consistent phase along with relative inter-annual variability.

(Frappart et al., 2011), the particular study delivers monthly estimates of groundwater anomalies within an large river basin dominated from extensive floodplains, current Negro River Basin, based on the synergistic analysis applying multi-satellite observations along with hydrological models. for period 2003–2004, changes throughout water kept with the aquifer will be isolated from the total water storage measured coming from GRACE by removing contributions connected with both ones surface reservoir, derived from satellite imagery along with radar altimetry, and also the root zone reservoir simulated coming from WGHM and also LaD hydrological models. Groundwater anomalies show a realistic spatial pattern compared by the hydrogeological map of a basin, and similar temporal variations to local throughout situ groundwater observations in addition to altimetry-derived level height measurements. Results highlight your current potential involving combining multiple satellite methods inside hydrological modeling to estimate ones evolution involving groundwater storage.

(Strassberg *et al.*, 2007), the study provides the very first comparison involving seasonal groundwater storage (GWS) variations derived through GRACE satellite details in groundwater-level measurements through the High Plains Aquifer, US (450,000 km^2). This study presents first comparison regarding seasonal groundwater storage (GWS) variations derived through GRACE satellite info with groundwater-level measurements with the High Plains Aquifer, USA (450,000 km^2). Correlation between seasonal GRACE terrestrial water storage (TWS) along with the variety connected with GWS estimated coming from pack measurements (2,700 wells) as well as soil moisture (SM) simulated from the land surface model is high ($R = 0.82$). Correlation between GRACE-derived as well as measured GWS are ($R = 0.58$). Seasonal GRACE-derived TWS along with GWS changes were detectable (≥ uncertainty) while in 7 and also numerous out regarding 9 monitored periods respectively, whereas maximum changes (between winter/ spring and summer/fall) throughout TWS and also GWS were detectable with a few monitored periods. These types of results show your current potential with regard to GRACE in order to monitor GWS changes within semiarid regions through which irrigation pumpage causes large seasonal GWS variations.

(Kuss et al., 2012) concluded that Gravity Recovery and Climate Experiment (GRACE) methods gravity anomalies at earth in order to estimate changes in overall water storage (TWS), may be a convenient tool regarding calculating changes within groundwater storage with regard to California's agriculturally productive Central Valley region. Under current California law, very well owners tend to be not needed to statement groundwater extraction rates, creating estimation of total groundwater extraction difficult. Being a result, various other groundwater change identification methods usually are used to estimate changes in groundwater storage for the Central Valley aquifer. By October 2002 in order to September 2009, GRACE feel meant to measure changes in TWS for its Sacramento River Basin, as well as the San Joaquin River Basin, of which contain Central Valley aquifer. Net groundwater storage changes were calculated by the changes throughout TWS from incorporating estimates with regard to added components of hydrological budget like soil moisture, snow pack, along with surface water storage. Changes throughout groundwater storage on the river basin along with regional level were after that as compared to modelled values calculated with all the California department of Water Re' Central Valley Groundwater-Surface Water Simulation Model (C2VSIM).

2.3 WATER BUDGET USING SATELLITE DATA AND HYDROLOGICAL MODEL

For selection of a hydrological model main possesses regarding distinguishing approaches are; the nature connected with uncomplicated algorithms (empirical, conceptual or even process-based), regardless of whether an stochastic or maybe deterministic approach will be taken, along with regardless of whether spatial representation will be lumped as well as distributed. The first feature defines if the model is based on a simple mathematical link between input and output variables of the catchment or it includes the description. Generally, when the observations are reliable and adequate, extremely simple statistical or parametric models are used. They vary from the simple regression models to the more recent Artificial Neural Networks models. These models are strongly dependent on the data used for calibration and, ought to non-linear behaviour of the rainfall-runoff process. Their reliability beyond the range of observations may be questionable. For this reason conceptual models are generally preferred. The term conceptual denotes also the fully distributed physically based models because, even if they use parameters which are related to physical characteristics of the catchment and operate in a distributed framework, they must use average variables and parameters at grid or element scales greater than the scale of variation of the processes modelled (NRSC Report, 2009).

A WRA report by NRSC and CWC explains another basic distinction between models is whether stochastic or deterministic representations and inputs are to be used. Most models are deterministic so they generate a single set of output. On basis of the spatial representation, hydrological models can be classified in to three main categories: lumped models, semi-distributed models, and distributed models. The semi - distributed in addition to distributed products carry a good explicit accounts connected with spatial variability involving processes, input, boundary conditions, and/or watershed attributes. Of course, lack of data prevents such a general formulation of distributed models that is these models cannot be considered fully distributed (NRSC Report, 2009).

Selection of a model is based on the objectives of study, data available, spatial and temporal scale of the study. Each model requires different type of input data, when we are doing hydrological modelling at basin level one has to optimise the model considering the availability of input data. It is obvious that distributed or semi-distributed models are more accurate in runoff estimation compared to lumped models. Land use, soil texture, and digital elevation models are basic topographic input for any distributed hydrological modelling, as stated in the WRA report by NRSC and CWC.

This study by (Nijssen et al., 2001) says that the ability to simulate coupled energy and also water fluxes over large continental river basins, throughout streamflow, feel largely non-existent a decade ago. Considering that the then, macroscale hydrological models (MHMs) may be developed, in which predict these types of fluxes on continental in addition to subcontinental scales. Because runoff formulation within MHMs must end up being parameterized from the large spatial scale with of which they are implemented, several calibration connected with model parameters will be inevitably necessary. However, calibration can be a time-consuming method and also very easily becomes infeasible as soon as ones modelled location or current range associated with basins increases. The methodology with regard to model parameter transfer is stated the item limits quantity of basins requiring straight calibration. Parameters initially were approximated with regard to ten large river basins. To be a very first attempt in order to transfer parameters, global land area was grouped through climate zone, and model parameters were transferred inside zones. The transferred parameters were and then designed to simulate water balance within 17 some other continental river basins.

In this paper coming from (Milewski et al., 2009), efforts to realize in addition to quantify precipitation and its partitioning straight into runoff evapo-transpiration, as well as recharge usually are hampered because of the absence as well as paucity associated with correct monitoring systems. They applied methodologies with regard to rainfall–runoff and groundwater recharge computations. That heavily rely in observations extracted by way of a great wide-range connected with global remote sensing info sets (TRMM, SSM/I, Landsat TM, AVHRR, AMSR-E, as well as ASTER) while using arid Sinai Peninsula (SP; area: 61,000 km2) plus the Eastern Desert (ED; area: 220,000 km2) regarding Egypt similar to his test sites. A two-fold exercise was conducted. Spatiotemporal remote sensing information (TRMM, AVHRR as well as AMSR-E) were extracted from global information sets through the test sites utilizing RESDEM, Remote Sensing data Extraction Model, as well as were next designed to brand and to check precipitation events with the past 10 years (1998–2007). The actual are done through an automated cloud detection program to recognize clouds along with their propagation prior to and also through the identified precipitation events, as well as via examining changes within soil moisture (extracted coming from AMSR-E data) after identification regarding to clouds.

This paper by (Xie et al., 2007) presents a methodology with regard to regional parameter estimation of a three-layer Variable Infiltration Capacity (VIC-3L) land surface model from the goal regarding improving ones streamflow simulation for river basins throughout China. This methodology is actually made to find model parameter estimates from a limited range involving calibrated basins and then regionalize them in order to uncalibrated basins According to climate capabilities as well as large river basin domains, and ultimately to be able to continental China. Fourteen basins by other climatic zones and large river basins were selected pertaining to model calibration. For each connected with these basins, nine runoff-related model parameters were calibrated using a systematic guideline calibration approach.

Most of these calibrated parameters were after that transferred on the climate and large river basin zones or perhaps climatic zones to the uncalibrated basins. To check efficiency of parameter regionalization method, a proof study am conducted with 19 independent river basins with China. Overall, regionalized parameters, whenever evaluated against the good priori parameter estimates, were in a position to reduce the model bias.

The study perform by (Karimi et al., 2013) demonstrates ones application form new water accounting plus (WA+) framework to supply all about depletion connected with water re, storage change, in addition to land and also water productivity on the Indus basin. It shows how satellite-derived estimates regarding land use, rainfall, evaporation (E), transpiration (T), interception (I) and biomass production works extremely well as well as measured basin outflow, regarding water accounting with WA+. This is demonstrated that this accounting results is usually interpreted to distinguish existing issues and verify merchandise because of its future. Based towards the results involving accounting exercise loss involving storage, low helpful depletion, and low land in addition to water productivity were identified just like main water re management issues.

A methodology regarding developing regional parameter estimation equations, created for in order to continental scale river basins, is described by (Abdulla and Lettenmaier, 1997). The approach, that'll be applied on the two-layer Variable Infiltration Capacity (VIC-2L) land surface hydrologic model, uses a great set associated with 34 unregulated calibration or even ‘‘training’’ catchments (drainage areas 102–104 km2) distributed over the Arkansas–Red River basin of any south central U.S. with regard to each associated with these kinds of catchments, parameters were determined by: a) prior estimation regarding two model parameters (saturated hydraulic conductivity and also pore size distribution index) by the U.S. Soil Conservation ASSISTANCE State Soil Geographic information Base (STATSGO) info base; and b) estimation of an remaining seven parameters by using a search procedure. The item minimizes quantity regarding squares regarding differences between predicted and also observed streamflow. Model did not perform in the same way properly because of its smaller range associated with arid to be able to semi-arid catchments.

2.4 CHANGE IN TERRESTRIAL WATER STORAGE AND GRACE

The Gravity Recovery and Climate Experiment (GRACE) is unprecedented in that it is the first satellite remote sensing mission directly applicable for regional groundwater mapping though its primary directive is to obtain accurate estimates of Earth’s gravity field variations claims (Rodell M. et al.,2006).

(Tapley et al., 2004), explains that the mission consists of two satellites flying in tandem in a polar, near circular orbit at 500 km altitude with an inter-satellite separation distance of approximately 220 km. The gravity field information is actually inferred from the inter-satellite distance which is measured within μm accuracy using a K-Band microwave system. Potential error sources such as atmospheric drag and satellite perturbations are measured and filtered out using readings from a highly accurate, on-board accelerometer while precise positioning is determined using on-board GPS receivers. The two satellites (also known as 'Tom' and 'Jerry') work in tandem to map the gravitational field of the Earth. When surface features that distort the gravitational strength such as mountains (which decrease the gravitational field strength) are encountered, the leading satellite accelerates by a certain amount followed by the trailing satellite which then catches up. These minute changes in the inter-satellite distance are then fed into what are essentially massive regression engines in order to determine the gravity field strength at the data processing facilities in Jet Propulsion Laboratory (JPL), University of Texas – Austin Centre for Space Research (CSR), and the GeoForschungZentrum (GFZ).

(Rodell M., 2013), describes the unique and hard aspects associated with GRACE terrestrial water storage information within his chapter. Also, examples of how the data may be used for research and also applications regarding freshwater vulnerability along with change, in addition to possibilities with regard to continued contributions connected with satellite gravimetry to help water resource science along with policy. The strain associated with Earth's gravity package varies within proportion in order to the level of mass near your own surface. Gravity Recovery and Climate Experiment (GRACE) could be the initial satellite mission dedicated to help monitoring temporal variations at the gravity field. The monthly gravity anomaly maps are usually being intended to infer changes throughout terrestrial water storage (the volume associated with groundwater, soil moisture, surface waters), which are very first regarding gravity variability. Other remote sensing methods are not able to detect water below land surface. Conventional ground-based strategies can be utilized in order to keep an eye on terrestrial water storage, but groundwater, soil moisture, and snow observation networks are generally sparse with many parts of the world. It do collect these types of information are usually rarely willing to share them. Thus, GRACE is usually unique within its ability to provide global data at variations on the availability of freshwater.

(Rodell M. et al., 2004), explained the item based on satellite observations connected with Earth's time variable gravity field with the Gravity Recovery and Climate Experiment (GRACE), it is possible to derive variations within terrestrial water storage, such as groundwater, soil moisture, as well as snow. Released auxiliary specifics towards the latter two, single will probably estimate groundwater storage variations. GRACE will be the singular hope with regard to groundwater depletion assessments with data-poor regions of any world. With this study, soil moisture along with snow were simulated because of the Global Land data Assimilation process (GLDAS) and also meant to isolate groundwater storage anomalies via GRACE water storage details for Mississippi River basin in addition to the four biggest sub-basins. Results were evaluated using water level records from 60 wells set at the unconfined aquifers of basin. Uncertainty with the program was furthermore assessed. GRACE-GLDAS estimates compared favorably from the well based time sequence for Mississippi River basin and also the 3 sub-basins which can be larger than 900,000 km^2. Continuing enhancement of the GRACE processing methods will be likely to help improve the skill of a method with the future, while likewise increasing ones temporal resolution.

(Kuss A.M. et al., 2012), described that estimates regarding groundwater availability throughout California have mentioned declines with GW levels that may pose a threat on the sustainability connected with the particular region. Gravity Recovery and Climate Experiment (GRACE) can be utilized to estimate variations throughout complete water storage (TWS) in addition to GW storage changes. However, employing GRACE details for the Central Valley aquifer (CVA) is hard for the coarse spatial resolution. Climate variability furthermore alters precipitation, GW recharge, and also pumping practices. Throughout the actual study, a good statistical downscaling approach applied to help GRACE facts with the sub-region level will be obtained next applied downscaled GRACE estimates to investigate influence of climate variability. Understanding effects involving climate variability on GW storage changes may improve GRACE-derived estimates involving GW availability while in periods connected with increased rain as well as droughts. Downscaling GRACE-derived GW storage estimates applying C2VSim data are successful employing linear products at the sub-region level. The results indicated variations throughout water availability. Study concludes the idea incorporation associated with these kinds of new ways for estimating variations with GW storage within productive aquifers can improve water management techniques.

(M. Rodell, 2013) in his paper titled Application of Satellite Gravimetry pertaining to Water Resource Vulnerability Assessment states the techniques additional remote sensing strategies are not able to detect water below primary few centimeters of the land surface. Conventional ground-based approaches can be utilized to account for terrestrial water storage, but groundwater, soil moisture, along with snow observation networks usually are sparse inside many parts of the world as well as the nations around the world. It do collect these kinds of data are usually rarely willing in order to share them. Thus, GRACE will be unique throughout their ability to give the global details from variations on the availability involving freshwater, which will be both essential to be able to life with land as well as vulnerable in order to climate variability and also mismanagement.

2.5 IMPACT OF LAND USE AND LAND COVER (LULC) ON HYDROLOGY

In the study coming from (Homdee et al., 2011) SWAT model was designed to investigate potential impacts regarding LULC at water budget Chi river basin throughout Thailand. Five plausible scenarios associated with land work with change were evaluated, like a good conversion of forested area, expansion of farmland, switching regarding rice paddy fields to energy crops as well as only two scenarios connected with conversion of farmland to rice along with sugarcane plantation. Results indicated this different land use scenarios contributed to help several effects inside annual along with seasonal water yield and also evapotranspiration (ET). Conversion associated with forested area and farmland showed slightly small changes in water flows and ET.

A study spatial and temporal changes with land use land cover (LULC) feel conducted utilizing Remote Sensing and GIS by (Raj and Azeez, 2010). They tested LULC involving Bharathapuzha river basin, south India applying multispectral LANDSAT imageries involving 1973-2005 day periods. Their study highlighted need intended for a great scientific management plan to its sustainability of a river basin, keeping with check out recent climatic anomalies along with hydrological ailments of a basin.

The SWAT model feel considered coming from (Githui et al., 2009) to be able to investigate ones impact regarding land-cover changes on the runoff of River Nzoia catchment, Kenya. Model calibrated against measured daily discharge, and also land-cover changes were examined in the course of classification regarding satellite images. Land-cover change scenarios were generated, namely worst-best-case scenarios. A comparison between 1970–1975 as well as 1980–1985 showed the idea land-cover changes accounted with regard to a good difference in surface runoff ranging by 55 to help 68% between only two time frame periods. One's land-cover scenarios taken showed magnitude of changes inside runoff due to help changes at the land covers considered.

(VanShaar et al., 2002) explains topographically explicit distributed hydrology–soil–vegetation model (DHSVM) intended to simulate hydrological effects involving changes inside land cover pertaining to four catchments in Columbia River basin. Surface fluxes (stream flow along with evapotranspiration) along with state variables (soil moisture and snow water equivalent) corresponding for you to historical (1900) in addition to current (1990) vegetation were compared. Comparisons with the macroscale variable infiltration capacity (VIC) model, that parameterizes topographic effects, show runoff predicted from DHSVM will be additional sensitive to be able to land-cover changes when compared with is usually runoff predicted coming from VIC. This was explained from model differences with soil parameters as well as evapotranspiration calculations, and through the more explicit representation of saturation excess within DHSVM in addition to higher sensitivity to be able to LAI changes on the calculation involving evapotranspiration.

(Nie et al., 2011) states that the assessment connected with Landuse and Landover (LULC) changes at hydrology will be expected to its development of sustainable water resource strategies. Specifically, understanding how change throughout each LULC class influences hydrological components may greatly improve predictability involving hydrological consequences to LULC changes along with will certainly assist stakeholders make superior decisions. However, granted the limited availability connected with digital LULC maps in addition to simultaneous changes of multiple LULC classes, this is challenging to quantify impacts regarding change throughout one LULC class at hydrology. With the particular study, an integrated approach associated with hydrological modeling as well as multiple regression analysis feel applied to quantify contributions regarding changes for sole LULC classes with changes throughout hydrological components. As being a case study, hydrological modeling are conducted with regard to each of the LULC map within four date periods (1973, 1986, 1992, AS WELL AS 1997) with the upper San Pedro watershed while using Soil as well as Water Assessment Tool (SWAT). Changes inside hydrological components between two simulations applying LULC maps throughout 1997 and 1973, respectively, were concerning changes associated with LULC in the multiple regression to help quantify effect regarding changes within LULC in order to that connected with hydrological components in the sub-basin scale.

(Menzel et al., 2009) features given overview of possible future land and water conditions of the greatest section of an Eastern Mediterranean region. They applied ones hydrological model TRAIN to help simulate current water availability (runoff as well as groundwater recharge) and irrigation water require with a 1 km ×1 km spatial resolution. Results demonstrated scarcity involving water resources with the study region, within extremely low values of water availability on the semi-arid and arid parts. Then, the set of four divergent scenarios to the future regarding water feel formulated having a stakeholder driven approach. Relevant drivers pertaining to LULC change were fed in to the LandSHIFT. R model to be able to present land-use and land-cover maps because of its some other scenarios. They used these kind of maps in the same way input to help TRAIN in order to develop scenarios of water availability and irrigation water demand to its region.

(Petchprayoon et al., 2010) purpose of study was to be able to discover hydrological impacts regarding land use/land cover (LULC) change at the Yom watershed within central–northern Thailand a lot more than 15-year period. They used the integration associated with remote sensing, Geographic facts System, statistical methods, and hydrological modelling. Coupling associated with surface observations, remote sensing, and rainfall-runoff modeling demonstrated impacts connected with changes in LULC from peak river discharge.

3. STUDY AREA AND DATA USED

The Narmada basin (extended study area) encompasses an area of 3,40,496 sq. km and lies between longitudes 68°10’ E to 81°83’ E and latitudes 25° N to 21°27’ N. The extended study area consists of river basins of Tapi, Mahi, Sabarmati, Bhadar and part of Luni. All are the west flowing rivers, which deposits into the Arabian Sea.

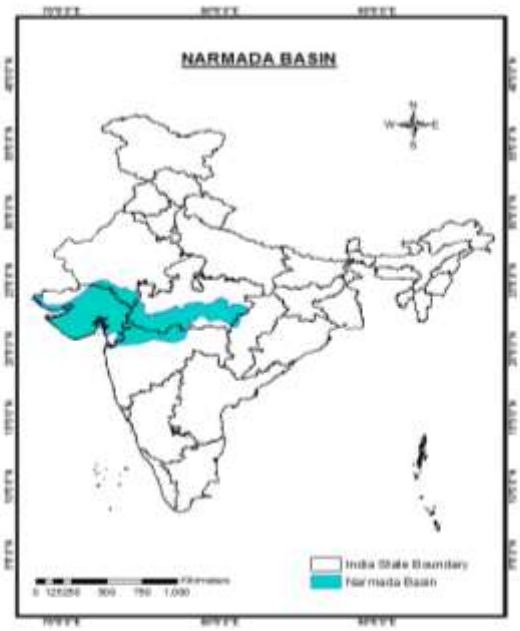


Figure 3-1 Study Area: Narmada Basin (extended)

3.1 NARMADA BASIN

3.1.1 Location and Physiography

The river falls into Gulf of Cambay (Arabian Sea) near Bharuch in Gujarat. It runs for 1,079 km in Madhya Pradesh, it creates a boundary line for a length of 35 km between Madhya Pradesh and Maharashtra and then for a length of 39 km between the States Maharashtra and Gujarat. The remaining length of 159 km flows through Gujarat. The catchment area up to Sardar Sarovar dam is 88,000 sq. km. The index map of the basin is shown in Figure 3.1.

To the east of Narmada basin lies the Maikala range, to the north lies Vindhyas, to the south lies the Satpuras and towards the west side lies the Arabian Sea. The basin length is 953 km (east to west) and width is 234 km (north south). The basin is divided into five physiographic zones which are the Upper hilly region (Balaghat, Durg, Mandla, Shahdol and Seoni), the Upper Plains (Betul, Chhindwara, Damoh, Hoshangabad, Jabalpur, Narsimhapur, Raisen, Sagar and Sehore), the middle plains (Dewas, Dhar, East Nimar, portion of west Nimar and Indore), the lower hilly (parts of Baroda, Dhule, Jhabua and west Nimar) and the lower plains (Broach and part of Baroda). The hilly regions are covered by forest. Cultivation is suitable in the lower, middle and upper plains. The land is fertile with black soils and alluvial clays along the coasts of Gujrat. (Source: *http://nca.gov.in/nb_geogr.htm)*

Table 3-1 Salient features of Narmada basin

Basin Extent	Longitude: 72° 38' to 81° 43' E Latitude: 21° 27' to 23° 37' N
Area Covered	Madhya Pradesh, Rajasthan, Gujarat (India)
Origin	Amarkantak Plateau of Maikala range, Shahdol, Madhya Pradesh
Length	1,312 km
Basin Area	98,796 sq km

(Source: http://india-wris.nrsc.gov.in)

3.1.2 Climate and Rainfall

Through the upper plains of Narmada basin crosses the tropic of Cancer. The basin has humid and tropical climate. During cold weather, the mean annual temperature ranges between 17.5° C to 20° C and during hot weather temperature range is 30°C to 32.5°C. The temperature experienced during South west monsoon is between 27.5°C to 30°C and 25°C to 27.5°C during post monsoon season. *(Source: http://nca.gov.in/nb_geogr.htm)*

During monsoon months (June to October), approximately, 90% rainfall is received. In July and August roughly 60% is obtained. Annual rainfall between 1400 mm to 1650 mm is experienced in the upper hilly regions. Near Jabalpur to Punasa dam site (the upper plains), the annual rainfall decreases from 1400 mm to less than 1000 mm. Annual rainfall exceeds 1800 mm in Pachmarhi and thus it is considered as the high rainfall zone. A rapid decrease in annual rainfall from 1000 mm (eastern region) and less than 650 mm around Barwani is witnessed in the lower plains. Thus, this part of Narmada Basin is characterized as the most arid region. *(Source: http://nca.gov.in/nb_geogr.htm)*

3.1.3 River System

Narmada River consists of 41 tributaries. Out of which, 22 falls on left bank and 19 falls on right bank. The important tributaries of the Narmada are listed below, *(Source: http://india-wris.nrsc.gov.in)*

3.1.3.1 Barna River

At an elevation of 450 m rises the Barna River (Vindhya Range, Raisen district, Madhya Pradesh). Barna is traced at 22°55' N and 77°44' E. Its length is 105 km and joins the Narmada near village Dimaria. *(Source: http://india-wris.nrsc.gov.in)*

3.1.3.2 Ganjal River

In the Satpura range emerges the river Ganjal (Betul district, Madhya Pradesh), at 800 m elevation. It lies at 22°0' N and 77°30' E. Length of the Ganjal River is 89 km. It meets the Narmada near village Chhipaner. *(Source: http://india-wris.nrsc.gov.in)*

3.1.3.3 Hiran River

At an elevation of 600 m, in the Bhanrer range rises the Hiran River (Jabalpur district, Madhya Pradesh). It originates at 23°12' N and 80°27' E. The river length in the south-westerly direction is 188 km. Thus partakes the Narmada River near village Sankal (from right side). *(Source: http://india-wris.nrsc.gov.in)*

3.1.3.4 Orsang River

At an elevation of 300 m, in the Vindhya ranges rises the Orsang (Jhabua district, Madhya Pradesh). It is located at 22°30' N and 74°18' E. It is 101 km long flowing (south-westerly direction) to run into the Narmada river near Chandod (from right side). *(Source: http://india-wris.nrsc.gov.in)*

3.1.3.5 Sher River

At an elevation of 600 m originates the Sher river through the Satpura range adjacent to Patan (Seoni district, Madhya Pradesh). Its coordinates are 22°31' N and 79°25'E. The river Sher runs (north-westerly direction) for 129 km to merge into Narmada River near Brahmand (from the left side). *(Source: http://india-wris.nrsc.gov.in)*

3.1.3.6 Tawa River

At an elevation of 900 m, the widest left bank tributary of River Narmada, the Tawa, emerges in the Mahadeo hills, Satpura range (Chhindwara district, Madhya Pradesh). Its lies at 22°13’N and 78°23’E. Tawa River courses (north-westerly direction) for 172 km to meet the river Narmada near Hoshangabad. *(Source: http://india-wris.nrsc.gov.in)*

3.2 MAHI BASIN

3.2.1 Physiography

Mahi River drains into the Gulf of Khambhat passing through Kheda (Gujrat) and is amongst the few interstate western flowing river existing in the Indian subcontinent. The Aravalli ranges bound the basin from the North and the North-West. Towards the East lies the ridge which separates it from the Chambal Basin. The Vindhyas covers the South and the Gulf of Khambhat on the West. The basin is 250 km wide with an elevation of 500 m. States of Gujarat, Madhya Pradesh and Rajasthan are traversed by the river. Kadana dam having catchment area of 25520 sq km and Wanakbori weir with 30665 sq km catchment area is sited on Mahi River at 25 km and 102 km respectively. *(Source: http://india-wris.nrsc.gov.in)*

The river route includes a path in northern direction from Dhar and Jhabua districts (Madhya Pradesh), turning to the left through Ratlam district (Madhya Pradesh), moving in the North-West direction to enter Banswara district (Rajasthan), then runs South-West to move into the Panchmahal district (Gujarat) and thus empties into the Gulf of Khambat (Arabian Sea) through Kheda district (Gujrat). *(Source: http://india-wris.nrsc.gov.in)*

Table 3-2 Salient features of Mahi basin

Basin Extent	Longitude: 72° 21’ to 75° 19’ E Latitude: 21° 46’ to 24° 30’ N
Area Covered	Madhya Pradesh, Rajasthan, Gujarat (India)
Origin	Dhar district, Sardarpura village, Madhya Pradesh
Length	583 km
Basin Area	34,842 sq km

(Source: http://guj-nwrws.gujarat.gov.in)

3.2.2 Climate and Rainfall

The summer (Mar-May), Monsoon (June-Sep) and winter (Oct-Feb) seasons are experienced by the Mahi basin. The sub-tropical wet climate is comprised in the northern part of the basin (covered by Rajasthan). The existence of Vindhyas and the Western Ghats causes the basin to be exposed to the tropical wet climate. The basin near the river experiences comparatively cooler and moderate rainfall climate reason being highly elevated forest land. As the river flows towards north entering into Rajasthan, the climate progressively becomes warm and dry. The climate slowly again fluctuates to tropical wet climate when the river bends towards south-west direction and enters Gujarat. *(Source: http://india-wris.nrsc.gov.in)*

The Mahi basin receives an average rainfall of about 785 mm. June mid to October first week is the South-West monsoon period. During the monsoon months 90% of total rainfall is received out of which 50% is received during July and August. Vadodara lies on the windward side of the Western Ghats thus it experiences more prominent effects. Since Ratlam lies between the Arravalli and hill ranges north of Western-Ghats, it receives same amount of Western monsoon. Monsoon contributes nearly 91-94% of annual precipitation in Vadodara and Ratlam respectively. *(Source: http://india-wris.nrsc.gov.in)*

3.2.3 River System

3.2.3.1 Som

At an elevation of 600 m rises Som river near Som and forms a right bank tributary of Mahi river. It lies on the Eastern slopes of the Aravalli hills (Udaipur, Rajasthan). It joins Mahi river at 6.3 km upstream of Paderdibadi site in Dungarpur, Rajasthan. Som river is 155 km long with 8707 sq km drainage area. The major right bank sub tributaries of Som are Gomti and Jakham. *(Source: http://india-wris.nrsc.gov.in)*

3.2.3.2 Panam

At an elevation of 300 m rises Panam river near Bhadra and forms the left bank tributary of Mahi river. It originates on Northern slopes of Vindhyas (Jhabua district, Madhya Pradesh). It runs through Panchmahal district (Gujarat) in the north-western direction. It is 127 km long with 2470 sq km drainage area. *(Source: http://india-wris.nrsc.gov.in)*

3.3 TAPI BASIN

3.3.1 Physiography

The River Tapi also known as Tapti, flows in East - West direction and transverses through Gujarat, Madhya Pradesh and Maharashtra and drains into the Arabian Sea. It is the second largest inter-state river. From the North, the Saputara mountain range, from South Ajanta and Satmala mountain range and from the East Mahadeva mountains surrounds basin of Tapi. In the Maharashtra region lies 80% of the Tapi basin. At a distance of 90 km and 120 km on Tapi River, Ukai dam with catchment area of 62225 sq km and Kakarapar weir with 62801 sq km catchment area is located. *(Source: http://india-wris.nrsc.gov.in)*

Table 3-3 Salient features of Tapi basin

Basin Extent	Longitude: 72° 33’ to 78° 17’ E Latitude: 20° 9’ to 21° 50’ N
Area covered	Madhya Pradesh, Maharashtra, Gujarat (India)
Origin	Betul District, Satpura Range, Madhya Pradesh
Length	724 km
Basin Area	65145 sq. km

(Source: http://india-wris.nrsc.gov.in)

3.3.2 Climate and Rainfall

Tapi basin receives an average rainfall of 830 mm. By June-mid, the south - west monsoon is set and ends by October-mid. During monsoon months, 90% of total rainfall is received out of which 50% is achieved during the months of July and August. The climate is claimed to be variable due to topographical characteristics. In winter, the temperature ranges between 5 °C to 14.5 °C. May is the hottest month of the year. In summers, the temperature contrasts between 38 °C to 48 °C. *(Source: http://india-wris.nrsc.gov.in)*

3.3.3 River System

3.3.3.1 Purna

The Purna is the left bank tributary originating in the Betul district (Madhya Pradesh). It is located in the Gawilgarh hills of the Satpura range. It drains the districts Amravati, Akola and Buldhana of Maharashtra (Vidharbha). *(Source: http://india-wris.nrsc.gov.in)*

3.3.3.2 Girna

The Girna, the left bank tributary, originates in the Western Ghats and drains the Nasik and Jalgaon districts of Maharashtra. The other major tributaries of the river Tapi are the Panjhra, Vaghur, Bori and Aner.

3.4 SABARMATI BASIN

3.4.1 Physiography

In India, Sabarmati River is one of the major Westwards flowing Interstate Rivers rising at an elevation of 762 m above MSL. It drains into the Gulf of Khambhat (Arabian Sea). The basin is boundary consists of Aravalli hills towards the North-East side and towards the south bounds the ridge that separates the basin from minor stream basins draining into Rann of Kutch and Gulf of Khambhat. The basin 105 km wide. Watrak, the source, being the apex point and main river as the base, the basin has a triangular shape. At 80 km, the Dharoi dam with catchment area of 5475 sq km and Vasna Barrage at a distance of 202 km consuming 10619 sq km catchment area are located on the Sabarmati River. *(Source: http://guj-nwrws.gujarat.gov.in/)*

Table 3-4 Salient features of Sabarmati basin

Basin Extent	Longitude: 70° 58’ to 73° 51’ E Latitude: 22° 15’ to 24° 47’ N
Area covered	Rajasthan, Gujarat (India)
Origin	Aravalli Hills, Rajasthan
Length	371 km
Basin Area	21674 sq. km

(Source: http://india-wris.nrsc.gov.in)

3.4.2 Climate and Rainfall

Summer (Mar-May), Monsoon (June-Sep) and Winter (Oct-Feb) are the sequenced seasons that Sabarmati Basin experiences. Sub-tropical wet climate persists in the northern part of the basin (Gujarat). Because of the Aravalli & the Western Ghats, majority of the basin has a tropical wet climate. In the Saurashtra, the climate is arid area while in north Gujarat it is semi–arid and in coastal areas the climate is humid. *(Source: http://india-wris.nrsc.gov.in)*

Rainfall is subjective to the south-west monsoon, from Saurashtra to the southern region of the basin, the rainfall fluctuates from a scanty mm to 1000 mm. Sabarmati Basin has an average annual rainfall of 787.5 mm. *(Source: http://india-wris.nrsc.gov.in)*

3.4.3 River System

3.4.3.1 Sei

It is a south-west flowing 95 km long river and draining an area of 946 km. It originates in the Aravalli hills of Rajasthan. It is a right bank tributary of Sabarmati river. *(Source: http://india-wris.nrsc.gov.in)*

3.4.3.2 Wakal

It is Left bank tributary of Sabarmati River rising in the Aravalli hills of Rajasthan. It flows for 88 km in South–West direction draining an area of 1625 sq km. The Menas being its major tributary. *(Source: http://india-wris.nrsc.gov.in)*

3.4.3.3 Harnav

It is a 75 km long river with a drainage area of 972 km, rising to the North of the Kulalia hills of Rajasthan. It joins the Sabarmati from left after flowing in South–West direction. *(Source: http://india-wris.nrsc.gov.in)*

3.4.3.4 Watrak

Rising from the Panchara hills in Dungarpur district (Rajasthan), it flows for 248 km to the Southwest direction and meets Sabarmati on the left bank. Watrak and its tributaries have a drainage area of 8638 sq km. *(Source: http://india-wris.nrsc.gov.in)*

3.5 LUNI BASIN

3.5.1 Physiography

The basin covers whole of Diu and also the areas of states of Gujarat and Rajasthan. Towards east, the Aravalli range and Gujarat plains the Luni basin. On the northern side sites the Rajasthan desert and the south and the west side is restricted by Arabian Sea. Luni river originates at an elevation of 772 m in Ajmer district (Rajasthan) from the western slopes of Aravalli ranges. The water spreads out without contributing any runoff, when the river flows forming a delta to the Rann of Kutch. (*Integrated Hydrological Data Book*, 2006)

Table 3-5 Salient features of Luni basin

Basin Extent	Longitude: 67° 52’ to 75° 19’ E Latitude: 20° 53’ to 26° 57’ N
Area covered	Rajasthan, Gujarat (India)
Origin	Aravalli Ranges, Ajmer, Rajasthan
Length	511 km km
Basin Area	32,879 Sq km

(Source: http://india-wris.nrsc.gov.in)

3.5.2 Climate and Rainfall

All the three seasons, summer and monsoon and winter season are experienced by the basin in a year. The temperature ranges between 2°C – 46°C all over the three seasons. The basin receives an average annual rainfall of 300 mm - 500 mm.

3.5.3 River System

The Bandi (Hemawas), Guhiya, Jawai, Khari Bandi, Lilri, Sagi, Sukri and the Sukri Bandi are amongst the major left bank tributaries of Luni river. While the Jojri river is the right bank tributary of the Luni river.

Shetrunji, the Bhadar, the Machhu, the Rupen, the Saraswati and the Banas are the independent rivers of the basin. Except for the Shetrunji and Bhadar rest drains into the Little Rann of Kutch. The other two outfalls into Gulf of Khambhat and Arabian Sea respectively.

3.6 DATA USED AND AVAILABILITY

3.6.1 Remote Sensing Data

- GRACE: GRACE monthly mass grids – land with level 5 developed by CSR (Center for Space Research at University of Texas, Austin) at 1° spatial resolution with time baseline January 2004 to December 2009. (Landerer F.W. and S. C. Swenson), (Swenson, S. C. and J. Wahr)
- AMSR-E (AQUA Satellite): Daily Soil Moisture at a spatial resolution 25km. *http://dx.doi.org/10.5067/AMSR-E/AE_LAND3.002*, (Njoku, E. G. 2004)
- Land Use Land Cover (ISRO-GBP) map at 1:250,000
- Shuttle Radar Topography Mission (SRTM): DEM at 90m (3 arc seconds) pixel spacing.

3.6.2 Ancillary Data

- CGWB (Central Ground Water Board): Groundwater level data (cm) from 2005 to 2013 district wise.
- NBSSLUP (National Bureau of Soil Survey and Land Use Planning): Soil Texture map at scale of 1:250,000
- IMD (Indian Meteorological Department): Daily Rainfall, Daily Maximum Temperature, Daily Minimum Temperature and Daily wind speed (point district-wise)

4. METHODOLOGY

This study is an integrated methodology that consists of selecting and parameterizing the hydrologic model outputs from hydrological model (VIC model) and satellite data (GRACE and AMSR-E), to close the water balance of Narmada basin (extended) for the year 2005 with maximum possible accuracy. The water budget components except for groundwater are derived from VIC model. Model is run in water balance mode. Generally, water balance mode has been run using daily rainfall, maximum temperature, and minimum temperature. But, for better estimation of water budget components especially evapotranspiration (ET) the wind speed is crucial. Parameter sensitivity analysis was done on Asan watershed, due to availability of data when the study was carried. All the other exploration were done for Narmada basin.

A wide range of hydrological models are available these days. In this study, models like SWAT, MIKE, VIC (Variable Infiltration Capacity) and HEC-HMS were compared to find the best suited model for the study. After much homework regarding the merits and demerits of each model, VIC model was concluded to be the perfect model amongst others and most appropriate for the study. The selection criteria is explained in the section 4.1.

The VIC model was initially parameterized. Wind speed has a potential impact on water balance components specially ET. Therefore, sensitivity of VIC model for the meteorological factor 'Wind speed' was studied. This sensitivity analysis was done for Asan watershed for a period of 1 year (2005).The results showed a remarkable change in both the cases (i) Results i.e. the water balance components while including Wind speed parameter and (ii) Results excluding Wind speed, in the meteorological forcing parameter file. Therefore, model was setup with the wind speed and the model was forced with 30 years (1980 – 2010) for three different types of LULC (Land Use Land Cover of 1985, 1995, and 2005) to study the effect of LULC change on hydrology of the Narmada basin. Thus, except for groundwater, the other water balance components, ET, runoff (R), change in soil moisture (ΔSM) and baseflow (BF) were obtained from the model for each LULC.

A correlation was developed between GRACE derived ΔGWS and seasonal variations of groundwater well level obtained from CGWB (Central Ground Water Board) for the year 2005 at 1°. This proves that the ΔTWS obtained from GRACE satellite can be substituted for ΔGWS attained from CGWB, ground data. Also $baseflow_{VIC}$ and ΔTWS_{GRACE} were correlated at 0.25° in order to prove that baseflow can be assumed to be the potential source of groundwater recharge. To separate ΔGWS from ΔTWS, ΔSM and ΔSW was to be subtracted. But, since ΔGWS in more dominant in ΔTWS, other components need not to be subtracted. The default time baseline (January 2004 to December 2009) was changed according to the study time baseline (January 2005 to December 2005).

This chapter describes the overall methodology of the work. Flow chart is given below for a better overview of the work done.

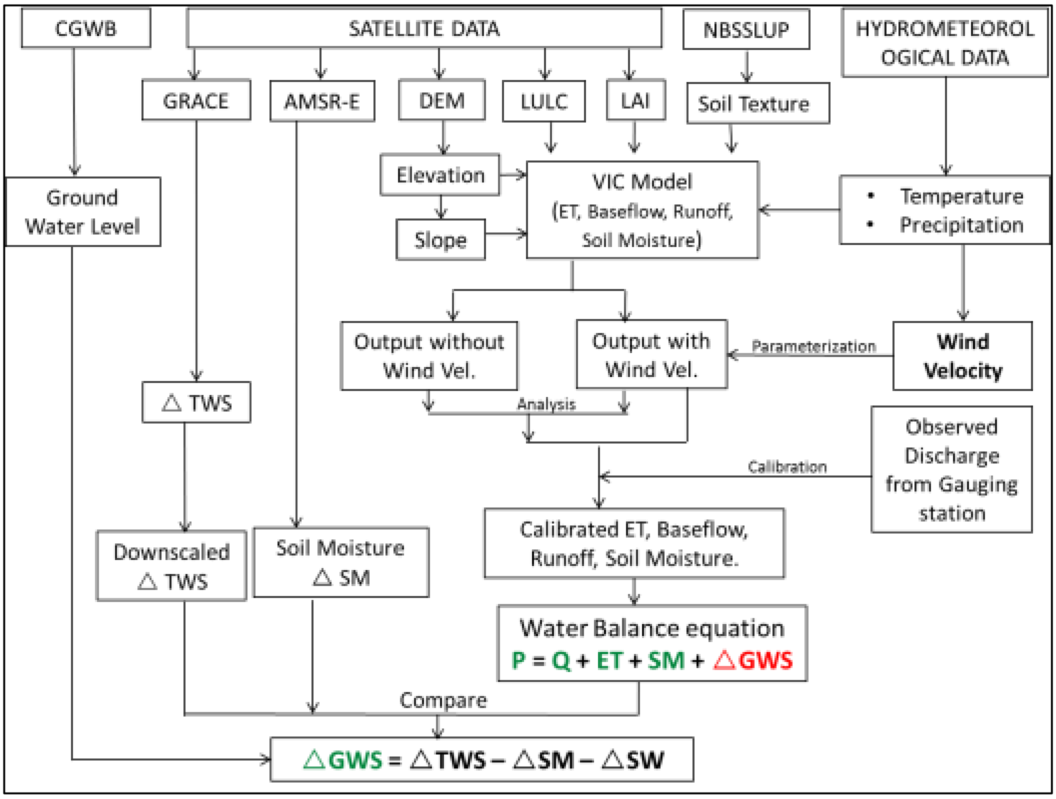


Figure 4-1 Methodology

4.1 HYDROLOGIC MODEL SELECTION

The table shows the merits and demerits of the hydrological models. Four models were selected, namely HEC-HMS (Hydrologic Engineering Center-Hydrologic Modelling System), SWAT (Soil and Water Assessment Tool), Mike, VIC (Variable Infiltration Capacity Model).

VIC model when compared against other three models based on the criteria mentioned below, proves to be the best suited model for the hydrological studies of the Narmada basin.

Table 4-1 Hydrologic model Specifications

Model	HEC-HMS	SWAT	MIKE	VIC
Main Advantage	Focus on runoff, channel routing and water control structure	Focus on water quantity and quality and representation of groundwater	Simulates complete land phase of hydrologic cycle	Subgrid Variability, Macroscale model, large-scale effects
Main Disadvantage	Suitable only for events not for long-term hydrological simulations	Snow process representation requires improvement	Simplified representation of forest cover; high purchase cost	Large grid size, Does not consider Urban class in LULC
Runoff	Empirical	Empirical	Physical	Physical
Baseflow/ Groundwater	Empirical	Empirical	Physical	Physical
Watershed Scale	Small to large	Small to large	Small to large	Medium to large
Climatic Regime	Rain or Snow	Rain or Snow	Rain or Snow	Rain or Snow / mixed
Snow/Glacial Melt	Yes	Yes	Yes	Yes
Outputs	FH, AY, PF, LF, SW, ET, WB, SM, IF, OF, SF, GF, RO.	FH, AY, PF, LF, SW, ET, WB, SM, IF, WT, OF, SF, GF, RO, SE, NF, WQ	FH, AY, PF, LF, SW, ET, WB, SM, IF, WT, OF, SF, GF, RO, WQ.	FH, AY, PF, LF, SW, ET, WB, SM, IF, OF, SF, GF, RO.

Where,

FH = Full hydrograph, AY = Annual yield, PF = Peak flow, LF = Low flow, SW = Snow water equivalent, ET = Evapotranspiration, WB = Water balance, SM = Soil moisture, IF = Infiltration, WT = Water table, OF = Overland flow, SF = Shallow subsurface flow, GF = Groundwater flow, RO = Basin total runoff, SE = Sediment soil erosion, NF = Nutrient fluxes, WQ = Water quality.

SWAT focuses on water quality and quantity, while Mike simulates complete land phase of hydrologic cycle. HEC-HMS concentrates on runoff, channel routing and water control structures but VIC calculates water balance at sub-grid level. SWAT also focuses on groundwater, but other models do not estimate groundwater. After studying the overview of all models, the merits of VIC model over other models were prevailing. Advantages of VIC on other model includes,

- ✓ Sub-grid variability
- ✓ Run in two modes Water Balance and Energy Balance
- ✓ Calculates the Water Budget at sub-grid level and presents the water balance of the entire grid as the sum of the sub-grids.
- ✓ It considers three layers of soil profile.
- ✓ Considers the non-linear baseflow.
- ✓ Takes into account the variability in the infiltration.

4.2 MODEL OVERVIEW

The overall VIC model framework has been described in detail in literature (Liang et al. 1994; Liang et al., 1996; Nijssen et al., 1997). Key capabilities of a grid-based VIC tend to be representation involving vegetation heterogeneity, multiple soil layers within variable infiltration, in addition to non-linear base flow.

Figure 4.1 shows the schematic of the VIC model with a mosaic representation of vegetation coverage and three soil layers. The surface of each grid cell is actually pointed out from N+1 land cover tiles, where n = 1, 2, N represents N tiles of vegetation, and also n = N+1 represents bare soil. Intended for each vegetation tile, vegetation characteristics, just like LAI, albedo, minimum stomatal resistance, architectural resistance, roughness length, relative fraction involving roots within each soil layer, as well as displacement length (in case involving LAI) usually are assigned. Penman-Monteith equation is used to calculate evapotranspiration according to which the evapotranspiration is a function of net radiation and vapor pressure deficit. Total precise evapotranspiration will be the amount connected with canopy evaporation in addition to transpiration by each vegetation tile and bare soil evaporation with the bare soil tile, weighted with the coverage fraction for each surface cover class. Related to each land cover type are the sole canopy layer, as well as multiple soil layers.

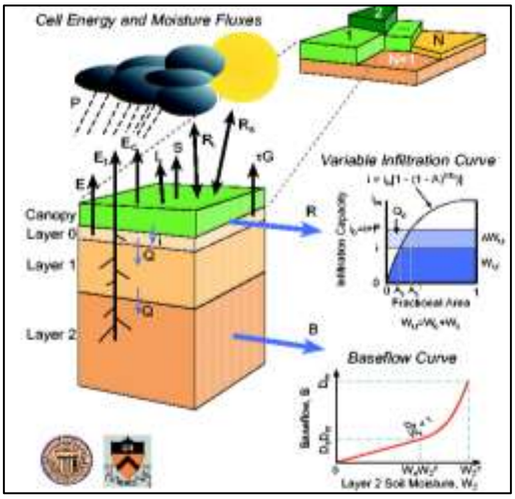


Figure 4-2 Schematic of VIC-3L model with mosaic representation of vegetation coverage
Source*: Cherkauer and Lettenmaier (1999)*

The water balance in the VIC model follows the continuous equation for each time-step: (Gao *et al*.,2009)

$$\frac{\partial S}{\partial t} = P - E - R \qquad (4.1)$$

Where,

$\partial S/\partial t$ = 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:

$$\frac{\partial Wi}{\partial t} = P - E_c - P_t \qquad (4.2)$$

Where,

Wi = Canopy intercepted water in mm,

P = Precipitation in mm,

E_c = Evaporation from canopy in mm and

P_t = Throughfall in mm

The VIC model considers three types of evaporation: evaporation from the canopy layer (E_c, mm) of each vegetation tile, transpiration (E_t, mm) from each of the vegetation tiles, and evaporation from the bare soil (E_1, mm) (Liang *et al*. 1994). Total evapotranspiration over a grid cell is computed as the sum of the above components, weighted by the respective surface cover area fractions. The formulation of the total evapotranspiration is:

$$E = \sum_{n=1}^{N} C_n \cdot (E_{c,n} + E_{t,n}) + C_{N+1} \cdot E_1 \tag{4.3}$$

Where C_n is the vegetation fractional coverage for the nth vegetation tile, C_{N+1} is the bare soil fraction, and $\sum_{n=1}^{N+1} C_n = 1$.

When there is intercepted water on the canopy, the canopy evaporates at the maximum value. The maximum canopy evaporation(E_c^*, mm) from each vegetation tile is calculated using the following formulation:

$$E_c^* = \left(\frac{W_i}{W_{im}}\right)^{2/3} E_p \frac{r_w}{r_w + r_o} \tag{4.4}$$

Where,

W_{im} = maximum amount of water the canopy can intercept (mm), approx. 0.2 times LAI (Dickinson, 1984); the power of 2/3 is as described by (Deardorff,1978).

r_o = architectural resistance is caused by the variation of the humidity gradient between the canopy and the overlying air (s m^{-1}). In the model, r_o is assigned for each land cover type according to the vegetation library.

r_w = aerodynamic resistance represents the transfer of heat and water vapor from the evaporating surface into the air above the canopy (s m^{-1}).

The aerodynamic resistance (r_w, s m^{-1}) is described as follows after (Monteith and Unsworth, 1990):

$$r_w = \frac{1}{C_w u_z} \tag{4.5}$$

Where,

u_z = wind speed (m s^{-1}) at level z,

C_w = transfer coefficient for water which is estimated taking into account the atmospheric stability. The algorithm for calculating C_w is based on (Louis, 1979).

E_p = potential evapotranspiration (mm) that is calculated from the Penman-Monteith equation (Shuttleworth, 1993) with the canopy resistance set to zero, which is:

$$\lambda_v E_p = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)/r_a}{\Delta + \gamma} \tag{4.6}$$

Where,

λ_v = latent heat of vaporization (J kg^{-1}),

R_n = net radiation (W m^{-2}),

G = soil heat flux (W m^{-2}),

$(e_s - e_a)$ = vapor pressure deficit of the air (Pa),

ρ_a = density of air at constant pressure (kg m^{-3}),

c_p = specific heat of the air (J kg^{-1} K^{-1}),

Δ = slope of the saturation vapor pressure temperature relationship (Pa K^{-1}),

γ = psychrometric constant (66 Pa K^{-1}).

The Penman-Monteith equation just as given above incorporates almost all parameters it governs energy exchange as well as corresponding latent heat flux (evapotranspiration) from uniform expanses connected with vegetation (Gao et al.,2007). ATBD (Water Budget Wood by Variable Infiltration Capacity (VIC) Model Algorithm Theoretical Basis Document) can be used for thorough explanation of any algorithms by (Gao et al., 2007).

4.3 INPUTS FOR VIC MODEL

The VIC model requires a grid file created in ArcGIS along with some pre-defined attributes. It also requires Soil parameter file, Vegetation parameter file, Meteorological forcings, Global file, and Vegetation library. Using these files a program needs to be run in Cygwin to derive Fluxes. While routing the model, files such as Fraction file, Station location file, Hydrograph and Flow direction files are to be prepared.

4.3.1 Grid Preparation

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 19 rows and 55 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 1056 out of which 513 grids were on landmass and considered as run grids. Shapefile of grid map contain following attributes which are required to run VIC model:

Table 4-2 Grid File Description

ATTRIBUTE	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 m
Rainfall	Mean annual rainfall of each grid in mm

4.3.2 Data for preparing Grid file

Following is the data required to add into the attributes of the grid file.

4.3.2.1 DEM

Using Digital Elevation Model (DEM), slope gradient m/m and elevation were derived for attribute of the grid file. In this study, Shuttle Radar Topographic Mission (SRTM) 90m was used.

4.3.2.2 Soil

For the basin area, soil texture map was prepared based on NBSSLUP. Each grid cell was assigned with the soil texture ID. The soil texture codes were then given according to the IGBP codes.

4.3.2.3 Rainfall

For the year 1985 and 2005, mean annual rainfall map was generated by using data from Indian Meteorological Department's (IMD) gridded rainfall data and its values were assorted to each grid.

4.3.3 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:

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

Soil parameter file describes the characteristics of each soil layer for each grid cell which also include gridcell information. The soil parameter file information can be referred to http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/SoilParam.shtml

Soil parameter file prepared as the input for VIC is as below,

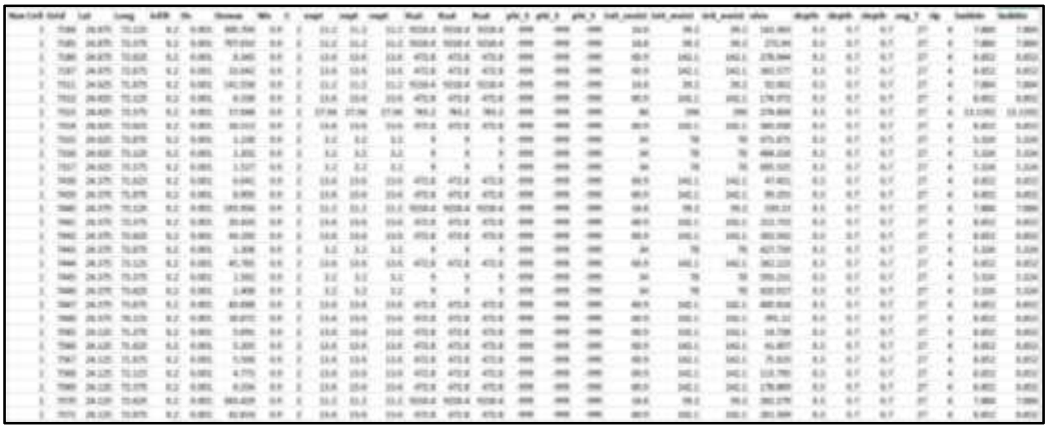


Figure 4-3 Sample of Soil Parameter File

4.3.4 Vegetation Library File

Land Use/Land Cover (LULC) has the most significant emphasis at Vegetation parameter file. Human beings use the land and its re with some purpose then it is described as Land Use, whereas the physical state of land is described by Land Cover. The amount precipitation actually reaching earth surface is usually largely dependent onto the nature and also density of any vegetation cover in addition to LULC practices. LAI is the key component for hydrologic fluxes generation. However, VIC model assumes Inter-annual variations connected with vegetation features are generally ignored in VIC by assuming that LAI values are constant for year to year and do not change for the specific class type. Roughness length, rooting depth, displacement height, architectural resistance in addition to minimum stomatal resistance these are the other parameters which are accounted by the model.

For the study area basin, LULC map prepared by ISRO-GBP under project entitled “Landuse/Landcover Dynamics and Impact of Human Dimension in Indian River Basins” was used. 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 snow. However, since vegetation library file, taken from GLDAS, was prepared using AVHRR LULC, ISRO-GBP LULC was recoded according to it. Contents of Vegetation library file library are stated below.

Table 4-3 Vegetation Library File

Variable Name	Units	Number of Values	Description
veg-class	N/A	1	Vegetation class identification number (reference index for library table)
overstory	N/A	1	Flag to indicate whether or not the current vegetation type has an overstory (TRUE for overstory present [*e.g.* trees], FALSE for overstory not present [*e.g.* grass])
rarc	s/m	1	Architectural resistance of vegetation type (~2 s/m)
rmin	s/m	1	Minimum stomatal resistance of vegetation type (~100 s/m)
LAI	fraction	12	Leaf-area index of vegetation type
VEGLIB-VEGCOVER (Only present if VEGLIB-VEGCOVER=TRUE in global parameter file)	fraction	12	Partial vegetation cover fraction
albedo	fraction	12	Shortwave albedo for vegetation type
rough	m	12	Vegetation roughness length (typically 0.123 * vegetation height)
displacement	m	12	Vegetation displacement height (typically 0.67 * vegetation height)

wind-h	m	1	Height at which wind speed is measured. If using snow interception routines please read the information page
RGL	W/m^2	1	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	1	Radiation attenuation factor. Normally set to 0.5, though may need to be adjusted for high latitudes.
wind-atten	fract	1	Wind speed attenuation through the overstory. The default value has been 0.5.
trunk-ratio	fract	1	Ratio of total tree height that is trunk (no branches). The default value has been 0.2.

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

For any further information visit the source website.

4.3.5 Vegetation Parameter File

Vegetation database file is required which includes rooting depth and fraction of each LULC class type for preparation of vegetation parameter file. Employing this file, vegetation library, LULC of same class with same number along with grid Shapefile, vegetation parameter file can be prepared which includes un grid number, class value falling in that grid, fraction of grid cell covered by each class in that grid, rooting depth and rooting fraction.

For further details refer http://www.hydro.washington.edu/ Lettenmaier/ Models/ VIC/ Documentation/ VegParam.shtml. The Vegetation parameter file is as below,

GRID CELL	No. of Veg. classes / Veg. Class ID	Vege. Class Fraction	Routing Depth	Routing Depth Fraction	Routing Depth	Routing Depth Fraction	Routing Depth	Routing Depth Fraction
7164	6							
	0	0.0004	0.1	0	1	0	0.5	0
	4	0.0912	0.1	0.08	1	0.8	0.5	0.12
	5	0.0272	0.1	0.089	1	0.889	0.5	0.022
	8	0.024	0.1	0.154	1	0.846	0.5	0
	11	0.36	0.1	0.133	1	0.867	0.5	0
	12	0.0016	0.1	0.125	1	0.875	0.5	0
7165	5							
	0	0.0384	0.1	0	1	0	0.5	0
	5	0.16	0.1	0.089	1	0.889	0.5	0.022
	8	0.0256	0.1	0.154	1	0.846	0.5	0
	11	0.552	0.1	0.133	1	0.867	0.5	0
	12	0.1648	0.1	0.125	1	0.875	0.5	0
7166	4							
	0	0.0416	0.1	0	1	0	0.5	0
	8	0.6304	0.1	0.154	1	0.846	0.5	0
	11	0.312	0.1	0.133	1	0.867	0.5	0
	12	0.0032	0.1	0.125	1	0.875	0.5	0
7167	6							
	0	0.0272	0.1	0	1	0	0.5	0
	4	0.0336	0.1	0.08	1	0.8	0.5	0.12
	5	0.2208	0.1	0.089	1	0.889	0.5	0.022
	8	0.0784	0.1	0.154	1	0.846	0.5	0
	11	0.3552	0.1	0.133	1	0.867	0.5	0
	12	0.0032	0.1	0.125	1	0.875	0.5	0

Figure 4-4 Sample of Vegetation Parameter File

4.3.6 Meteorological Forcing File

Meteorological data plays keys role in model to produce every one of the outputs in both water balance and full energy balance mode. High accuracy forcing info is essential to obtain variable that affects runoff in addition to deriving hydrological cycle. Precipitation plays the tick role in the same way it is the main input associated with water to be able to earth. Satellite data provides further accurate results with additional spatial coverage could possibly help involving sparsely located weather stations as well as hilly terrain by which rainfall depends on orography. Many meteorological parameters are usually needed to simulate VIC model including maximum temperature, minimum temperature, precipitation, wind speed, atmospheric pressure and humidity, relative humidity, incoming shortwave in addition to longwave radiation.

However, these variables tend to be derived from model itself counting on different parameters. Consequently essential parameters expected usually are maximum in addition to minimum air temperature with °C and also precipitation in mm either in daily or even sub-daily basis. For the required year 1985 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. Most of these forcing files were prepared by taking z-profile of Tmax, Tmin and also precipitation with regard to each pixel as well as placing those values in American Standard Code for Information Interchange (ASCII) file throughout identify “data-y-x” in which y will be the latitude along with x is the longitude regarding the pixel location. Meteorological Forcing File used in the study is shown below,

data_8.125_77.375				
Tmax °C	Tmin °C	Precipitation (mm)	Wind_Vel (m/s)	Cloud_Cover
31.12399	22.0967	0	6.16667	0.5375
31.06799	21.84416	0	5.83333	0.4875
31.08407	21.74782	0	5.77778	0.5
31.14697	21.82777	0	6.27778	0.475
31.24148	21.64337	0	6.22222	0.4875
31.00381	21.54455	0	5.83333	0.4625
31.16453	21.34542	0	5.72222	0.3875
31.24111	21.6407	0	5.5	0.525
31.25023	21.87374	0	5.69444	0.5
31.21093	21.90835	0	5.66667	0.45
31.28792	21.80948	0	5.58333	0.425
31.25187	21.67255	0	5.63889	0.4625
31.41968	21.62506	0	5.72222	0.45
31.47745	21.47662	0	5.88889	0.45
31.45041	21.60044	0.12782	5.38889	0.475
31.52749	21.7227	4.80924	5.72222	0.475

Figure 4-5 Sample of Meteorological Forcing File

4.3.7 Lake and Wetland Model

In the VIC model, the effects of lakes and wetlands are simulated by creating a lake/wetland tile that can be added to the grid cell mosaic, in addition to the vegetation and bare soil tiles (Bowling and Lettenmaier, 2009). The lake/wetland tile represents seasonally flooded ground as well as permanent water bodies. The tile contains a body of open water (lake) whose areal extent is allowed to change in response to the lake water balance. The wetland portion of the tile is the (time-varying) remaining portion of the lake/wetland tile not covered by the lake. Water and energy components of the combined lake and wetland are resolved at each model time step. The energy balance of the lake component builds on the work of Hostetler and Bartlien (1990), Hostetler (1991), and Patterson and Hamblin (1988), while that of the exposed wetland follows Cherkauer and Lettenmaier (1999).

Lake Algorithm is explained below,

Evaporation from the water surface is calculated in each time step by solving a surface energy balance using the formulations by Hostetler and Bartlien (1990), and Hostetler (1991). The energy exchange with the atmosphere occurs within the surface water layer, which is limited to a user-specified depth (z_{surf}), typically around 0.6 m. The absorption of solar radiation by the surface water layer is assumed to follow Beer's law. The radiation intensity at the depth h is assumed to be a two-band system and expressed as (Patterson and Hamblin 1988):

$$I(h) = I_o\left[A_v \cdot \exp(-\lambda_v h) + A_{NIR} \cdot \exp(-\lambda_{NIR} h)\right] \qquad (4.7)$$

Where,

I_o = net shortwave radiation at the water surface (Wm^{-2}),

A_v and A_{NIR} = fractions of total radiation in the visible and near-infrared bands, set to 0.7 and 0.3, respectively,

λ_v and λ_{NIR} = attenuation coefficients of the two bands.

The interaction of the simulated lake within the VIC model grid cell and the capacity to represent wetlands of different area these are the key features of VIC lakes and wetland algorithm. The algorithm can be summarized as follows (see Figure 4.2):

- All open water bodies within a model grid cell are simulated together as an effective grid cell lake.
- The runoff from vegetated areas within the grid cell is diverted to the lake, which is defined by the user in fractions. This represents the storage retardation effect of lakes on seasonal streamflow.
- Once the new lake level is calculated, as a function of the lake level runoff is released from the lake. Base flow is calculated from bottom of lake as a function of the saturated wetland soils.
- Specification of a variable depth-area relationship allows for the representation of the reduction in surface water extent and the emergence of wetland vegetation following drainage of seasonally flooded wetlands.

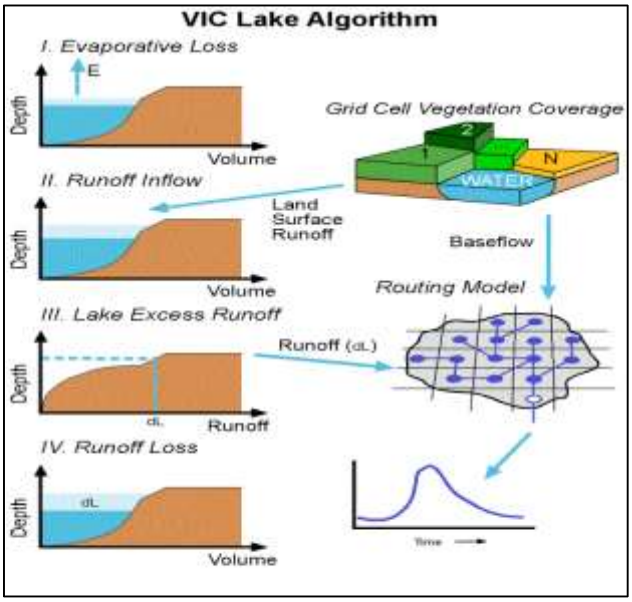


Figure 4-6 Schematic of the VIC Lake and wetland algorithm. *(Source: Gao et al., 2007)*

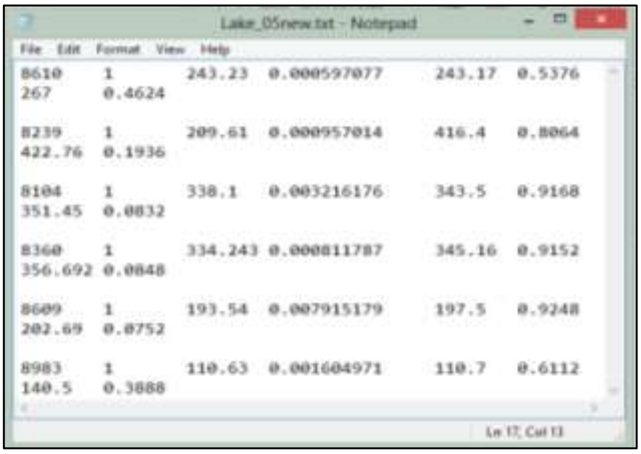
4.3.8 Lake / Wetland Parameter File

The parameter files for lakes and wetland specification in VIC have varied a bit during the development phase of the lake and wetland algorithm, such that there are small differences between the format required for the model code used for Bowling and Lettenmaier (2009) and that specified in the current release version of VIC (4.1.2). This is for earlier versions than 4.1.2 of VIC.

Line 1: [gridcell no.] [No. nodes] [Min. depth for runoff] [Width fraction] [Starting depth] [Contributing frac]

Line 2: [depth 1] [fractional area 1] ... [depth n] [fractional area n]

Where, n = no. nodes and depth 1 = lake and wetland max. depth



```
Lake_05new.txt - Notepad
File  Edit  Format  View  Help
8610    1       243.23  0.000597077     243.17  0.5376
267     0.4624

8239    1       209.61  0.000957014     416.4   0.8064
422.76  0.1936

8104    1       338.1   0.003216176     343.5   0.9168
351.45  0.0832

8360    1       334.243 0.000811787     345.16  0.9152
356.692 0.0848

8609    1       193.54  0.007915179     197.5   0.9248
202.69  0.0752

8983    1       110.63  0.001604971     110.7   0.6112
140.5   0.3888
Ln 17, Col 13
```

Figure 4-7 Sample of Lake Parameter File

4.3.9 VIC model simulation and commands

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.

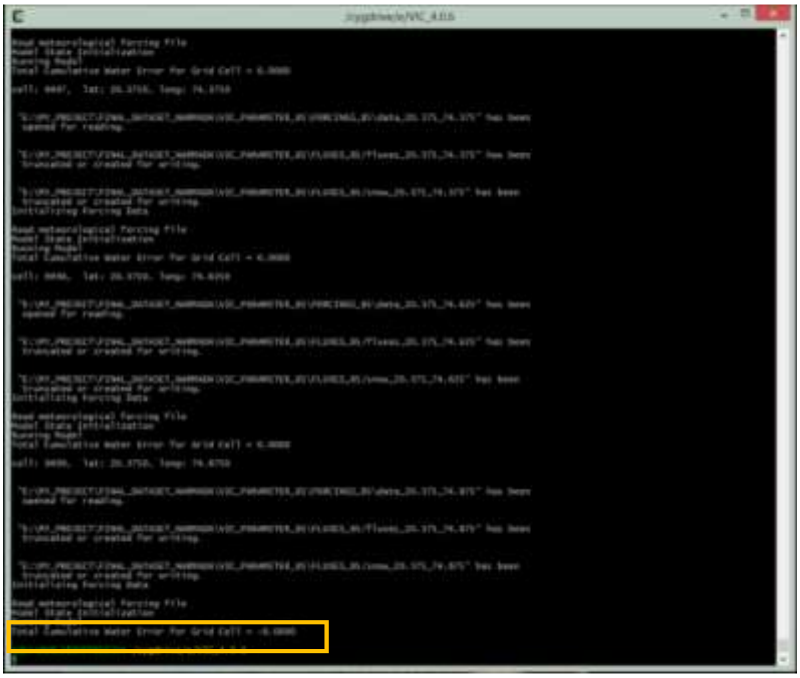


Figure 4-8 VIC Run-Time

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

4.4 PREPARATION OF INPUT FILES FOR ROUTING:

(Source:www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/Routing/Rout ing 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.

4.4.1 Fraction file

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.

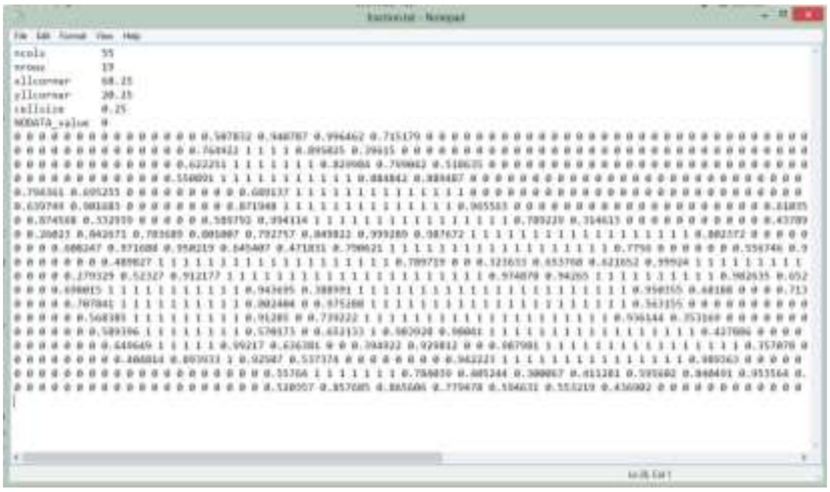


Figure 4-9 Sample of Fraction File

4.4.2 Preparing flow direction file requires DEM

- Correct DEM by using FILL operation in ArcHydro tool,
- Use FLOW DIRECTION operation in the same tool,
- 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 4-10 Sample of Flow Direction File

4.4.3 Station 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.

```
1        GARUD   18      6       -9999
NONE
1        MOTIN   18      5       -9999
NONE
1        GUNGA   11      10      -9999
NONE
```

Figure 4-11 Sample of Station file

4.4.4 VIC Routing model simulation

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).

❑ ./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.

Equations followed during Routing are:

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:

i. Routing within grid cell and
ii. River channel routing.

Following equations are involved in these (Gao et al., 2007).

4.4.4.1 Routing within a Grid Cell

To simulate the in-grid-dynamic of the horizontal routing process, one first separates the fast and slow components of the measured discharge with the linear model described in (Duband et al., 1993):

$$\frac{dQ^S(t)}{dt} = -k \cdot Q^S(t) + b \cdot Q^F(t) \quad (4.8)$$

Where $Q^S(t)$ is the slow flow, $Q^F(t)$ is the fast flow, and $Q(t)$ is the total flow with

$$Q(t) = Q^S(t) + Q^F(t) \quad (4.9)$$

For each river basin, the parameters b and k are assumed to be constant over the period of calculation. The ratio of *b* over *k* represents the ratio of water in the slow flow over water in the fast flow. The fast and slow components are analytically connected by:

$$Q^S(t) = b\int_0^t \exp(-k(t-\tau))Q^F(\tau)d\tau + Q^S(0)\exp(-kt) \quad (4.10)$$

The equation shows that the initial condition $Q^S(0)$ decays exponentially with the mean residence time of water in the flow ($1/k$) and the half-life decay is $T_{1/2}=(ln2)/k$. With discrete data the discharge equation can be solved with:

$$Q^S(t) = \frac{\exp(-k \cdot \Delta t)}{1 + b \cdot \Delta t} Q^S(t - \Delta t) - \frac{b \cdot \Delta t}{1 + b \cdot \Delta t} Q(t) \quad (4.11)$$

Based on the assumption that there is a linear relationship between measured streamflow and effective precipitation (P^{eff}, the part of the precipitation that becomes streamflow), it is sufficient to find an impulse response function connecting the fast component, Q^F, and P^{eff}, due to the analytical connection of the fast and slow components. This impulse response function and P^{eff} can be found by solving the following equation iteratively:

$$Q^F(t) = \int_0^{t_{max}} UH^F(\tau)P^{eff}(t-\tau)d\tau \quad (4.12)$$

In the equation $UH^F(\tau)$ is the impulse response function (also called unit hydrograph) for the fast flow component and t_{max} is the time taken for all fast processes to decay. The equation for Q^F can be expressed in its discrete format, in which there are *n* data points at the time step of Δt, and $t_{max} = (m-1) \cdot \Delta t$. Starting with the measured precipitation, the following discrete equation is solved iteratively for the calculation of UH_i^F .

$$\begin{pmatrix} Q_m^F \\ \vdots \\ Q_n^F \end{pmatrix} = \begin{pmatrix} P_m^{eff} \cdots P_1^{eff} \\ \vdots \quad \ddots \quad \vdots \\ P_n^{eff} \cdots P_{n-m+1}^{eff} \end{pmatrix} \begin{pmatrix} UH_0^F \\ \vdots \\ UH_{m-1}^F \end{pmatrix} \tag{4.13}$$

After each of the iteration steps the following constraint is applied:

$$\sum_{i=0}^{m-1} UH_i^F = \frac{1}{1+\frac{b}{k}} \text{ with } UH_i^F \geq 0 \ \forall i \tag{4.14}$$

The constraint results from the fixed fraction of the water in the fast and slow component, the fact that $\int_0^{\infty} UH(t)dt = 1$ and the non-negative assumption of UH(t). The calculated UH^F is then put into the following discrete equation to solve for P^{eff}.

$$\begin{pmatrix} Q_m^F \\ \vdots \\ \vdots \\ Q_n^F \end{pmatrix} = \begin{pmatrix} UH_{m-1}^F & \cdots & UH_0^F & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots 0 & UH_{m-1}^F & \cdots & & UH_0^F \end{pmatrix} \begin{pmatrix} P_1^{eff} \\ \vdots \\ P_n^{eff} \end{pmatrix} \tag{4.15}$$

Again, after each iteration step the constraint ($0 \leq P_i^{eff} \leq Precipitation, \forall i$) is applied.

The newly calculated P^{eff} is then put back into the first discrete equation and the deconvolutions are repeated until convergence is reached. Grid cell impulse response functions can be obtained via deconvolution of the catchment impulse response function with the river network impulse response function belonging to that catchment (Lohmann et al., 1996).

4.5 GROUNDWATER ASSESSMENT

The change in the groundwater level can be obtained by using the following equation,

$$\Delta GWS = \Delta TWS - \Delta SM - \Delta SW \tag{4.16}$$

Where ΔTWS is obtained from GRACE (downscaled to 0.25 degree), ΔSM is obtained from AMSR-E and ΔSW is the difference between the volume of surface water bodies calculated using depth of reservoir, river, lakes and water spread area.

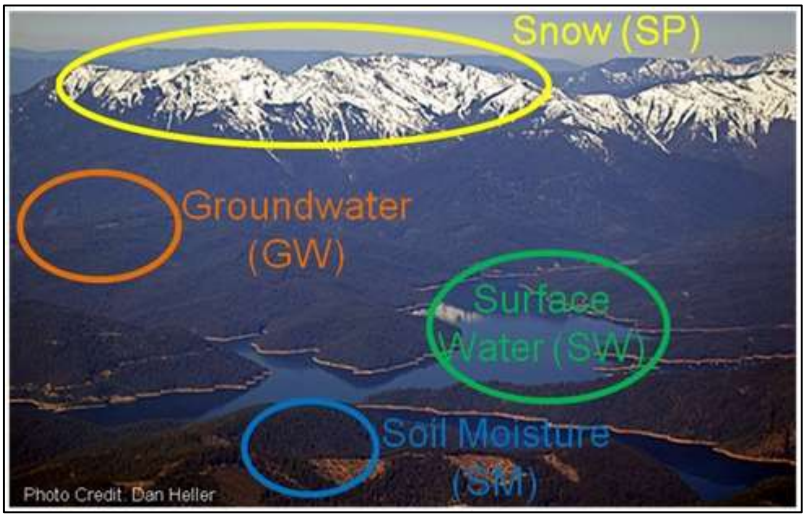


Figure 4-12 Visual example of each of the variables of the hydrologic cycle considered in the groundwater calculation. (Source: *http://www.earthzine.org)*

The Groundwater Level data is acquired from *http://gis2.nic.in/cgwb/Gemsdata.aspx***,** Central Groundwater Board (CGWB) official website.

Figure 4-13 Groundwater Level Data *(Source: http://gis2.nic.in/cgwb/Gemsdata.aspx)*

The location of each groundwater well was procured from the *http://www.india-wris.nrsc.gov.in/GeoVisualization.html* website. It is an official website by NRSC (National Remote Sensing Center).

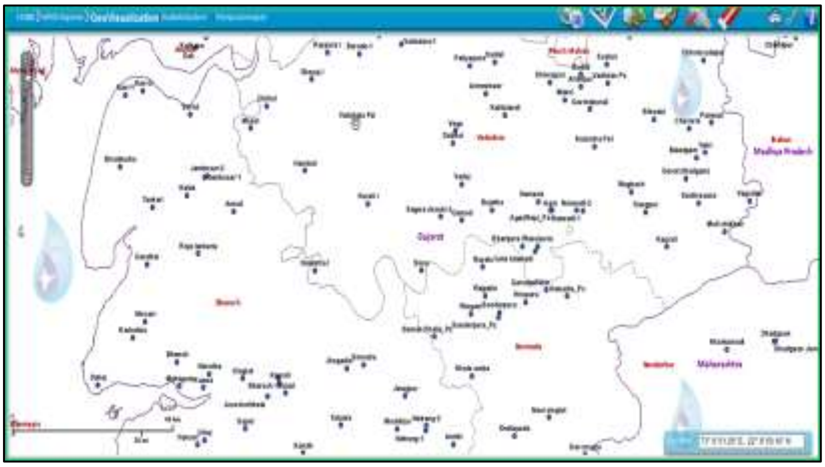


Figure 4-14 Groundwater well location *(Source: http://www.india-wris.nrsc.gov.in/GeoVisualization.html)*

A database was created in excel which includes the Groundwater well locations, Water level data district wise and season-wise for a particular year. It also has Names of the groundwater wells alongwith a unique 'ID_CODE', since the names on the website and the CGWB database names doesn't match for every year's data. The database seems to be as given below,

ID	SITE NAME	LONG	LAT	JAN	MAY	AUG	NOV	AVG
Narm_1	Amayar	73 45 53	21 32 51	3.37	5.52	2.35	2.37	3.4
Narm_2	Chikada	73 38 35	21 31 1	2.92	5.35	3.6	2.02	3.47
Narm_3	Dedlapada	73 34 51	21 38 1	6.07	7.8	4.77	4.97	5.9
Narm_4	Garudeshwar	73 38 57	21 53 30	11.16	11.98	8.65	8.85	10.16
Narm_5	Gola talawadi	73 37 21	21 57 27		31.8			31.8
Narm_6	Hirapura	73 35 56	21 52 4	8.22	5.7	5.2	3.46	5.64
Narm_7	Kanbi pitha	73 03 56	21 37 11	1.16	3.28	3.55	1.03	2.26
Narm_8	Khota amba	73 28 23	21 44 1	1.17	1.57	1.11	1.13	1.25
Narm_9	Namaria	73 37 24	22 02 41	14.5	15.17	13.9	13.23	14.2
Narm_10	Nani singlot	73 39 57	21 40 12	8.12	8.8	6.32	7.48	7.68
Narm_11	Rajpipla	73 29 52	21 52 30	26.83	28.01	25.67	25.19	26.42
Narm_12	Rasela	73 29 22	21 55 31		11.26	9.54	3.43	8.08
Narm_13	Rasulpura_Pz	73 13 50	22 35 39	24.2	25.24	25.3	24.36	24.78
Narm_14	Ringani	73 27 54	21 50 30	2.61	2.08	2.22	1.97	2.22
Narm_15	Selemba	73 48 42	21 27 15	7.68	8.86	6.8	8.86	8.05
Narm_16	Sunderpura	73 31 57	21 50 52	34.2	34.2	28.7	34.2	32.83

Figure 4-15 Groundwater well database

A shapefile was created with this data using Arc GIS 10.0 for each five states. Every Shapefile was attributed with Name, Id Code, Latitude, Longitude, Season-wise water level data and its average. The format is shown below,

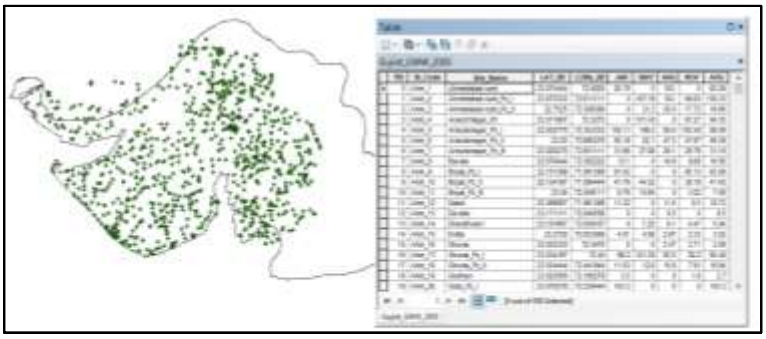


Figure 4-16 Shapefile of Groundwater wells in Gujarat State

The point data created of all the groundwater wells in the study area is shown below,

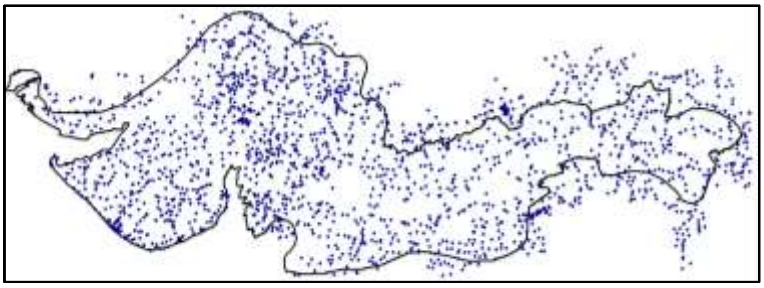


Figure 4-17 Groundwater wells in the Narmada Basin

The groundwater level database was interpolated spatially using Inverse Distance Weightage (IDW) technique to study the spatial variation of groundwater and is as follows,

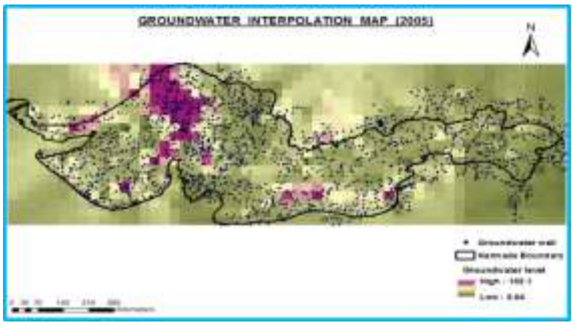


Figure 4-18 Interpolation (IDW) of Groundwater well data (Seasonal mean, 2005)

The interpolation was done for the four seasons, i.e January, May, August and November for the year 2005. Interpolation helps in obtaining data all over the study area.

4.5.1 Correlation between GRACE data and CGWB data to assess Groundwater (2005)

GRACE satellite gives the variation in terrestrial water storage (ΔTWS), which is the change in the TWS of a month with respect to a long—term average value of TWS. In this case, long-term denotes a time baseline from January 2004 to December 2009. Monthly seasonal data, i.e January, May, August and November (2005) was to be used. Therefore, for May season, sum of monthly ΔTWS from January to April was used. Similarly, for August, sum of May to July, for November August to October and for January the sum of monthly data of November to December was used. To calculate ΔGWS, we need to subtract the ΔSM and ΔSW from ΔTWS acquired from GRACE. Soil moisture data was obtained from AMSR-E (Advanced Microwave Scanning Radiometer – Earth Observing System) instrument on board the Aqua satellite. All the data used is for the four above mentioned seasons. Difference is calculated as May – Jan, Aug – May and Nov – Aug. Raster maps of these soil moisture variations are obtained. The ΔSM map for the season AUG is shown below,

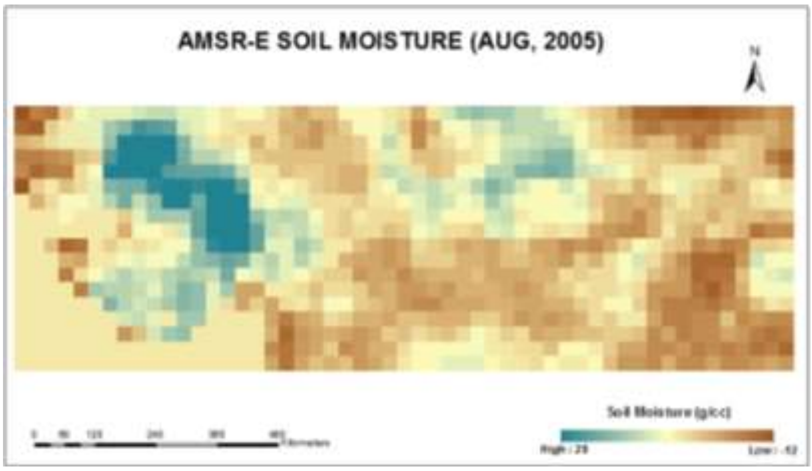


Figure 4-19 AMSR-E Soil Moisture (gm/cc)

After subtracting ΔSM from ΔTWS, a remarkable difference was not observed. This shows that ΔSM is not dominant in ΔTWS. Hence, we assumed that ΔGWS is more dominant than ΔSM and ΔSW in GRACE derived ΔTWS. Therefore, in this study we considered ΔTWS ≈ ΔGWS.

Keeping this in mind, ΔTWS can now be directly correlated to ΔGWS (CGWB) data. A correlation needs to be established between the ΔGW_{CGWB} data with ΔGW_{GRACE} data at specific point locations. The approach followed here for downscaling is Statistical Downscaling. Since, grid size of GRACE data is 100km x 100km, the CGWB GW level data must be calculated as per the GRACE grid size. This is done in order to obtain equal values for correlation. The methodology for solving this case is as below,

i. A Polygon / Rectangle feature class is created which covers whole of the study area.
ii. Using the 'Grid Index' option from the ArcGIS Toolbox, the rectangle was divided into grids of 100 km (same as the GRACE data grid size).
iii. With the help of spatial join (One to many), the attributes of GW wells falling in each grid were attributed.
iv. The .dbf file, which is created in the folder along with the shapefile generation, was used to calculate the average of the GW level per pixel.
v. The attribute table can also be exported as .dbf file.
vi. GRACE Raster data was converted to Point data for the ease to obtain GRACE data from each pixel.
vii. The idea behind this was to correlate the GRACE and CGWB GW level data on GRACE pixel wise basis so that every value from GRACE has a unique CGWB value (average of the GW level in a grid of 100 km).
viii. A strong correlation with $R^2 = 0.635$ was obtained.
ix. Correlation graph and the equation obtained for May (2005) is demonstrated below,

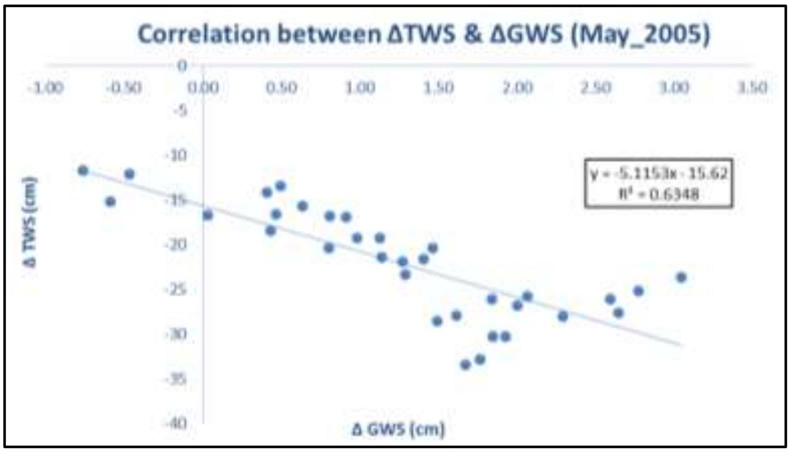


Figure 4-20 Correlation plot between ΔTWS and ΔGWS (CGWB) for May 2005

The equations attained were considered valid since the coefficient of determination (R^2) obtained was robust. Each equations were labeled as Y = GRACE ΔTWS and X = CGWB ΔGWS.

For the months of January, February, March, April the equation given below is applicable –

$$y = - (5.1153)\, x - 15.62 \tag{4.17}$$

For the months of May, June, July equation valid is –

$$y = 2.4954x - 14.367 \tag{4.18}$$

For the months of August, September, October, November and December equation valid is –

$$y = 5.1457x + 33.29 \tag{4.19}$$

This correlation can be used to support the statement that data received directly from the satellite is acceptable and can be used as a substitute of ground truth data.

4.5.2 Correlation between GRACE ∆TWS and Baseflow from VIC model

The correlation between GRACE ∆TWS and Baseflow obtained from VIC model was derived in order to check whether the baseflow can be considered as the potential recharge of groundwater. The coefficient of determination (R^2) was obtained for the season-wise correlation. A robust R^2 was achieved for each pair of correlation. Season-wise here specifies rainfall season. This includes months of July, August and September. Strong correlation for June was not obtained. This might be because baseflow takes time to occur. Scatter plot for month of July is shown in section 5.4.

4.6 WATER BALANCE CLOSURE

The Water balance for Narmada basin (extended) was studied for the year of 2005. The water balance components were obtained from VIC model. Average values obtained for each component are given below. The water balance is closed with minimum possible error.

The literal meaning of Water Balance closure is supposed to be,

$$P - Q + ET + \Delta SM = 0 \tag{4.20}$$

But, this is not possible to obtain because the model cannot estimate accurate values due to insufficient inputs. The water budget calculated in this study is given in section 5.6.

4.7 SURFACE WATER ASSESSMENT

At a basin level, surface water assessment can be done by calculating the surface runoff. Surface runoff was estimated by VIC Model. Also, the storage capacity of the Narmada basin was estimated. The storage here denotes to the reservoir capacity. Runoff map of Jan_2005 are shown in section 5.6. Volume of surface water was then calculated using the equation,

$$\text{Volume (m}^3\text{)} = \text{Area (m}^2\text{)} * \text{Depth (m)} \qquad (4.21)$$

For Surface Water storage capacity, two components, depth of the water body and its area, are required to estimate the volume of the surface water in Narmada basin. Only the Water Body class from the vector of LULC (2005) was extracted as a new feature layer. The average depth of reservoir/lake/dam was retrieved through www.india-wris.gov.in website. The water spread area was assessed with the area of water bodies extracted from LULC map of 2005. Thus, surface water storage capacity in the Narmada basin was determined. Surface water has been quantified in terms of volume, m^3. Given below is the preview of Water bodies existing in the basin and its attributes are as follows,

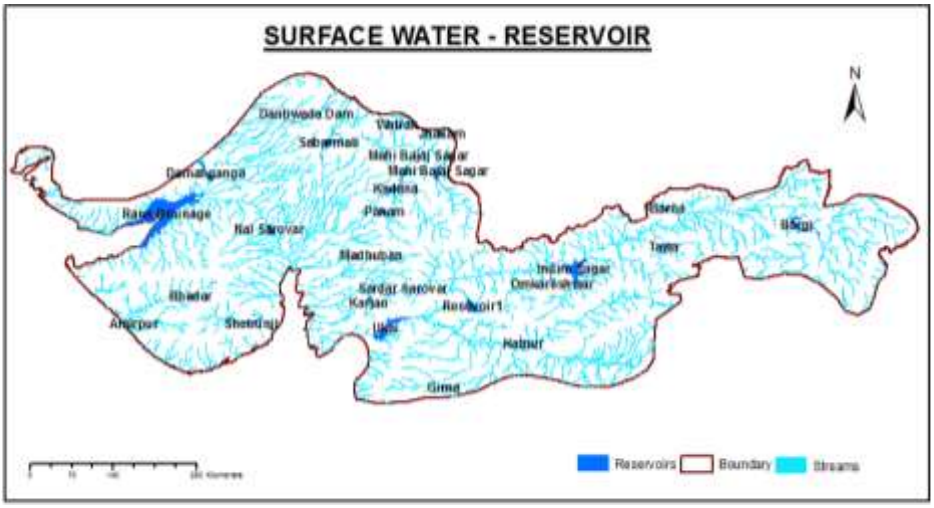


Figure 4-21 Reservoirs in the basin (2005)

An excel sheet was prepared which includes Reservoir name, Latitude, Longitude, Depth (m) and Depth (m) season-wise. The sheet was transformed into shapefile. The data was joined with the attributes of the extracted surface water bodies. Volume was thus calculated by equation 4.21, in the attribute table.

FID_WATER	LAKE_NAME	AREA_sq.m	DEPTH_m	VOLUME_cu.m	VOLUME_MCM
81	Amirpur	13663435.29	600.53	8205302795.72	8205.30
1794	Bargi	290914556.72	415.31	120819724550.00	120819.72
1793	Barna	56237587.02	388.65	21856738196.00	21856.74
81	Bhadar	59350455.62	103.83	6162357807.27	6162.36
821	Damanganga	156165323.40	51.57	8053445727.63	8053.45
1013	Dantiwada Dam	112214358.03	167.70	18818347842.00	18818.35
1192	Girna	71109099.63	392.93	27940898516.30	27940.90
1192	Hatnur	123200575.55	211.57	26065545768.10	26065.55
1792	Indira Sagar	569203355.07	247.13	140667225137.00	140667.23
1204	Jhakam	23458341.45	351.15	8237398601.47	8237.40
1204	Kadana	169528624.22	125.02	21194218360.00	21194.22
1204	Karjan	29788072.82	108.66	3236771992.09	3236.77
1204	Madhuban	14048726.39	74.24	1042977447.54	1042.98
1204	Mahi Bajaj Sagar	167862377.96	274.55	46086615868.40	46086.62
1195	Nal Sarovar	125537471.77	322.33	40464493274.30	40464.49
1795	Omkareshwar	32845450.94	180.94	5943055892.63	5943.06
1204	Panam	86907396.65	124.10	10785207924.40	10785.21
1206	Rann Drainage	2658901110.72	1.00	2658901110.72	2658.90
1204	Resevoir1	239377231.78	540.46	129373818688.00	129373.82
1204	Sabarmati	203598901.01	180.91	36833077181.70	36833.08
1204	Sardar Sarovar	125545914.84	111.25	13966983026.10	13966.98
280	Shetrunji	107935894.82	74.26	8015319549.11	8015.32
1013	Sipu Dam	17682890.44	174.05	3077707081.52	3077.71
1796	Tawa	137394266.30	346.99	47674436462.70	47674.44
1791	Ukai	559626096.44	96.50	54003918306.50	54003.92
701	Watrak	46687423.29	129.73	6056759423.97	6056.76

Figure 4-22 Excel sheet with Reservoir

4.8 IMPACT OF LULC CHANGE ON HYDROLOGY OF BASIN

This section of the study includes the setting up of hydrological model, run the model at daily time-step and to evaluate the effect of Land Use change on hydrology of Narmada basin. All the water balance components were obtained from VIC and were calibrated. The model was forced for 30 years (1980 to 2010) with maximum and minimum temperature, daily precipitation, wind velocity, over a 25km x 25km grid size derived from Indian Meteorological Department gridded data. For studying the impact of Land Use change, two LULC scenarios (1985 and 2005) were taken into account. A substantial increase in evaporation (0.56%) component was observed, while the Runoff (42.42%), Baseflow (34.18%), and Discharge (34%) of Narmada basin decreased in 2005 as compared to 1985. It was noticed that the Indira Sagar Dam with a capacity of 12.22 Bm^3 was commissioned in 2005. It was the major change in the LULC during the analysis period, which played an important role for the remarkable change in water balance components for the year 2005. The discharge data was validated with *in situ* (CWC) data. The impact of lake/wetland on basin hydrology is observed. The work also specifies its importance in the accurate water balance and water resource assessment studies.

The LULC of the year 1985 and 2005 is shown in section 5.8.

5. RESULTS AND DISCUSSION

In this study an integrated methodology consisting of selection and parameterization of the hydrologic model outputs from VIC model and satellite data (GRACE and AMSR-E) is adopted to close the water balance of Narmada basin (extended) for the year 2005 with high precision. Run in water balance mode, the VIC model has been used for estimating the water budget components except for groundwater. Since, the wind speed is a critical factor which affects ET, its consideration is justified.

From a wide range of hydrological models like SWAT, MIKE, VIC and HEC-HMS, VIC has been preferred to be the most suitable model for the study. The selection criteria is explained in the section 4.1. The VIC model was initially parameterized and the sensitivity of VIC model for the meteorological factor 'Wind speed' was studied on Asan watershed for a period of 1 year (2005). The results showed a remarkable change in both the cases, (i) Results i.e. the water balance components while including Wind speed parameter and (ii) Results excluding Wind speed. To study the effect of LULC change on hydrology of the Narmada basin, the model was setup with the wind speed and the model was forced with 30 years (1980 – 2010) for three different types of LULC (Land Use Land Cover of 1985, 1995, and 2005). For each LULC, the water balance components, ET, runoff (R), change in soil moisture (ΔSM) and baseflow (BF) were obtained except for groundwater. A substantial increase in evaporation of 0.56% was observed, while a decrease in the Runoff by 42.42%, Baseflow by 34.18% and Discharge by 34% was witnessed in Narmada basin for LULC of 2005 as compared to LULC of 1985.

At 1°, GRACE derived ΔGWS and groundwater well level data (ΔGWS, seasonal variations) obtained from CGWB (Central Ground Water Board) for the year 2005 were correlated. This proves that the ΔTWS obtained from GRACE satellite can be substituted for ΔGWS attained from CGWB, ground data. In order to prove that baseflow can be presumed to be the potential source of groundwater recharge, the baseflow_{VIC} and ΔTWS_{GRACE} were correlated at 0.25°. ΔGWS in more dominant in ΔTWS. The default time baseline (January 2004 to December 2009) was changed according to the study time baseline (January 2005 to December 2005) for each calculation.

5.1 VIC MODEL PARAMETER SENSITIVITY ANALYSIS

The first objective is to select a hydrological model and to parameterize the model. A parameter sensitivity analysis with and without wind speed variable was carried to observe its effect on the water budget components.

Wind speed has a potential impact on water balance components specially ET. Therefore, sensitivity of VIC model for the meteorological factor 'Wind speed' was necessary to analyze. The relation of wind speed with ET can be observed by the equations (4.3), (4.4) and (4.5) in section 4.2. In VIC model, the default value of wind speed is set to 1.5 m/s. But, this is not true for every location. Hence, this variable (wind speed) has to be considered as one of the necessary and important input in the meteorological forcing. With the evapotranspiration algorithm, canopy responses to wind profile and surface radiation budget (Wigmosta et al., 1994).

VIC model was forced for one year, 2005, over the Asan watershed. The data availability at the time of this study, was the real reason behind carrying out the analysis on Asan watershed. LULC of 2005 was used. The input files were generated as detailed in the section 4.3.

The water balance obtained through VIC model is shown below,

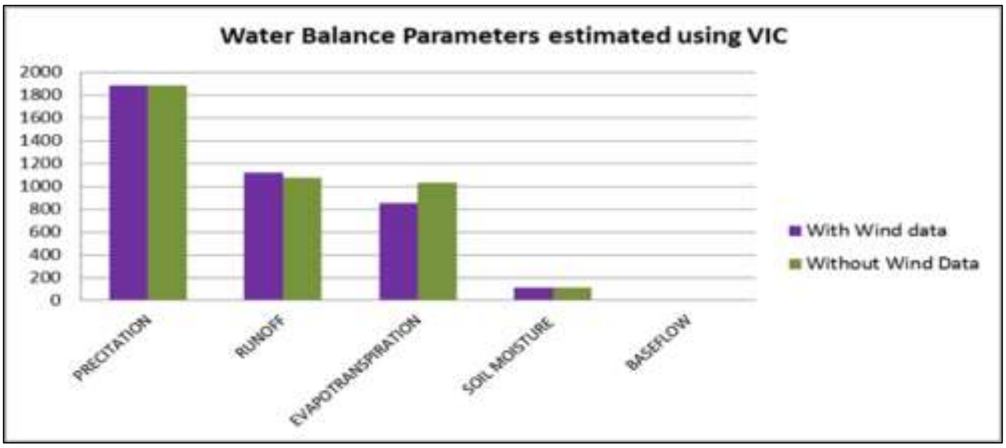


Figure 5-1 Water Budget components derived by VIC model (2005)

A visible difference was seen in Runoff and Evapotranspiration. Two scenarios were created (I) Water Balance including 'Wind speed' parameter (II) Water Balance excluding 'Wind speed' parameter. The consideration of wind speed in the meteorological parameters is inter-related to the water balance components. This can be proved from the equations (4.5) and (4.6). Greater the wind speed lesser will be the aerodynamic resistance and thus lesser will be the evaporation from the canopy. Therefore, we can observe a decrease in the evaporation. The runoff is greater in scenario-I as compared to runoff in scenario-II. While opposite is the case with evaporation. No considerable effect was observed in terms of soil moisture and baseflow.

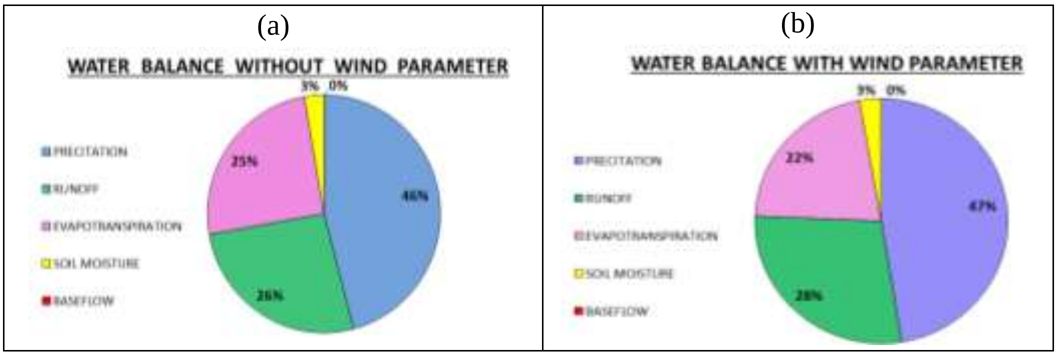


Figure 5-2 Water balance for 2005 (a) without wind velocity variable (b) with wind velocity variable.

5.2 WATER BUDGET COMPONENT ANALYSIS THROUGH VIC MODEL

Precipitation maps of Narmada basin for the year 2005 are displayed in the Figure 5.3 above. Maximum precipitation is observed in the month of June and minimum is observed in the month of October. The average precipitation range for the year 2005 in Narmada basin was between 0 – 39.7 mm.

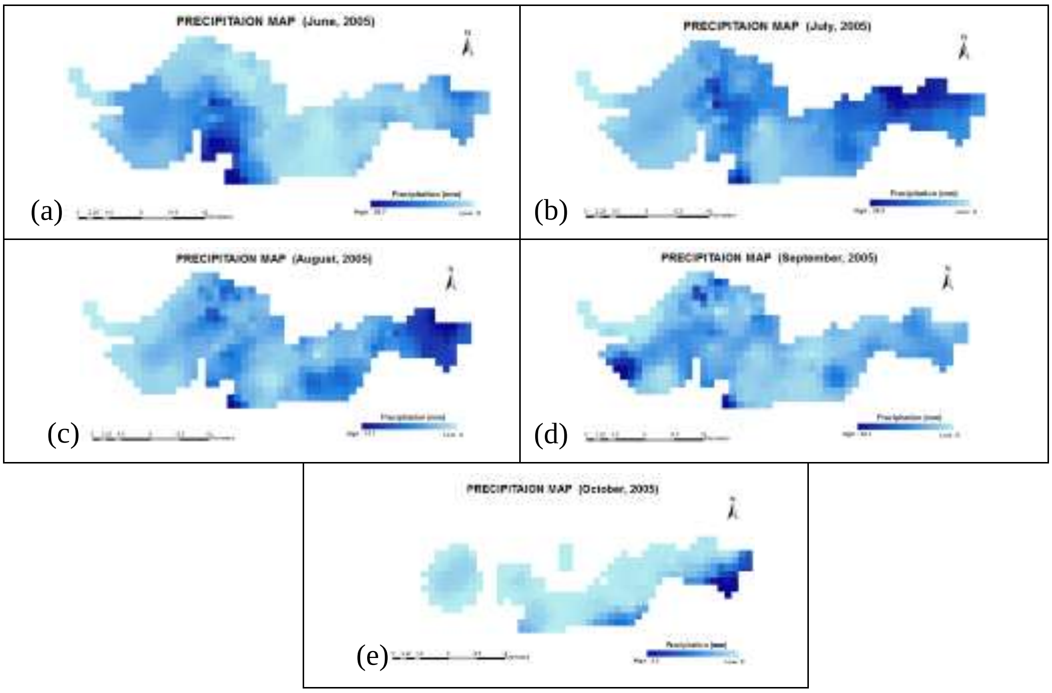


Figure 5-3 Average Precipitation map of 2005 from VIC model for (a) June, (b) July, (c) August, (d) September and (e) October

After studying the VIC model sensitivity for the wind speed, it was incorporated into the meteorological forcings. This will help in achieving more accurate water budget components. The model was run for a period of 30 years (1980 - 2010) with LULC of 2005. A long-term period was opted since the model takes some period for warming up. And results obtained for the year 2005 will be precise. The input files required by the model are Vegetation parameter file, Soil parameter file, Vegetation library, Meteorological forcing file. The description of preparing the file is mentioned in section 4.3. The discharge is calculated by using a routing the model. Then, it is validated with the ground data at the outlet, Garudeshwar, of the basin.

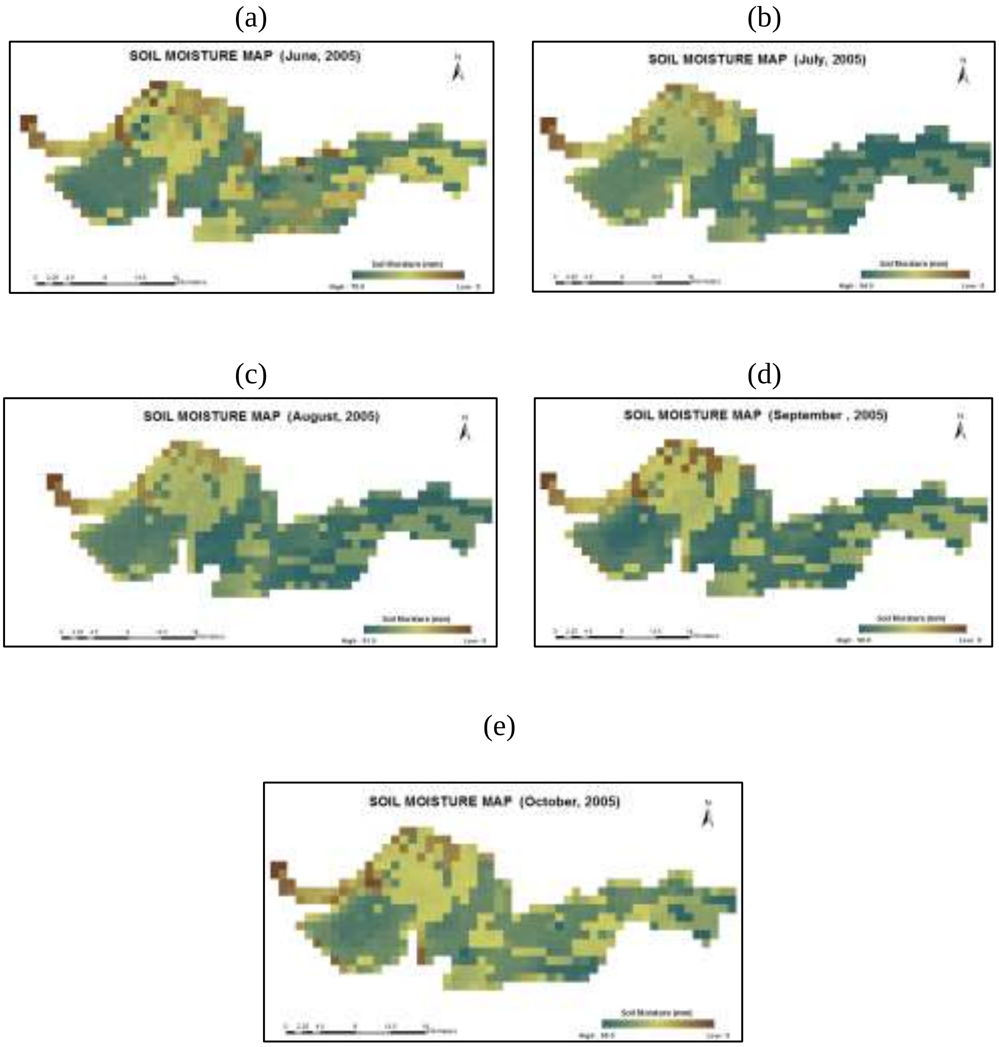


Figure 5-4 Average Soil Moisture map of 2005 from VIC model for (a) June, (b) July, (c) August, (d) September and (e) October

Soil moisture maps of Narmada basin modelled from VIC for the year 2005 are shown above in Figure 5.4. The range of average soil moisture in the basin for the year 2005 was 0 – 94.9 mm. Maximum soil moisture is observed in the month of July. While lowest soil moisture is observed in the month of June.

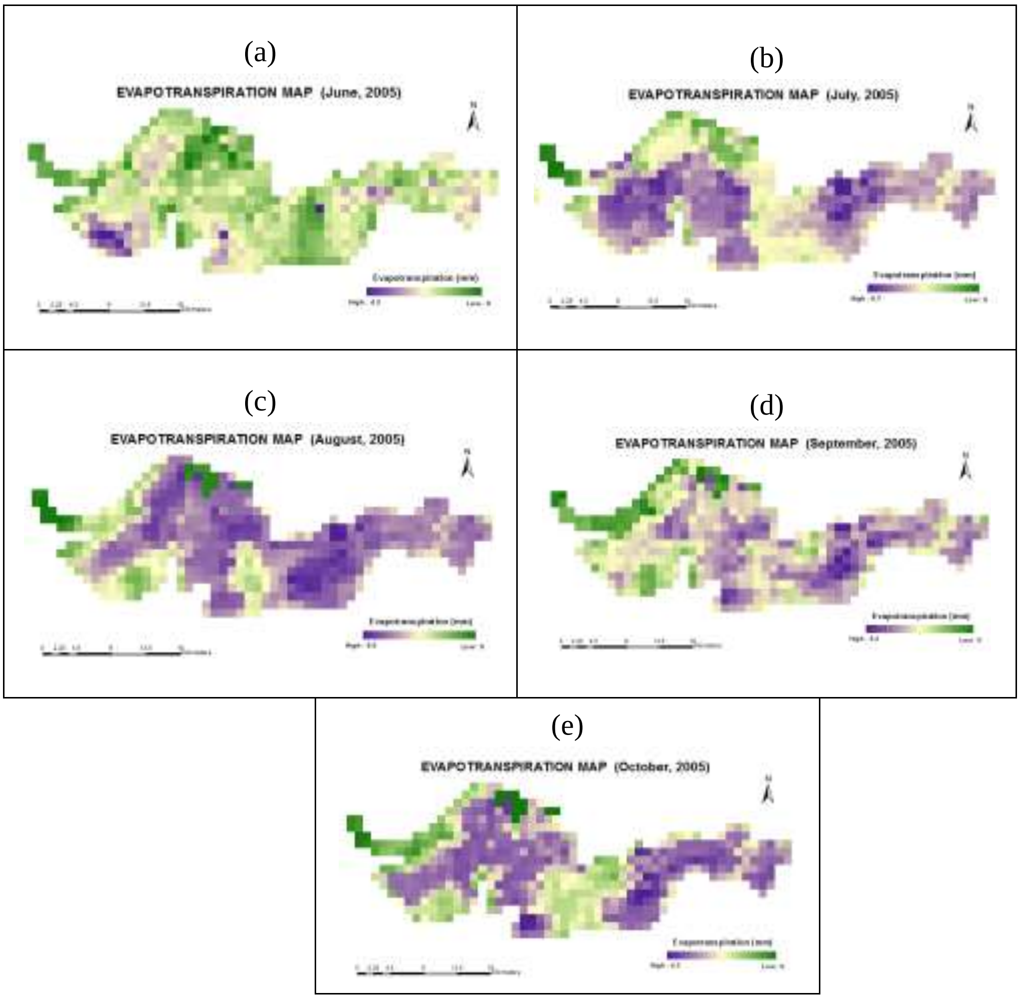


Figure 5-5 Average Evapotranspiration map of 2005 from VIC model for (a) June, (b) July, (c) August, (d) September and (e) October

Evapotranspiration maps of Narmada basin for the year 2005 are displayed in the Figure 5.5. Maximum ET was observed in the month of July (6 mm) and minimum was observed in the months of June and October. The average ET range for the year 2005 in Narmada basin was between 0 – 6 mm.

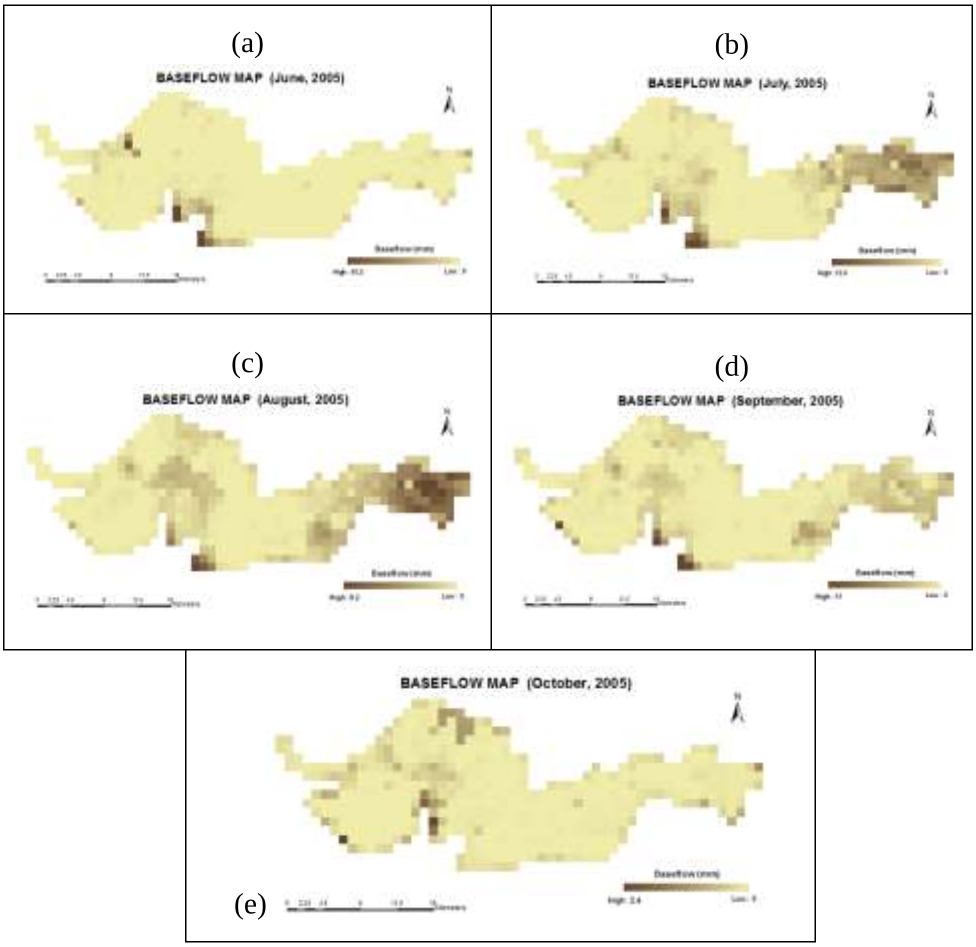


Figure 5-6 Average Baseflow map of 2005 from VIC model for (a) June, (b) July, (c) August, (d) September and (e) October

Baseflow maps of Narmada basin for the year 2005 are displayed in the Figure 5.6. Maximum baseflow occurred in the month of July (12.6mm) and minimum was occurred in the month of October (2.4 mm). The average ET range for the year 2005 in Narmada basin was between 0 – 12.6 mm.

Thus, the water balance components are spatially derived from the VIC model. To close the water balance groundwater is essential. Groundwater cannot be derived using VIC. Therefore, groundwater assessment was done for the same year (2005). Part of the assessment is explained in the section 4.5.

5.3 GROUNDWATER ASSESSMENT

Groundwater assessment consists of estimating the groundwater recharge sources (inputs), the fluctuation in the water table and the groundwater draft. The exact amount of groundwater extraction is difficult to obtain. The major potential source of recharge is the Rainfall (precipitation). But, the extracted groundwater through wells for agriculture again leads to the recharge of the water table. Hence, assessment of groundwater can be correctly done only if the required data is accurately available, either incorporated into the model or ground data is made obtainable. The water table fluctuation ΔWT can be expressed as,

$$\Delta WT = R_{rainfall} + GW_{draft} + R_{irri} \quad (5.1)$$

Where,

$R_{rainfall}$ = Recharge through Rainfall

GW_{draft} = Recharge through Groundwater

R_{irri} = Recharge through Irrigation

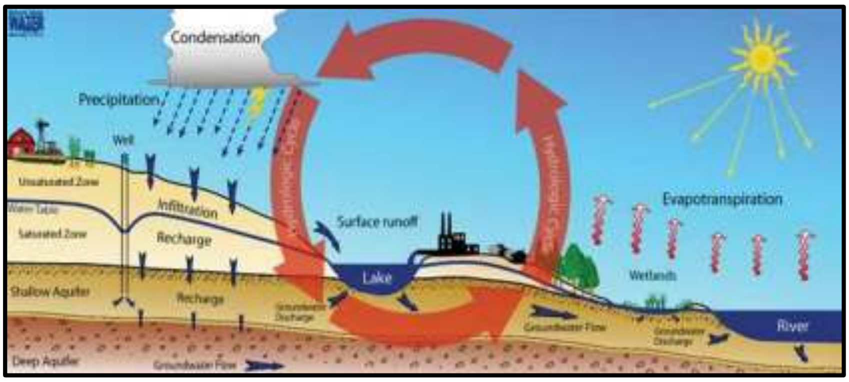


Figure 5-7 Sources of Groundwater recharge *(Source: http://www.esri.com)*

In terms of the equation above, we only have the recharge through rainfall. This is modelled from VIC model. The baseflow is assumed to be the groundwater recharge. The other two parameters cannot be estimated accurately by model. It needs to be measured on ground. Deficiency of the necessary data leads to an incomplete assessment of the groundwater. If the GW_{draft} and R_{irri} data are exactly available a satisfactory assessment of groundwater can be done.

The interpolated maps of the groundwater level data for the year 2005 are shown below,

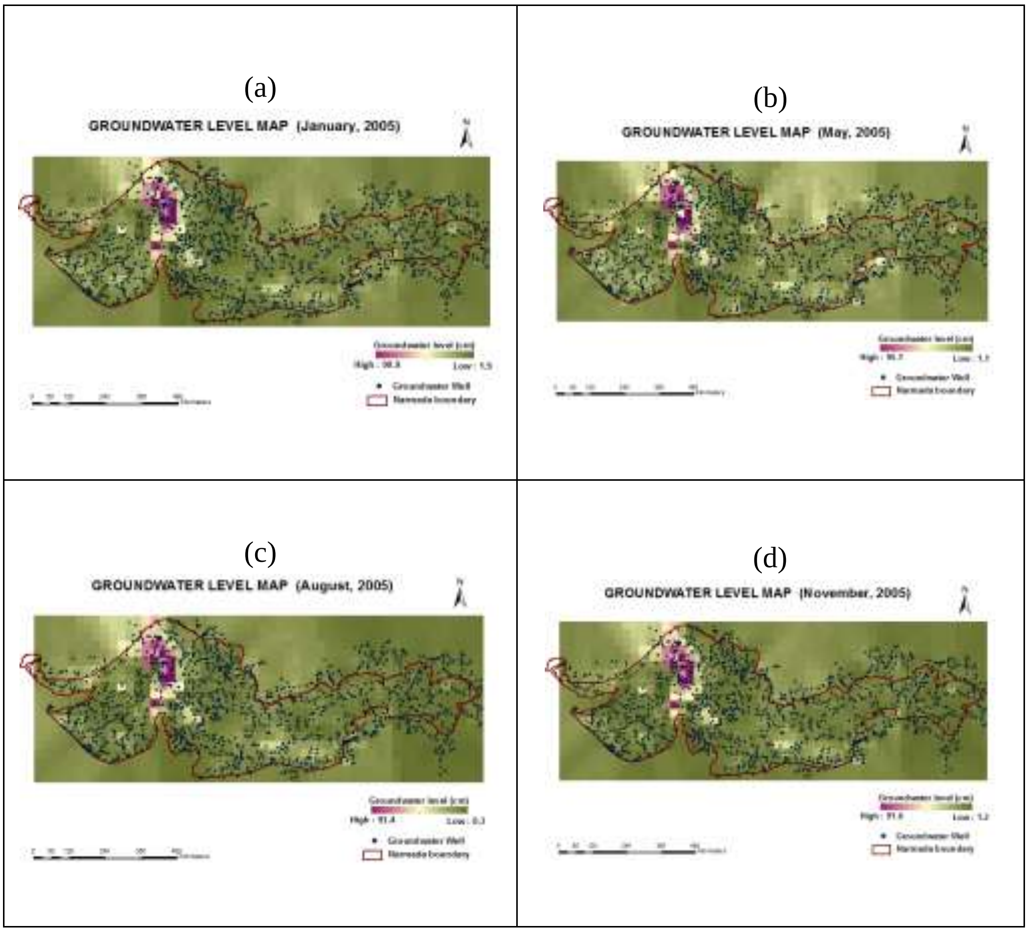
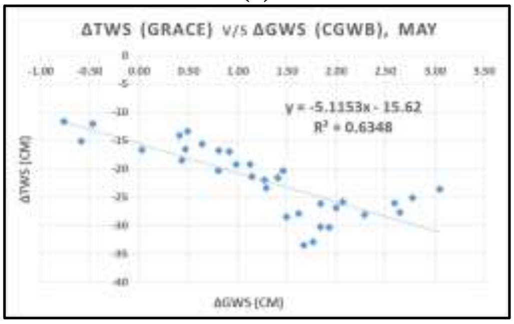


Figure 5-8 Season-wise Groundwater level Interpolation maps (2005) for (a) January (b) May (c) August (d) November

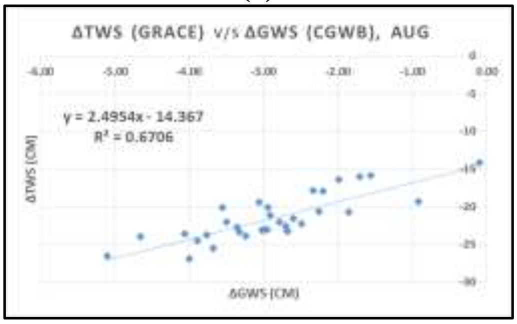
5.4 CORRELATION BETWEEN GRACE DERIVED ΔTWS AND CGWB's ΔGWS

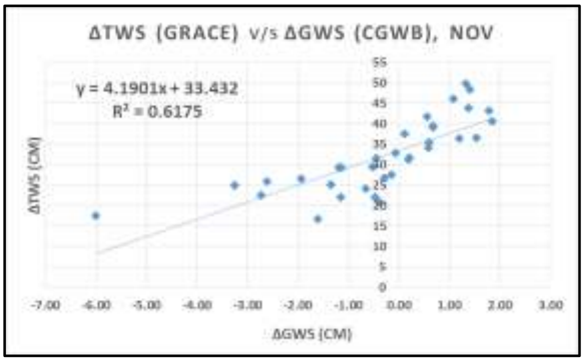
Correlation was developed for average values of the grid (1°) so that every grid has a unique value of ΔTWS and ΔGWS both. And a one to one correlation can be established. The equation thus obtained can be used to downscale GRACE ΔTWS from 1° to 0.25°. The strong correlation proves that the data received from GRACE (ΔTWS) is valid and ΔGWS can be derived from the data. Correlation plots between GRACE derived ΔTWS and CGWB's ΔGWS are given below,

(a)



(b)





(c)

Figure 5-9 Correlation between ΔTWS (GRACE) and ΔGWS (CGWB) for (a) May (Summer - season) (b) August (Monsoon - season) (c) November (Post-Monsoon season)

The summer season includes month of January, February, March and April. While, Monsoon-season consists of May, June, July and August, September, October, November and December together comprises of Post-monsoon season. When coefficient of determination, R^2 is above 0.60 (60%), the correlation thus attained between the two datasets is said to be valid. The R^2 achieved for summer was 0.6348 hence we can say that the data is 63.4% correlated. Similarly, R^2 for the monsoon season was 0.6706 and R^2 for post monsoon is 0.6175. A healthy correlation proves that the ΔTWS data can be used to derive ΔGWS without reducing ΔSM and ΔSW from ΔTWS.

5.5 CORRELATION BETWEEN BASEFLOW AND GRACE ΔTWS AT 0.25°

The idea behind correlation of VIC derived baseflow and GRACE derived ΔTWS is that, we can prove that baseflow is the potential source for groundwater recharge. Hence, to hold this statement to be effective, firstly we correlated ΔTWS (GRACE) and ΔGWS (CGWB) at 1° and then baseflow with ΔTWS (GRACE) at 0.25°.

The obtained correlation is given below with its coefficient of determination (R^2) and the equation of the trend-line.

(a) (b)

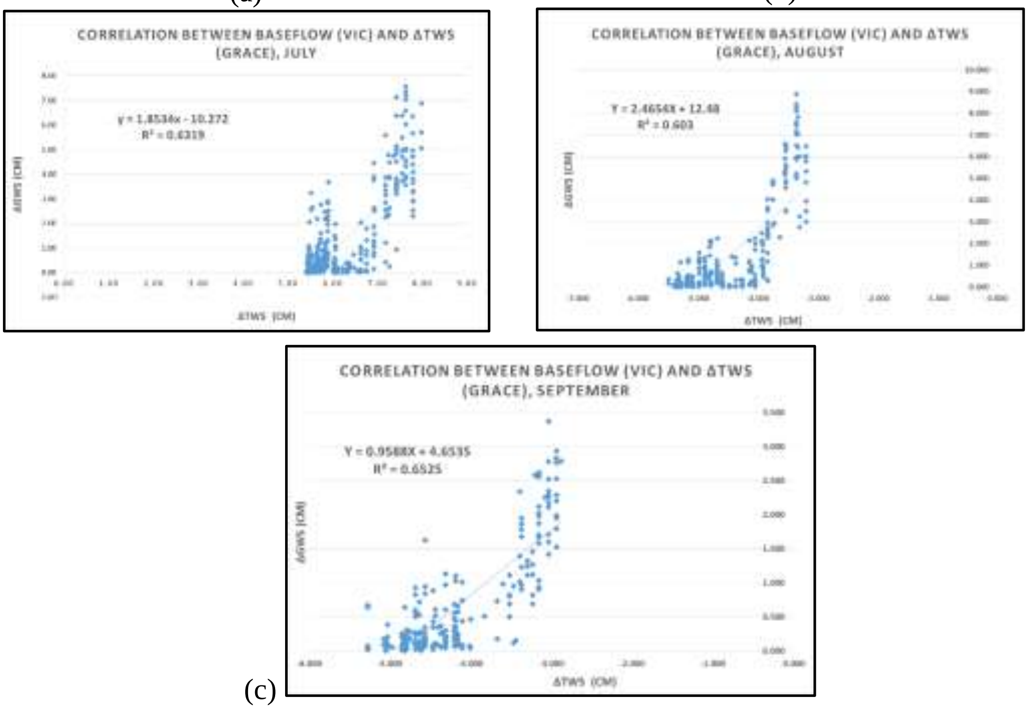


Figure 5-10 Correlation between Baseflow (VIC) and ΔTWS (GRACE) for (a) July (b) August (c) September

The baseflow will be maximum during the frequent precipitation. Therefore, the R^2 was determined for the monsoon months only. The R^2 for July was 0.6319, for August it was 0.603 and for September the R^2 was 0.6525. We can deduced the above statistics as, baseflow and ΔTWS are 63.19% correlated for the month of July, 60.3% correlated for August and 65.25% correlated for the month of September. Thus, it can be interpreted as the baseflow to be the potential recharge of the groundwater.

5.6 SURFACE WATER ASSESSMENT

Surface water assessment can be estimated by considering runoff modelled from VIC model. The water storage capacity of the extended Narmada basin is estimated. The table showing the reservoir capacity is given below,

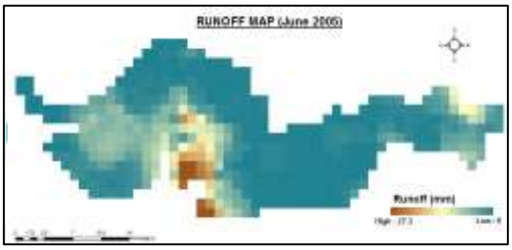
Table 5-1 Surface water storage capacity in the basin

Sr. No.	RESERVOIR	VOLUME (MCM)	Sr. No.	RESERVOIR	VOLUME (MCM)
1.	Amirpur	8205.30	14.	Mahi Bajaj Sagar	46086.62
2.	Bargi	120819.72	15.	Nal Sarovar	40464.49
3.	Barna	21856.74	16.	Omkareshwar	5943.06
4.	Bhadar	6162.36	17.	Panam	10785.21
5.	Damanganga	8053.45	18.	Rann Drainage	2658.90
6.	Dantiwada Dam	18818.35	19.	Sabarmati	36833.08
7.	Girna	27940.90	20.	Sardar Sarovar	13966.98
8.	Hatnur	26065.55	21.	Shetrunji	8015.32
9.	Indira Sagar	140667.23	22.	Sipu Dam	3077.71
10.	Jhakam	8237.40	23.	Tawa	47674.44
11.	Kadana	21194.22	24.	Ukai	54003.92
12.	Karjan	3236.77	25.	Watrak	6056.76
13.	Madhuban	1042.98			
TOTAL					**817241.24**

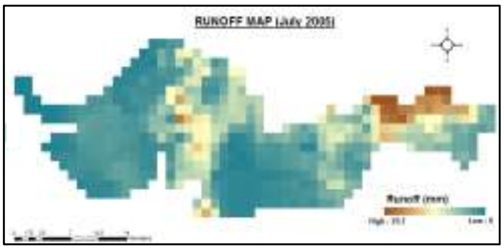
Runoff from the model considers every geographic and geologic parameter which affects the runoff. Modelled runoff is the sum of the surface runoff as well as the baseflow. But, we can separate both the runoff and baseflow using a code run in IDL which gives average of every water budget component. And thus, only surface water is used for the assessment purpose.

The average runoff monthly maps for the year 2005 are given below,

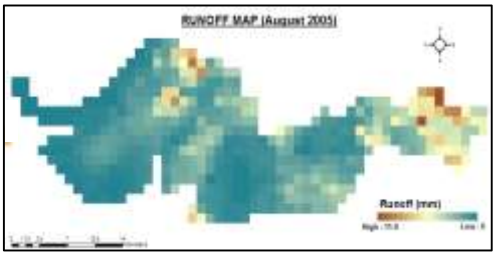
(a)



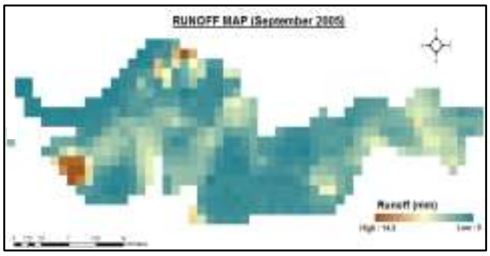
(b)



(c)



(d)



(e)

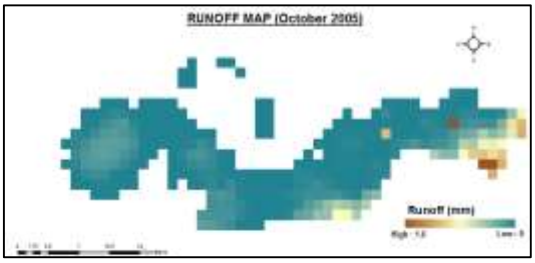


Figure 5-11 Average Runoff maps of 2005 for months (a) June (b) July (c) August (d) September (e) October

Maps above demonstrates the runoff (surface water) for the monsoon months of June, July, August and September. The surface water is assessed in terms of the runoff over the basin. The period when maximum runoff can occur is the monsoon season. Thus, only the rainy months are taken into consideration while assessing the surface water.

5.7 WATER BALANCE CLOSURE

The water balance study of extended Narmada basin was done for the year 2005. The perfect water balance closure states that the input – output = 0, i.e. sum of water balance components should be equal to the amount of precipitation.

$$P - Q + ET + \Delta SM = 0 \quad (5.2)$$

But, this is practically impossible to achieve due to insufficient inputs. The water balance is closed with minimum possible error of 37.27 mm. The complete statistics is demonstrated below,

Table 5-2 Water Balance for 2005 (VIC model)

Water Budget Component	Values in mm
Precipitation (P)	927.79
Runoff (including baseflow) (Q)	427.42
Evapotranspiration (ET)	498.40
Change in Soil Moisture (ΔSM)	-35.30
ERROR	**37.27**

The Precipitation is obtained from the IMD data. Runoff, ET and change in soil moisture was estimated from the VIC model. The ΔSM is considered only from the first layer. This is so because we assumed that the change in the second layer is constant since period of analysis is one year.

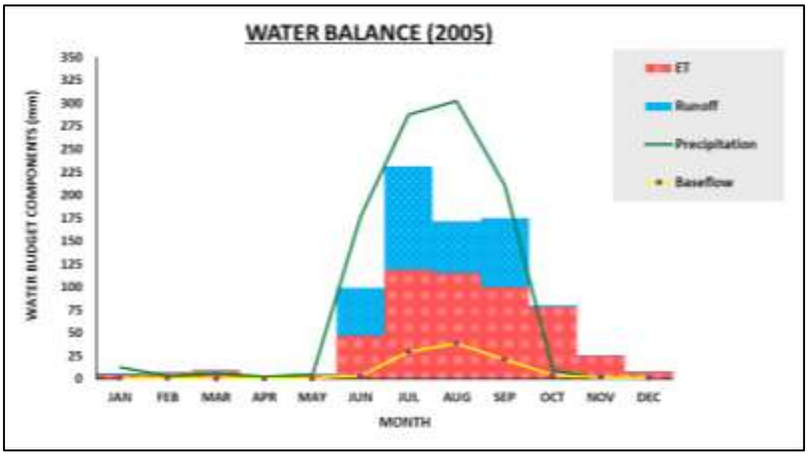
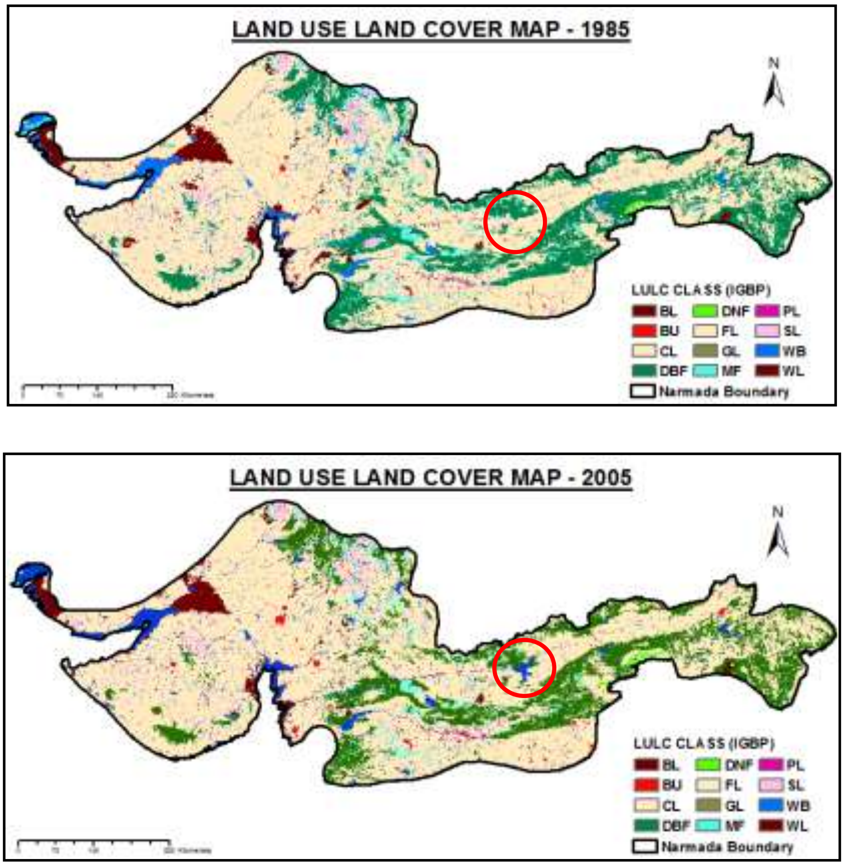


Figure 5-12 Water Budget of Narmada basin for 2005

5.8 IMPACT ON HYDROLOGY DUE TO LULC CHANGE

To study the effect of LULCC on hydrology of the basin, two different LULC scenarios were taken into consideration (1985 and 2005) as shown below,



(a)

(b)

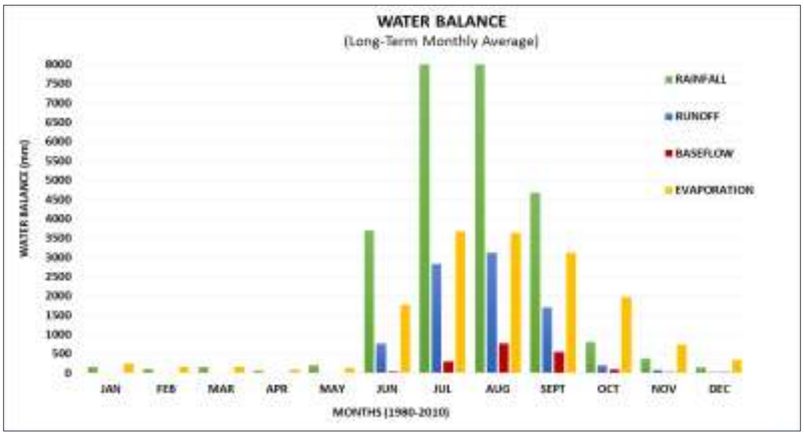
Figure 5-13 Land Use Land Cover map of Narmada basin for (a) 1985 (b) 2005

The two scenarios consists of (I) Meteorological forcing from 1980 – 2010 with LULC of 1985 (II) Meteorological forcing from 1980 – 2010 with LULC of 2005. The analysis period was taken 30 years. The major change in the LULCs is highlighted with red circle. The variances were observed due to the presence of a new reservoir (Indira Sagar dam with a capacity of 12.22 Bm^3) in the scenario-II. Existence of the major reservoir affects the hydrology of the basin. It is important to consider the reservoir/lake/wetland while estimating the water balance of the basin. The hydrologic components affected by the presence of reservoir were runoff, baseflow, evapotranspiration and discharge. This can be witnessed from the alterations observed in the water budget and its components. Also the discharge routed from VIC model shows a remarkable difference.

A substantial increase in evaporation of 0.56% was observed, while a decrease in the Runoff by 42.42%, Baseflow by 34.18% and Discharge by 34% was witnessed in Narmada basin for LULC of 2005 as compared to LULC of 1985.

The water balance for monthly long-term is derived for Narmada basin to understand the impact of LULC change on the water balance of the basin.

(a)



(b)

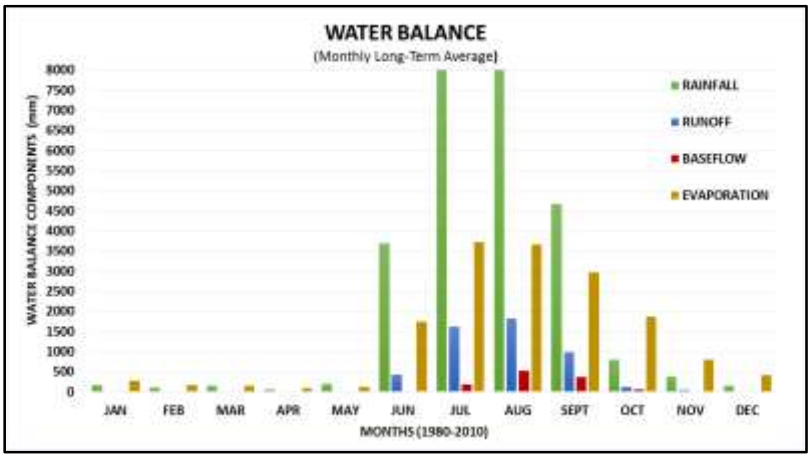
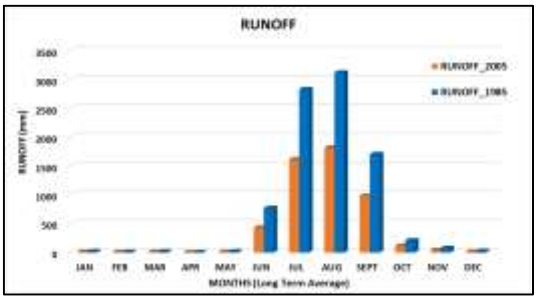


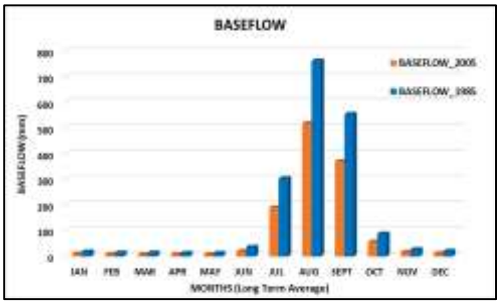
Figure 5-14 Long-term monthly (1980-2010) Water Balance of Narmada basin with LULC of (a) 1985 and (b) 2005

Following graph shows the impact of LULCC on the hydrology of Narmada basin (extended), in terms of water budget components and discharge.

(a)



(b)



(c)

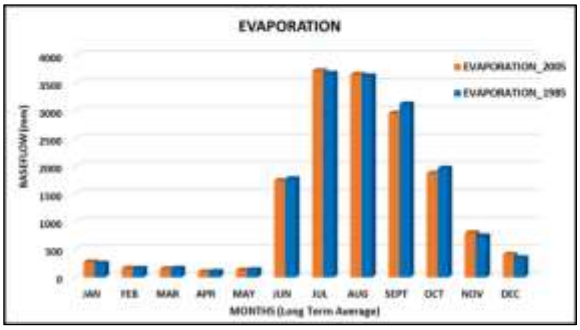


Figure 5-15 Water Budget of Narmada basin of 2005 for (a) Runoff, (b) Baseflow and (c) Evaporation

The impact of land use and land cover changes can be clearly seen through the differences in water budget components graphed above. It can be noticed that runoff reduced scenario-II as compared to the scenario-I. The justification for this cause is that initially runoff gets stored into the reservoir and then it further flows. The Lake algorithm explained in section 4.4.7 defends this reason. Understanding the Lake algorithm helps to figure out the exact logic for estimating the runoff. The runoff first enters into the lake, it fills the lake up to the height specified in the lake parameter file and then the remaining runoff flows into the channels for routing.

(a)

(b)

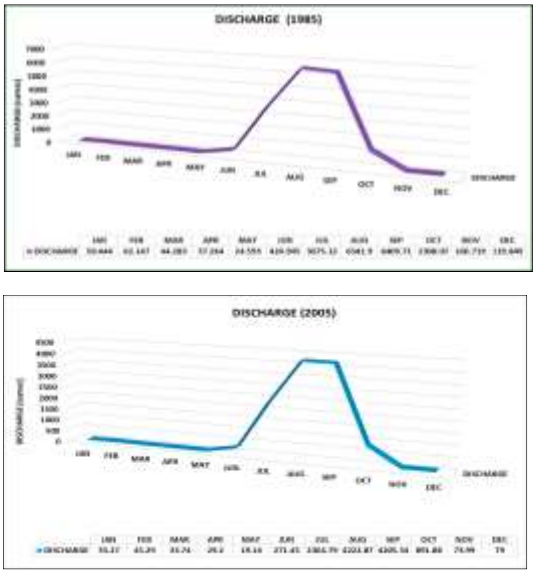


Figure 5-16 Discharge for the time span of 30 years (1980-2010) with LULC of (a) 1985 (b) 2005

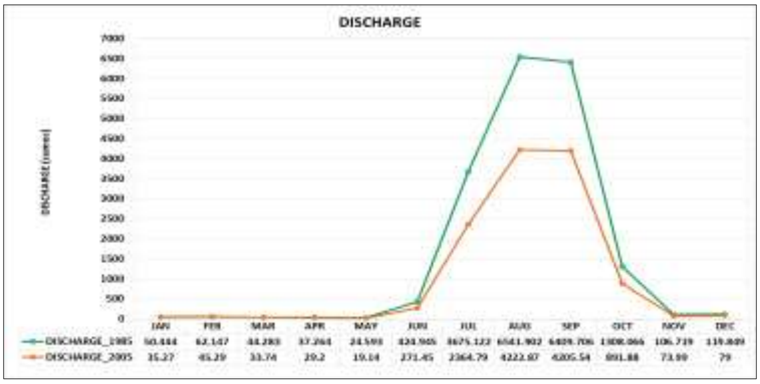


Figure 5-17 Discharge comparison with two LULC scenarios (1985 and 2005)

Routing of the model is elucidated in section 4.5.5. The runoff routed through the channel flow is measured at a station point. This location is specified into the station location file. The discharge is obtained through routing of the VIC model at Garudeshwar. The discharge in scenario-I can be perceived to exceed than in scenario-II. In view of the fact that initial quantity of runoff has been stored into the reservoir in scenario-II while in scenario-I it is evaluated as the surface runoff. The Lake algorithm validates this analysis.

6. CONCLUSION AND RECOMMENDATION

In this study, the VIC model was preferred amongst the finest of existing models. The selection criteria (Section–4.1) included the smallest unit on which the model operates, inputs, outputs and major advantages like incorporation of remote sensing inputs, etc. A parameter sensitivity analysis was carried on Asan watershed for a period of one year (2005). The results showed a remarkable change in both the cases (i) Results i.e. the water balance components while including Wind speed parameter and (ii) Results excluding Wind speed, in the meteorological forcing parameter file. This study was necessary because, VIC when run in Water Balance mode needs only three mandatory parameters (daily rainfall, daily maximum temperature, and minimum temperature). Wind speed influences the water balance components specially evapotranspiration (ET). Since, we are expecting to close the water balance with maximum precision, every component of the water budget needs to be modelled carefully and accurately. So, this study was obligatory. Hence, an accurate water balance is attained for year 2005 for the Narmada basin.

The model was setup with the wind speed and the model was forced with 30 years (1980 – 2010) for three different types of LULC (Land Use Land Cover of 1985, 1995, and 2005) to study the effect of LULC change on hydrology of the Narmada basin. Thus, except for groundwater, the other water balance components, ET, runoff (R), change in soil moisture (ΔSM) and baseflow (BF) were obtained from the model for each LULC.

VIC estimated runoff, ET, ΔSM, baseflow but groundwater. ΔGWS_{GRACE} is observed to be more dominant in ΔTWS_{GRACE}. The default time baseline (January 2004 to December 2009) was changed according to the study time baseline (January 2005 to December 2005) for each calculations. The seasonal variations of ΔTWS_{GRACE} and ΔGWS_{CGWB} were correlated for the year 2005 at 1°. This was derived to state that the ΔTWS_{GRACE} (satellite data) can be used as an auxiliary data for ΔGWS_{CGWB} (ground data). The baseflow can be potential source of groundwater recharge was proved by correlating the $baseflow_{VIC}$ and ΔTWS_{GRACE} at 0.25°.

The derived conclusions and the necessary recommendation are stated in this chapter.

6.1 CONCLUSIONS

i. VIC model was designated as the model with highest precision. This statement was noted after a theoretical study of the hydrologic models, SWAT, MIKE and HEC-HMS. Main advantages of VIC over other three models was that it simulates on sub-grid basis, it considers the non-linear baseflow, and it takes into account the LULC at a sub-grid level. VIC is a semi-distributed macroscale model. Also VIC calculates water balance at sub-grid level and estimates the water balance of the grid as a sum of all sub-grids. The lake/wetland parameter is optional but if provided as one of the inputs to the model, it finely computes the water budget components.

ii. VIC model is sensitive to the wind speed parameter. It was deduced from the study after observing the variations in the water budget components. Evapotranspiration was highly affected by the presence and absence of the wind speed input. Hence, wind speed must always be included in the meteorological forcing file while carrying out the water balance studies. Wind speed thus proves to be the necessary input amid the hydro-meteorological data.

iii. The R^2 for the correlation between ΔGWS_{CGWB} and ΔTWS_{GRACE} at 1°, helped in understanding that the ΔTWS from GRACE (satellite data) of can be used as an auxiliary data for ΔGWS (achieved from groundwater well level data). In GRACE, the ΔTWS comprises of ΔSM, ΔSW and ΔGWS_{GRACE}. It was detected that removal of ΔSM and ΔSW from ΔTWS_{GRACE} does not alter ΔGWS_{GRACE}. Thus, ΔTWS obtained from GRACE can directly be used in the studies related to groundwater or its assessment.

iv. It is necessary to use the ΔTWS_{GRACE} with time baseline same as the period of analysis. This is so because, the default time baseline of the GRACE data is January 2004 – December 2009.

v. The VIC modelled baseflow was concluded to be responsible for the groundwater recharge. This was deduced on the basis of the strong correlation between seasonally derived $baseflow_{VIC}$ and ΔTWS_{GRACE} at 0.25°.

vi. Groundwater cannot be accurately assessed due to lack of data regarding the groundwater draft and the recharge through irrigation.

vii. The surface water of the basin is assessed in terms of the runoff calculated by VIC including the lakes in the basin. The storage capacity of the Narmada basin is also calculated. Runoff modelled from VIC includes the baseflow as well.

viii. The water balance is closed with an acceptable error of 37.27mm

ix. Impact of LULC change on hydrology of Narmada basin was studied. The existence of lake/reservoir/wetland in a basin bothers the water budgeting (components) of the basin. This statement hold true since a substantial increase in evaporation of 0.56% was observed, while a decrease in the Runoff by 42.42%, Baseflow by 34.18% and Discharge by 34% was witnessed in Narmada basin for LULC of 2005 as compared to LULC of 1985.

x. The reservoirs/lakes cannot be ignored while modelling the hydrology of a basin.

6.2 RECOMMENDATIONS

i. To assess groundwater, the input data for instance say groundwater recharge, groundwater draft through wells, recharge through irrigation, etc. must be attained from ground sampling.
ii. If not available from ground (field), the mandatory data mentioned above must be incorporated in the model.
iii. Downscaling of GRACE from 1° to desired grid size is suggested.
iv. The model should take into account the urban class of LULC.

7. REFERENCES

Abdulla, F.A., Lettenmaier, D.P., 1997. Development of regional parameter estimation equations for a macroscale hydrologic model. J. Hydrol. 197, 230–257.

Amir AghaKouchak, 2013. A multivariate approach for persistence-based drought prediction: Application to the 2010–2011 East Africa drought. Journal of Hydrology 526, 127-135.

Almhab Ayoub, Busu Ibrahim, Cracknell Arthur, 2007. Comparison of Regional Scale Evapotranspiration using NOAA-AVHRR and LANDSAT-TM images: A case study in an arid area in the Sana's Basin, Republic of Yemen. The 28th Asian conference on Remote Sensing (ACRS) 2007.

Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling: a review. Hydrol. Process. 9, 251–290.

Bowling, L.C., J.W. Pomeroy and D.P. Lettenmaier, 2004, Parameterization of blowing snow sublimation in a macroscale hydrology model J. Hydromet. Vol. 5, No. 5, pp 745-762. doi: 10.1175/1525-7541

Bowling, L. C., and D. P. Lettenmaier (2009), Modeling the effects of lakes and wetlands on the water balance of Arctic environments, Journal of Hydrometeorology, submitted.

Chang, J., Okimoto, G., 1970. Global Water Balance According to the Penman Approach. Geogr. Anal. 2, 55–67.

Cherkauer, K. A., and D. P. Lettenmaier (1999), Hydrologic effects of frozen soils in the upper Mississippi River basin, J. Geophys. Res.-Atmos., 104(D16), 19599-19610.

Cherkauer, K.A., Bowling, L.C., Lettenmaier, D.P., 2003. Variable infiltration capacity cold land process model updates. Glob. Planet. Change 38, 151–159. Doi: 10.1016/S0921-8181(03)00025-0.

Deardorff, J. W. (1978), Efficient prediction of ground surface-temperature and moisture, with inclusion of a layer of vegetation, Journal of Geophysical Research-Oceans and Atmospheres, 83(NC4), 1889-1903.

Dickinson, R. E. (1984), Modeling evapotranspiration for three-dimentional global climate models, in Climate Processes and Climate Sensitivity, Monogr. Ser., edited by J. E. Hansen and T. Takahashi, pp. 58-72, Washington, D.C.

Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., Scanlon, B.R., 2012. Impact of water withdrawals from groundwater and surface water on continental water storage variations. J. Geodyn. 59-60, 143–156. doi:10.1016/j.jog.2011.05.001.

Duband, D., Obled, C., Rodriguez, J.Y., 1993. Unit hydrograph revisited – an alternate iterative approach to UH and effective precipitation identification. Journal of Hydrology 150 (1), 115–149.

Frappart, F., Papa, F., Güntner, A., Werth, S., Santos da Silva, J., Tomasella, J., Seyler, F., Prigent, C., Rossow, W.B., Calmant, S., Bonnet, M.-P., 2011. Satellite-based estimates of groundwater storage variations in large drainage basins with extensive floodplains. Remote Sens. Environ. 115, 1588–1594. doi:10.1016/j.rse.2011.02.003.

Gao, H., Q. Tang, X. Shi, C. Zhu, T. J. Bohn, F. Su, J. Sheffield, M. Pan, D. P. Lettenmaier, and E. F. Wood, 2007: Water Budget Record from Variable Infiltration Capacity (VIC) Model. In Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records

García, A., Sainz, A., Revilla, J.A., Álvarez, C., Juanes, J.A., Puente, A., 2008. Surface water resources assessment in scarcely gauged basins in the north of Spain. J. Hydrol. 356, 312–326. doi:10.1016/j.jhydrol.2008.04.019

Githui, F., Mutua, F., Bauwens, W., 2009. Estimating the impacts of land-cover change on runoff using the soil and water assessment tool (SWAT): case study of Nzoia catchment, Kenya / Estimation des impacts du changement d'occupation du sol sur l'écoulement à l'aide de SWAT: étude du cas du bassin de Nzoia, Kenya. Hydrol. Sci. J. 54, 899–908. doi:10.1623/hysj.54.5.899

Haddeland, I., D.P. Lettenmaier, and T. Skaugen, 2006a: Effects of irrigation on the water and energy balances of the Colorado and Mekong River basins, *J. Hydrol.*, 324(1-4), 210-223

Haddeland, I., T. Skaugen, and D.P. Lettenmaier, 2006b: Anthropogenic impacts on continental surface water fluxes, *Geophys. Res. Lett.*, 33, L08406, doi: 10.1029/2006GL026047

Haddeland, I., T. Skaugen, and D.P. Lettenmaier, 2007: Hydrologic effects of land and water management in North America and Asia: 1700-1992, *Hydrol.Earth Sys. Sci.*, 11(2), 1035-1045

Homdee, T., Pongput, K., Kanae, S., 2011. Impacts of land cover changes on hydrologic responses: a case study of Chi River Basin, Thailand. 土木学会論文集 B1 水工学 67, I_31–I_36.

Hostetler, S. W., and P. J. Bartlein (1990), SIMULATION OF LAKE EVAPORATION WITH APPLICATION TO MODELING LAKE LEVEL VARIATIONS OF HARNEY-MALHEUR LAKE, OREGON, Water Resour Res, 26(10), 2603-2612.

Hostetler, S. W. (1991), Simulation of lake ice and its effect on the late-Pleistocene evaporation rate of Lake Lahontan Climate Dynamics, 6, 43-48.

Jain, S.K., 2012. India's water balance and evapotranspiration. Curr. Sci. 102, 964–967.

Jain, S.K., Agarwal, P.K., Singh, V.P., 2007a. Groundwater, in: Hydrology and Water Resources of India. Springer, pp. 235–294.

Jain, S.K., Agarwal, P.K., Singh, V.P., 2007b. Narmada Basin, in: Hydrology and Water Resources of India. Springer, pp. 513–559.

Karimi, P., Bastiaanssen, W.G.M., Molden, D., Cheema, M.J.M., 2013. Basin-wide water accounting based on remote sensing data: an application for the Indus Basin. Hydrol. Earth Syst. Sci. 17, 2473–2486.

Krysanova, V., Bronstert, A., Müller-Wohlfeil, D.-I., 1999. Modelling river discharge for large drainage basins: from lumped to distributed approach. Hydrol. Sci. J. 44, 313–331.

Kuchment, L.S., 2004. The Hydrological Cycle and Human Impact on It. Water Resources Manage. Eolss.

Kuss, A., Brandt, W.T., Randall, J., Floyd, B., Bourai, A., Newcomer, M., Schmidt, C., Skiles, J.W., 2012. Comparison of changes in groundwater storage using GRACE data and a hydrological model in California's Central Valley, in: ASPRS Ann. Conf., Sacramento, CA.

Kuss, A.J., Newcomer, M., Hsu, W.-C., Bourai, A., Puranam, A., Landerer, F., Schmidt, C., 2012. Earth Science and Climate Change. Earth Sci. 2012.

Landerer F.W. and S. C. Swenson, Accuracy of scaled GRACE terrestrial water storage estimates. Water Resources Research, Vol 48, W04531, 11 PP, doi: 10.1029/2011WR011453 2012

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J. (1994). “A simple hydrologically based model of land surface water and energy fluxes for general circulations models.” J. Geophys. Res., [Atmos.], 99 D7, 14415–14428.9yg

Liang, X., Wood, E. F., and Lettenmaier, D. P. (1996b). “Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification.” Global and Planetary Change, 13, 195–206

Liang, X., and Z. H. Xie (2003), Important factors in land-atmosphere interactions: surface runoff generations and interactions between surface and groundwater, Global Planet Change, 38(1-2), 101-114.

Lohmann, D., Nolte-Holube, R. and Raschke, E., (1996), A large scale horizontal routing model to be coupled to land surface parameterization schemes, Tellus (48A), 708-721.

Lohmann, D., Raschke, E., Nijssen, B., Lettenmaier, D.P., 1998a. Regional scale hydrology: II. Application of the VIC-2L model to the Weser River, Germany. Hydrol. Sci. J. 43, 143– 158.

Lohmann, D., Raschke, E., Nijssen, B., Lettenmaier, D.P., 1998b. Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model. Hydrol. Sci. J. 43, 131– 141.

Louis, J. F. (1979), Parametric Model of Vertical Eddy Fluxes in the Atmosphere, Bound-Lay Meteorol, 17(2), 187-202.

Milewski, A., Sultan, M., Yan, E., Becker, R., Abdeldayem, A., Soliman, F., Gelil, K.A., 2009. A remote sensing solution for estimating runoff and recharge in arid environments. J. Hydrol. 373, 1–14. doi:10.1016/j.jhydrol.2009.04.002.

Miloradov, R. M.; Marjanovic, P.; Cukic, Z. River basin management for sustainable development proceedings of the 7th International Symposium on River Basin Management, held in Kruger National Park, South Africa, 15-17 May, 1995. 1st ed. Oxford; New York: Pergamon Press, 1995. p. 45-53.

Monteith, J. L., and M. H. Unsworth (1990), Principles of Environmental Physics, 2nd ed., Routledge, Chapman and Hall, New York.

Nie, W., Yuan, Y., Kepner, W., Nash, M.S., Jackson, M., Erickson, C., 2011. Assessing impacts of Landuse and Landcover changes on hydrology for the upper San Pedro watershed. J. Hydrol. 407, 105–114. doi:10.1016/j.jhydrol.2011.07.012

Nijssen, B., Lettenmaier, D. P., Liang, X., Wetzel, S. W., and Wood, E. F.: 1997, Streamflow Simulation for Continental-Scale River Basin, Water Resour. Res.33, 711–724.

Nijssen, B., O'Donnell, G.M., Hamlet, A.F., Lettenmaier, D.P., 2001. Hydrologic sensitivity of global rivers to climate change. Clim. Change 50, 143–175.

Njoku, E. G. 2004. AMSR-E/Aqua Daily L3 Surface Soil Moisture, Interpretive Parameters, & QC EASE-Grids. Version 2. Boulder, Colorado USA: NASA National Snow and Ice Data Center Distributed Active Archive Center.

Patterson, J. C., and P. F. Hamblin (1988), THERMAL SIMULATION OF A LAKE WITH WINTER ICE COVER, Limnology and Oceanography, 33(3), 323-338.

Petchprayoon, P., Blanken, P.D., Ekkawatpanit, C., Hussein, K., 2010. Hydrological impacts of land use/land cover change in a large river basin in central-northern Thailand. Int. J. Climatol. 30, 1917–1930. doi:10.1002/joc.2131

Punmia B.C., Lal Pande, Jain A.K., Jain Arun, 2009. Irrigation and Water Power Engineering.

Raj, P.P.N., Azeez, P.A., 2010. Land Use and Land Cover Changes in a Tropical River Basin: A Case from Bharathapuzha River Basin, Southern India. J. Geogr. Inf. Syst. 02, 185–193. doi:10.4236/jgis.2010.24026

Rodell M., (2004). Basin scale estimates of evapotranspiration using GRACE and other observations. Geophys. Res. Lett. 31.

Rodell, Matthew, Chen, J., Kato, H., Famiglietti, J. S., Nigro, J., and Wilson, C. R. (2006). Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. Hydrogeology Journal, 15(1), 159–166. Doi: 10.1007/s10040-006-0103-7.

Rodell M., (2013), Application of Satellite Gravimetry for Water Resource Vulnerability Assessment, Reference Module in Earth Systems and Environmental Sciences, from Climate Vulnerability, Volume 5, Pages 151-159.

Sahoo, A.K., Pan, M., Troy, T.J., Vinukollu, R.K., Sheffield, J., Wood, E.F., 2011. Reconciling the global terrestrial water budget using satellite remote sensing. Remote Sens. Environ. 115, 1850–1865. doi:10.1016/j.rse.2011.03.009.

Saxton K.E., Rawls W.J., 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solution. Soil Science Society of America Journal.

Sene K., 2013. Flash Floods: Forecasting and Warning, DOI 10.1007/978-94-007-5164-4_2. Springer Science.

Sharma, S.K., Kansal, M.L., Tyagi, A., 2015. Resource assessment and strategic planning for improvement of water supply to Shimla city in India using geo-spatial techniques. Egypt. J. Remote Sens. Space Sci. 18, 85–97. doi:10.1016/j.ejrs.2015.04.001

Shuttleworth, W. J. (1993), Evaporation, in Handbook of Hydrology, edited by D. R. Maidment, pp. 4.1-4.53, McGraw-Hill, Inc., New York.

Singh V.P. and Frevert Donald, 2006. Mathematical models of small watershed hydrology and applications. Water Resources, Highlands Ranch, CO.

Strassberg, G., Scanlon, B.R., Rodell, M., 2007. Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA). Geophys. Res. Lett. 34. Doi: 10.1029/2007GL030139.

Subramanya K. Engineering Hydrology. New Delhi, India, 1994.

Swenson, S., Famiglietti, J., Basara, J., Wahr, J., 2008. Estimating profile soil moisture and groundwater variations using GRACE and Oklahoma Mesonet soil moisture data: GRACE ESTIMATES OF GROUNDWATER VARIABILITY IN OKLAHOMA. Water Resour. Res. 44, n/a–n/a. doi: 10.1029/2007WR006057.

Swenson, S., Wahr, J., 2006. Estimating large-scale precipitation minus evapotranspiration from GRACE satellite gravity measurements. J. Hydrometeorol. 7, 252–270.

Swenson, S. C. and J. Wahr, Post-processing removal of correlated errors in GRACE data, Geophys. Res. Lett., 33, L08402, doi: 10.1029/2005GL025285, 2006.

UNESCO/WMO (1992) International Glossary of Hydrology. Second edition. UNESCO/WMO.

VanShaar, J.R., Haddeland, I., Lettenmaier, D.P., 2002. Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. Hydrol. Process. 16, 2499–2520. doi:10.1002/hyp.1017

Wang X., F.B. Ma, J.Y. Li, 2012. Water Resources Vulnerability Assessment based on the Parametric-system Method: a Case Study of the Zhangjiakou Region of Guanting Reservoir Basin, North China. Procedia Environmental Sciences. Volume 13, 2012, Pages 1204–1212

Wigmosta, M. S., Vail L. W., Lettenmaier D. P., (1994), A DISTRIBUTED HYDROLOGY-VEGETATION MODEL FOR COMPLEX TERRAIN, Water Resour Res, 30(6), 1665-1679.

Xiang-Hu Li, Qi Zhang, Chong-Yu-Xu, 2012. Suitability of the TRMM satellite rainfalls in driving a distributed hydrological model for water balance computations in Xinjiang catchment, Poyang lake basin. Journal of Hydrology, Volumes 426-427 (pages 28-38).

Xie, Z., Yuan, F., Duan, Q., Zheng, J., Liang, M., Chen, F., 2007. Regional Parameter Estimation of the VIC Land Surface Model: Methodology and Application to River Basins in China. J. Hydrometeorol. 8, 447–468. doi:10.1175/JHM568.1.

Zhang, Y., Wegehenkel, M., 2006. Integration of MODIS data into a simple model for the spatial distributed simulation of soil water content and evapotranspiration. Remote Sens. Environ. 104, 393–408.

Websites:

http://geochange.er.usgs.gov/sw/changes/natural/et/ (2014)

http://gis2.nic.in/cgwb/Gemsdata.aspx (2014)

http://www.earthzine.org (2014)

http://india-wris.nrsc.gov.in (June, 2015)

http://nca.gov.in/nb_geogr.htm (June, 2015)

www.unesco-ihe.org (June, 2015)

www.hydro.washington.edu